

FLUID FLOW AND PARTICLE SIZE IN GAS ATOMIZATION FOR  
FINE POWDERS

MICHAEL J. NAYLOR

PhD

IMPERIAL COLLEGE

LONDON SW7 2AZ

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## ABSTRACT

The production of rapidly solidified fine metal powders has become of increasing interest in recent years as the microstructural benefits such as refined grain size, increased solid solubility and elimination of segregated phases has become apparent. The cooling rate associated with solidification is the single most important process variable affecting the microstructure and therefore the properties of the product. Gas atomization can produce average cooling rates of up to  $10^6$  K/sec and is the only currently available mass production method for fine metal powders. However the effect of process variables on particle size are badly documented and confusing.

In order to investigate the effect of the nozzle size, geometry, and process variables, on particle size an experimental apparatus was constructed to carry out low temperature modelling of the atomization process using wax. A prefilming type nozzle design was selected for study and air was used as the atomizing gas. The experimental apparatus permitted independent control of the gas and liquid flowrates. Gas flow outside the nozzle was characterized by measuring the suction created at the tip of the nozzle, by using Schlieren photography to visualize the gas flow, and pitot tubes to measure the Mach number.

Investigations carried out included changes in the nozzle size and geometry, gas flow, liquid flowrate and liquid properties. High speed photography was used to observe the process of atomization. Detailed size analysis of the powder size produced was carried out using a Malvern Particle Size Analyser. The particle sizes measured were fitted to known size distributions using a computer program, which also calculated mean diameters and the dispersion of the particles about the mean. S.E.M. work was also been carried out to look into the shape of the wax particles produced to see whether they are similar to those of metals.

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## CHAPTER ONE

### LITERATURE SURVEY

## 1. INTRODUCTION

Metal powders obtained by rapid solidification techniques have been shown to produce materials which have superior properties over those produced by the conventional ingot casting route<sup>(1,2)</sup>.

The techniques available to produce powders are numerous and depend greatly upon such factors as quantity required, alloy system and particle size, to name a few<sup>(2,3)</sup>. Atomization has become the generally accepted term which describes the creation of fine particles typically smaller than 150 microns. The atomization techniques which impose a high cooling rate during solidification have been reviewed recently by Savage and Froes<sup>(3)</sup>. The present project is concerned with two fluid gas atomization which is the most widely used technology in this field. However before discussing two fluid atomization in detail the advantages of gas atomized powders over materials cast in bulk will be discussed.

### 1.1 ADVANTAGES OF GAS ATOMIZED POWDERS OVER MATERIALS CAST IN BULK

The production of rapidly solidified metal powders, obtained by gas atomization, has resulted in new alloys by enabling new phases to be formed and by extending the equilibrium phase fields. It has the additional advantage that the metal particles formed have a more uniform composition than a cast structure, and macrosegregation is eliminated. This results in a more even distribution of constituents, grain size homogeneity, improved workability and reproducibility of properties.

For the full benefits of rapid solidification the particle size should be as fine as possible and the heat transfer from the droplet should be as high as possible. This allows large nucleation undercooling which is an important factor in rapidly solidified microstructures<sup>(4)</sup>.

Rapid solidification also causes the structure of the metal powder to be refined and Grant<sup>(5,6)</sup> lists the following benefits of structural refinement, and he also mentions some of the shortcomings of prior research:

(a). Decreased Segregation - although there is a lack of general knowledge on exactly what benefits decreased segregation causes it has been found that decreased segregation of S and P to the grain boundaries in steel has improved properties.

(b). Refined Grain Size - a broad range of alloys has been produced with grain sizes as low as 1 micron. This improves strength, ductility, toughness, corrosion resistance etc. However there is little knowledge of the improvements that a grain size of 0.1 micron would produce. Areas which would benefit from further research are the recrystallization of glassy powders to highly refined grain sizes, and the role of 2nd phase precipitates in enhancing grain refinement. Also what are the specific effects on strength, fracture toughness, ductility and corrosion resistance of fine grain size?

(c). Increased Solid Solubility - increases in solid solubility depend on the cooling rate and there is considerable interest here. For example the use of lithium in aluminium alloys and the use of iron, cobalt, nickel, zirconium and cerium in aluminium for high strength, moderately high temperature alloys. However there is need for more work on the control of precipitation processes in a supersaturated matrix.

(d). Elimination of Segregation Phases - as the cooling rate increases and grain size decreases all elements in dilute quantities tend to be maintained in solution. As such they can be precipitated by an appropriate heat treatment to provide the optimum size, shape and distribution. It has been reported<sup>(6)</sup> that an alloy (Mar M-509 - high temperature cobalt based alloy) containing stoichiometric amounts of hafnium and carbon, when produced by a twin-roll splat technique, contained only HfC and no chromium carbide or  $\text{Co}_6\text{C}$ , both of which are found in slow cooled precision cast alloys. The absence of chromium carbides results in an increase of  $75^\circ\text{K}$  in the melting temperature of the alloy and ductility improvements at low and high temperatures.

Hence, this maybe an important area for study as there is potential for much higher alloy contents.

## 1.2 TWO FLUID ATOMIZATION.

In two fluid gas atomization, also known as pneumatic or blast atomization<sup>(7)</sup>, a high velocity gas (subsonic or supersonic velocity <sup>(8)</sup>) is used to disintegrate a continuous stream of liquid (e.g. metal). The major functions of the working fluid are to break up the molten metal stream into small particles and to solidify them. The atomizing gas impinges on the liquid metal, thereby breaking up the stream into metal droplets. However there are numerous different atomization nozzle geometries and ways in which the gas and metal can interact. The production of fine particles in atomization requires a full understanding of the gas flow and the metal break up in the process, and the influence on particle size of process variables and nozzle design. The literature<sup>(9-15)</sup>, up to the present time, lacks detailed information on the fine range of powders, below approximately 50 microns, of interest in atomization. It also does not deal with all the atomization process variables which affect the particle size of powder produced. The information which is available is confusing and contradictory, resulting in comments like those made by Gummerson<sup>(4)</sup> - "The atomization process is still somewhat of an art and not yet based on well recognized scientific principles".

Savage<sup>(3)</sup> noted in a recent review that in two fluid gas atomization the pressures used normally vary between 2-8 MPa and the powders produced have a particle size in the range 50-100 microns in diameter. He also says that powders solidify in flight at around  $10^2$ - $10^3$  °K/sec, and are usually smooth and spherical. Savage however does not mention what particle size classification is being used (i.e Mass Median Diameter, Sauter Mean Diameter etc.) The particle size quoted for gas atomization does not agree with the findings of Unal<sup>(39)</sup> who found the particle size to be below 30 microns mass median diameter in all but the most exceptional cases and obtained a minimum mass median diameter of

13.5 microns. The cooling rates mentioned by Savage are 2 to 3 orders of magnitude lower than those calculated, from measurements of dendrite arm spacing of Unal's powder, by Marshall<sup>(16)</sup>.

Gas atomization is widely used to make powders of aluminium, tool steels, super alloys, copper, iron, tin and low alloy steels on a tonnage basis for a wide variety of applications. Control of the particle size and the width of the particle size distribution in atomization is difficult and varies with a number of interrelated operating parameters. In order to understand the effect of the operating parameters it is necessary to investigate the operation of atomization nozzles and how the nozzles bring about the interaction between the metal and atomizing gas.

### 1.3 ATOMIZATION NOZZLES

The atomization nozzles used for gas atomization may be classified as "confined" or "free fall", as described by Klar and Shafer<sup>(14)</sup>, depending on whether the gas and liquid metal meet at the nozzle exit or at a point downstream of the nozzle exit. The two types are shown schematically in Figure 1.1

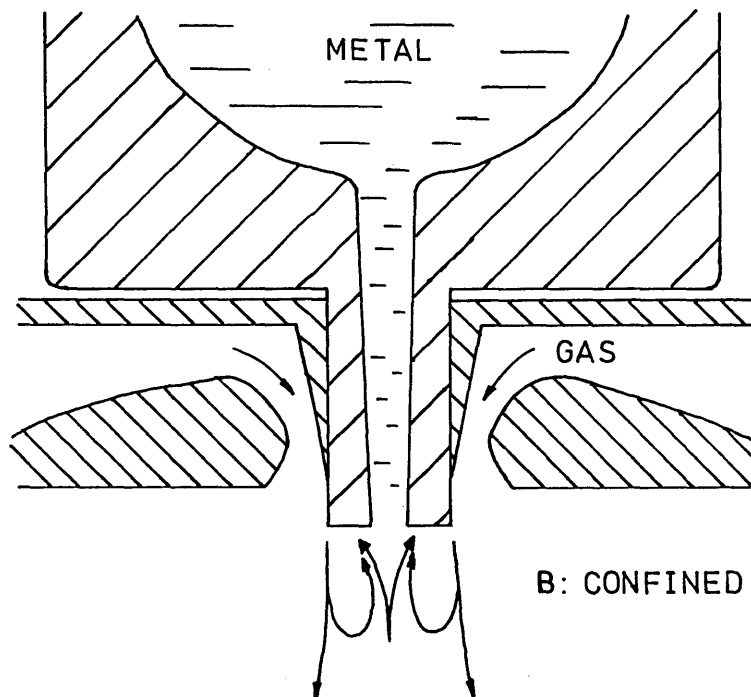
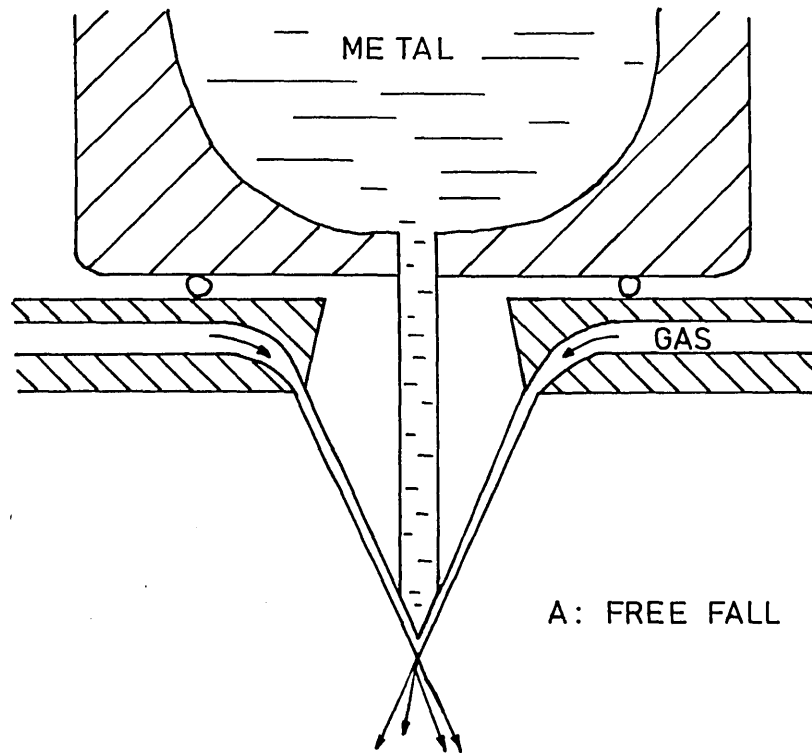
#### FREE FALL

The free fall nozzle, also known as the 'v-jet' nozzle, was developed by Hoeganaes in Sweden. A short metal stream, of between 50 and 200 mm, falls under the influence of gravity and is atomized by gas jets directed at the metal stream. The gas jets can take the form of either discrete jets or an annular jet concentric with the metal stream. A recent version of this design is Ultrasonic Gas Atomization (USGA) using discrete gas jets into which ultrasonic pulsations are introduced by using a Helmholtz cavity in the gas flow duct<sup>(17)</sup>.

#### CONFINED

In the confined design, the liquid metal is brought a short distance beyond the gas exit by means of a flow tube and the metal meets the gas jet, which is almost always annular, at the periphery of the tip of the tube in the form of a thin film. The nozzles can be operated in the horizontal, vertically upwards or

FIGURE 1.1     ATOMIZATION NOZZLES (14)



vertically downwards positions and the energy transfer, from gas to metal is maximized and more likely to be uniform than in the free fall design.

Confined nozzles can be designed to have supersonic, sonic or subsonic exit velocities. The convergent type of nozzle, with a sonic exit velocity, is the most common and has been used by numerous experimenters. (5,8,10,11,18)\*

For metal atomization the high temperatures involved and the difficulty of finding suitable nozzle materials require the use of externally mixing atomization nozzles in which the contact between the metal and atomizing gas takes place outside the nozzle. The nozzle materials must be able to withstand both the corrosion and erosion from the liquid metal as well as the thermal shock which occurs with liquid metal on the inside of the metal flow tube and the gas on the outside.

Atomization nozzles are mechanically inefficient. Gummerson<sup>(4)</sup> states, "for all its commercial successes, atomization of high melting temperature metals and alloys with external nozzles is a crude process in terms of efficiency and energy utilization" and Kim and Marshall<sup>(19)</sup> note that "It is surprising how few of the fundamental principles of disintegration of a liquid in a gas stream have been applied to the great number of designs of two fluid atomizers in the last century. Their mechanical efficiency is still extremely low and there is an increasing demand for atomizers of greater energy transfer". The efficiency of the atomization process is increased as the particle size decreases<sup>(18)</sup>. The efficiency has been measured as being of the order of 1 to 2 % <sup>(6)</sup>.

The atomization nozzle used by Thompson<sup>(9)</sup> is shown in Figure 1.2. The protrusion of the metal flow tube is of particular interest as this is one of the few designs which incorporates this feature (Klar and Shafer<sup>(14)</sup> also have a nozzle with a protrusion). Thompson found that operation with a 0 mm flow tube protrusion was impossible as freezing of aluminium occurred at the tip of the protrusion blocking the flow tube and the gas annulus. A protrusion of at least 3 mm was required before the operation of the nozzle was satisfactory and no blockages occurred. The diameter of the gas annulus was 13/16"

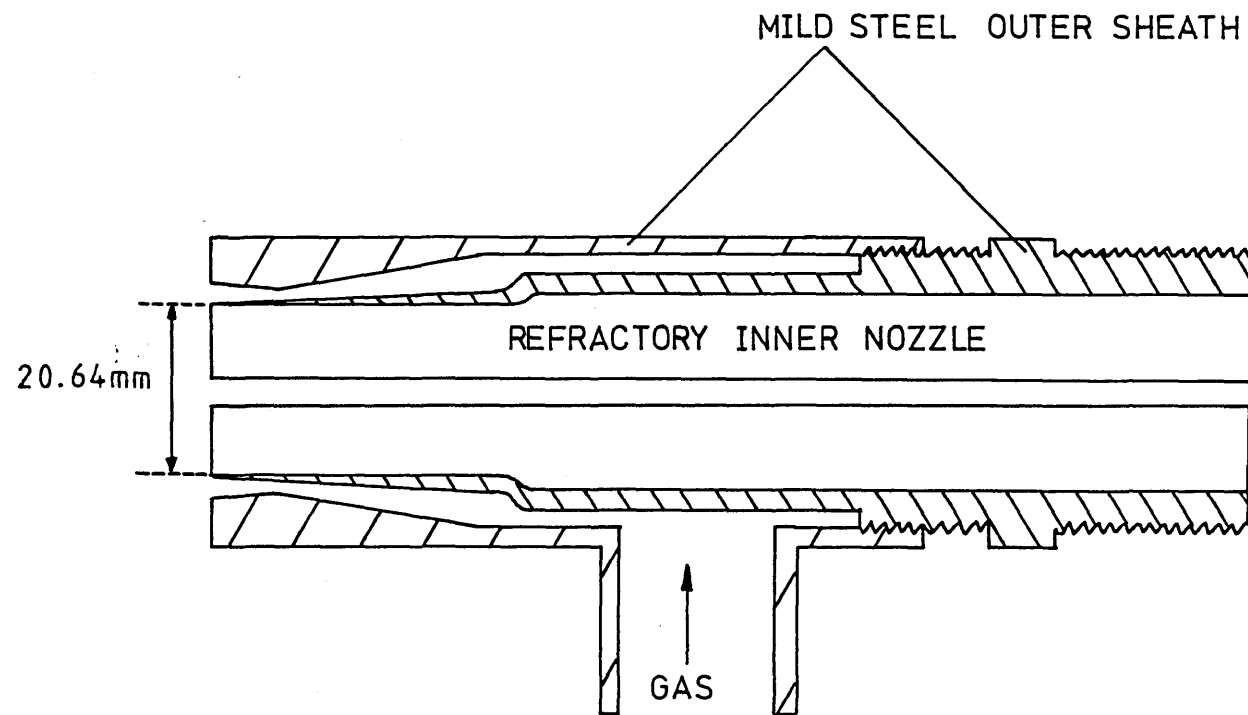


FIGURE 1.2      THOMPSON'S ATOMIZING NOZZLE (9)

TABLE 1.1

NOZZLE VARIABLES IN THE LITERATURE

| AUTHOR         | VARIABLES                          |                                       |                                  |                              |                                 |
|----------------|------------------------------------|---------------------------------------|----------------------------------|------------------------------|---------------------------------|
|                | metal<br>flow tube<br>bore<br>(mm) | annular<br>nozzle<br>diameter<br>(mm) | annular<br>nozzle<br>gap<br>(mm) | air/gas<br>pressure<br>(MPa) | flow tube<br>protrusion<br>(mm) |
| Dixon(20)      | 10 - 13                            | 19-25                                 | 3.0                              | 14.0                         | -                               |
| Kim(19)        | 0.37 - 5.64                        | -                                     | 3.05 - 6.91                      | -                            | -                               |
| Hugo(11)       | 3.00                               | -                                     | 0.5 - 2.00                       | -                            |                                 |
| Thompson(9)    | 3.96                               | 20.6                                  | 1.59                             | 0.52                         | 6.35                            |
| Gretzinger(23) | 0.37 - 5.51                        | 3.68-7.08                             | 0.74 - 1.85                      | -                            | -                               |
| Klar(14)       | 5.56-7.94                          | 12.7                                  | -                                | 6.94                         | 9.52                            |

(20.6mm). Thompson investigated the effect of nozzle geometry on particle size and concluded that the nozzle design is of minor importance!

The atomizing gas in an annular nozzle has been found by Dixon<sup>(20)</sup> to cause a drop in pressure in the metal flow tube. The explanation put forward is that the atomizing gas jet in an annular nozzle forms a cone around the top of the flow tube. There is an aspirating effect in the cone, and any gas inside the cone is entrained into the atomizing gas jet causing a pressure drop in the metal flow tube. See et al<sup>(21)</sup> and Couper and Singer<sup>(22)</sup> also found that a suction was created in the flow tube by the atomizing gas.

The formation of a uniform gas pressure distribution in an annular gas jet was a problem found by Gretzinger and Marshall<sup>(23)</sup> and mentioned in a review by Dixon<sup>(20)</sup>. This lack of concentricity was probably caused by the absence, in both cases, of a plenum chamber in which the gas pressure equalizes. Gretzinger and Marshall found that a lack of concentricity causes wide powder size distributions and unreproducible results and is therefore undesirable.

A summary of the nozzle characteristics and operating pressures from various authors is given in Table 1.1.

The formation of fine particles involves several phenomena and principles simultaneously including:

- (1) complex fluid dynamics
- (2) heat transfer and energy conservation
- (3) chemical kinetics and thermodynamics.

However most important of the above is the way the fluid dynamics of the atomizing gas affect the disintegration or break up of the liquid being atomized.

#### 1.4 THE PROCESS OF DISINTEGRATION OF THE MOLTEN METAL STREAM

The process of disintegration is described in most work on atomization as being a three-stage process (5,6,7,10,24,25) involving the formation of sheets, ligaments and finally droplets of liquid.

#### 1.4.1 Filming or Sheet Formation

The formation of sheets, or thin films, of liquid before the atomization occurs has been shown to be a very important consideration in nozzle design and has been shown to be necessary in designs where large liquid volumes are being atomized<sup>(8)</sup>. Figure 1.3 from Field et al<sup>(26)</sup> shows the gas flow above an annular jet. This illustrates that in an annular nozzle the atomizing gas entrains fluid from itself, at a point downstream from the tip, so setting up a recirculating flow within the cone since there is no gas within the cone formed by the atomizing gas (it has been entrained). It can be seen that the recirculating gas in the cone will cause the liquid leaving the flow tube (in the centre of the annular jet) to film on the top surface of the tube. Liquid break up therefore occurs at the perimeter of the nozzle flow tube as soon as it meets the atomizing gas. Operating in a vertical direction will be an advantage as gravity will also aid the filming process. The filming in a confined annular nozzle has been clearly observed by Unal<sup>(27)</sup> and has also been shown to happen by Fraser<sup>(28)</sup>. Klar and Shafer<sup>(14)</sup> also studied the liquid flow above the flow tube and found that the liquid formed a hollow cone the outer diameter of which was determined by the diameter of the flow tube. However they specifically point to the occurrence of the cone as proof of prefilming, as do Gretzinger et al<sup>(23)</sup> and do not mention prefilming on top of the flow tube. In some early work Thompson<sup>(9)</sup> also observed that the liquid formed a conical shell. However the metal flow rates were so high that the metal "fountained" out of the flow tube. He concluded that atomization occurred by the fountaining metal being drawn back onto the nozzle tip and subsequently expelled.

The filming process may well be enhanced in the liquid flow tube of atomizers by changing the shape of the output section, thereby causing the metal to attach itself to the output section and so film. A nozzle used by Fraser et al<sup>(7)</sup> enhanced filming by having a bowl shaped output section. Figure 1.4 schematically illustrates the output section and the gas flow above the nozzle. The bowl above the liquid flow tube provides a surface over which the liquid can spread in a thin film, before meeting the gas jet

FIGURE 1.3  
GAS FLOW ABOVE AN ANNULAR JET

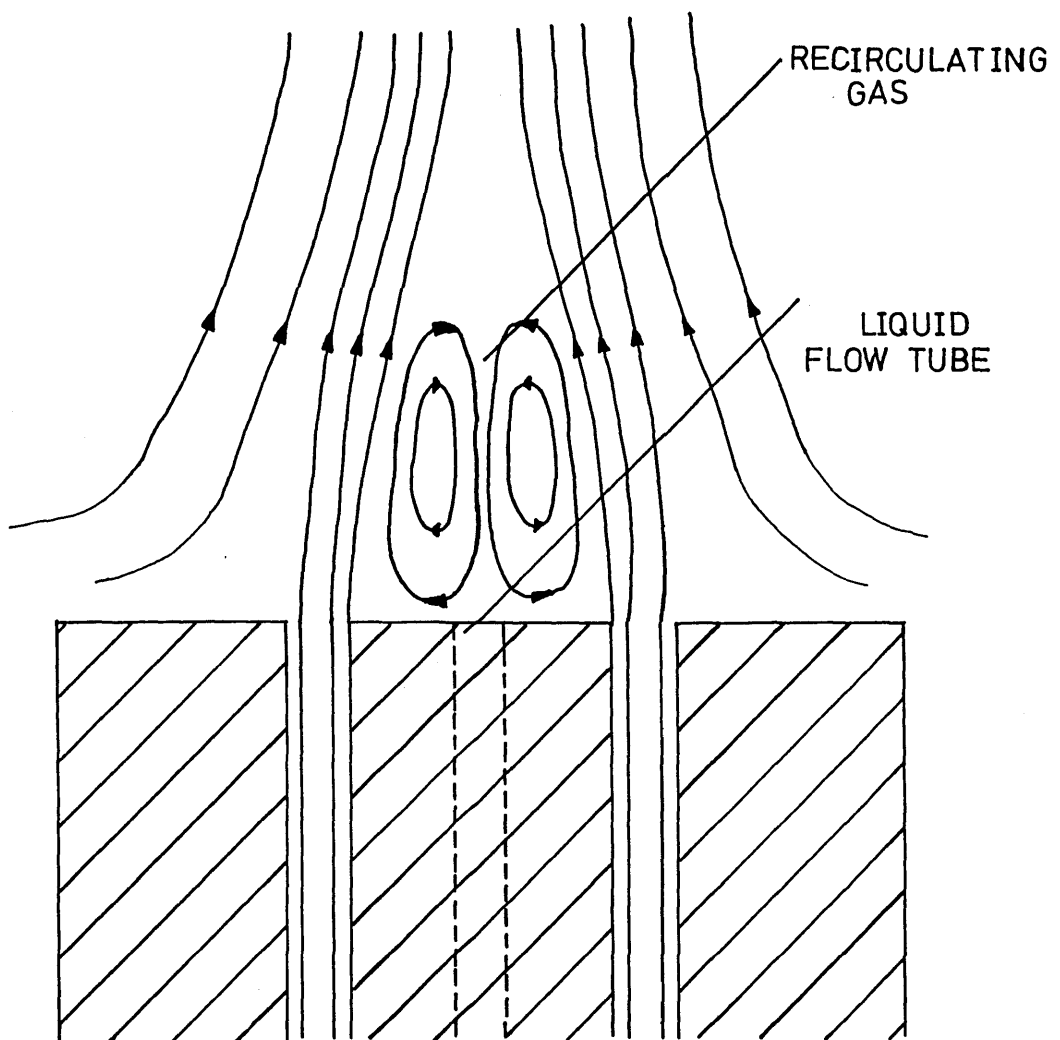
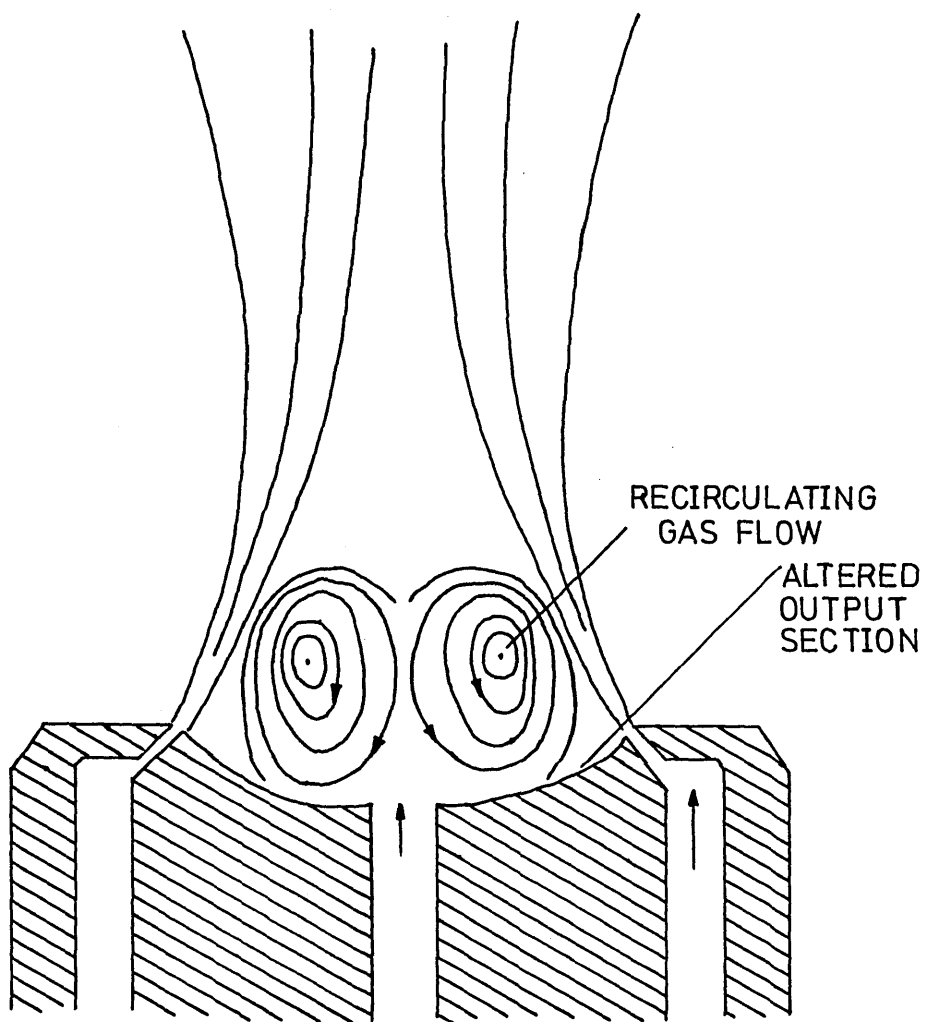


FIGURE 1.4  
GAS FLOW ABOVE A NOZZLE OF ALTERED OUTPUT SECTION (7)



outlet and being atomized.

#### 1.4.2 Liquid break up

The classical study of disintegration was by Dombrowski<sup>(25)</sup>. His work was carried out using a pressure atomizer where a fast moving liquid sheet was sprayed into stationary air. This is the converse of the twin fluid atomizer situation where fast moving gas is jetted onto nearly stationary fluid. His work indicates that rapidly growing waves occur on the sheet. These are due to the interaction of the liquid sheet with the surrounding atmosphere. Disintegration occurs when the wave amplitude reaches a critical value and tears occur in the troughs and crests, and fragments of sheet are torn off. The size of these fragments corresponds to one half wavelength. These fragments rapidly contract, under the action of surface tension, into unstable ligaments which subsequently break down into droplets. Dombrowski's work is of value when considering the break up of liquid sheets.

Figure 1.5<sup>(27)</sup>, which shows aluminium atomization in a confined nozzle, clearly shows that the liquid being atomized forms droplets without the prior formation of sheets and ligaments. It should be noted that the contact between the liquid metal and the gas does not occur at the perimeter of the flow tube but a short distance down the side of the flow tube protrusion. The photograph also shows that the droplets formed are larger than the final particle size and so further disintegration must occur in flight. Unal<sup>(29)</sup> has divided the break up of liquid in a confined annular nozzle into two regimes; primary break up, the initial break up at the tip, and secondary break up, the break up of liquid droplets in flight.

Not much is known about the primary break up stage. However, one may hypothesise that the thinner the films of liquid formed on the top surface of the flow tube protrusion the more efficient the break up. The process of forming droplets from the liquid at the tip perimeter must be due to high shearing forces caused by friction between the liquid surface and the gas travelling at a relatively high velocity. Therefore high gas velocities and turbulence at the protrusion tip should expedite the break up

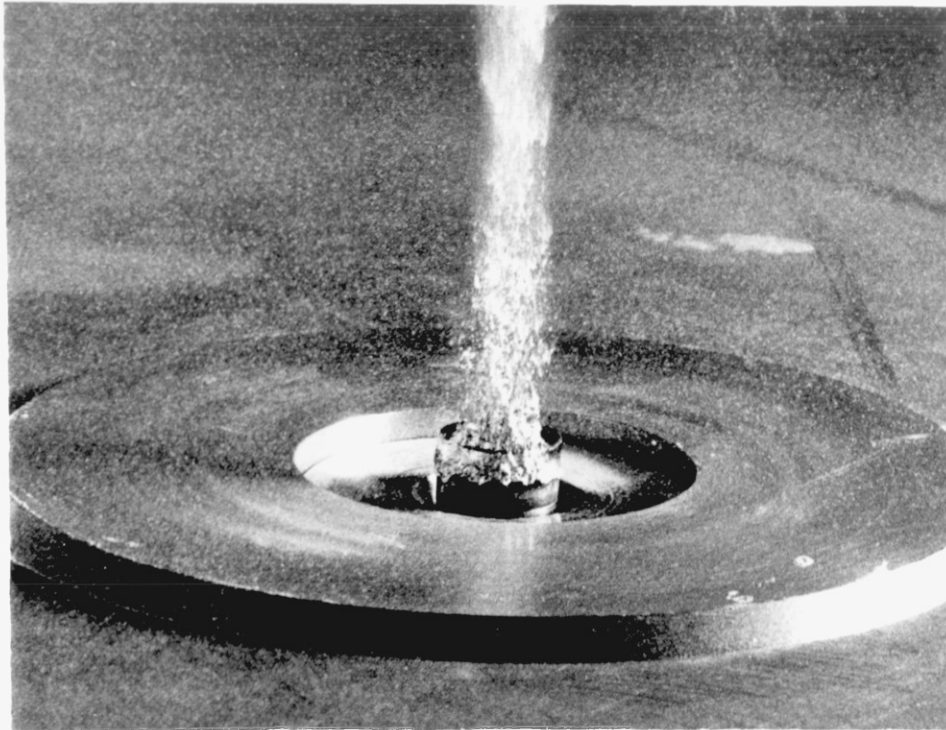


FIGURE 1.5

ALUMINIUM ATOMIZATION IN A CONFINED NOZZLE(27)

(Note metal rundown on the protrusion)

process. However, once the liquid has been accelerated to the velocity of the gas the shearing forces are no longer present and break up will not occur. Thus it is important that the droplets be formed as quickly as possible.

It has been found that droplets must be larger than a critical size to undergo break up in a gas stream, i.e. secondary break up. Small particles will remain stable. Experimental work on particle break up in gas streams has related the critical size,  $d_{crit}$ , below which break up does not occur, to the dimensionless Weber number,  $We = \rho_g V_{rel}^2 d / \sigma_1$ , a ratio of dynamic forces ( $\rho_g V_{rel}^2$ ) to surface tension forces ( $\sigma_1/d$ ). The critical Weber number depends upon the relative velocity of the droplet wrt atomizing gas,  $V_{rel}$ , and the surface tension of the liquid,  $\sigma_1$ . Kim and Marshall<sup>(9)</sup> have calculated the smallest observed critical Weber number, from data given by Hinze<sup>(30)</sup>, as approximately 13 for an inviscid liquid. The smallest critical droplet diameter which can survive without undergoing secondary break up can therefore be estimated by putting the Weber number equal to 13 so  $d_{crit} = 13\sigma_1 / \rho_g V_{rel}^2$ . Thus as the relative velocity increases the stable droplet size becomes smaller.

For particles which are larger than the stable particle size experimental work by Lane<sup>(31)</sup> has noted three different disintegration mechanisms:

- (1) a vibrational mechanism in which waves are set up in the surface of the drop until it breaks up
- (2) a mechanism in which droplets present a convex shape, to the gas stream, and liquid is stripped off the side of the convex droplet
- (3) a mechanism in which droplets flatten, and then inflate to form a bowl shape attached to a circular rim and then burst.

Lane has shown the vibrational mechanism to be a relatively slow process which only occurs for particles just larger than the critical size given earlier. In mechanism 2 the liquid is stripped from the sides of the convex droplet as sheets and ligaments which disintegrate into fine droplets. As the relative

velocity between the droplet and gas decreases the thickness of the sheets formed in the stripping process increases. Thus a wide range of droplet sizes can be formed by this mechanism. In mechanism 3 the droplet is blown into a bowl shape, rather than presenting a convex shape to the atomizing gas, with a circular rim. When the bowl breaks it forms a shower of small droplets, and the rim breaks into larger droplets.

The second mechanism is reported to occur at higher relative velocities than mechanism 3 and may be the mechanism which occurs in supersonic atomization.

The discussion so far has covered the operation of atomization nozzles and the interaction between atomizing gas and metal but ignored the way in which the operating parameters effect the characteristics of the powder produced. The following section discusses these characteristics.

## 1.5 PARTICLE CHARACTERISTICS IN GAS ATOMIZATION

The important characteristics of powders produced by atomization techniques are as follows:

- 1) Particle size
- 2) Particle size distribution
- 3) Particle shape
- 4) Particle structure and chemistry.

### 1.5.1 PARTICLE SIZE

A great deal of effort has been put into deriving correlations between operating conditions and particle size, for given nozzle designs. However little work has been done on trying to assess the way in which operating conditions affect the mechanisms which occur in particle formation.

In particle formation there is an increase in the surface area of the liquid being atomized, and so there is an increase in the total energy of the liquid. This energy must come from the

atomization process. However, in practice, only an insignificant amount of the energy used in atomization goes into the creation of new surfaces<sup>(6,32,33)</sup>. The remaining energy goes into accelerating the particles as well as overcoming drag, imparting momentum to surrounding gas, and in generating heat. After formation small drops must not encounter other drops, before freezing has occurred, or they will coalesce to form bigger drops or attach themselves to larger particles which is known as satelliting.

If we consider the relationship that has been proposed by Lubanska<sup>(34)</sup>, between the particle size and the operating parameters, the factors which affect particle size can be identified and discussed.

Lubanska's relationship was based on work done by Wigg<sup>(32)</sup> and proposed the following equation for the average mass median particle size,  $d_m$ :

$$d_m/D_1 = K[(v_m/v_g)(1/We)(1+[\dot{m}_1/\dot{m}_g])]^{0.5}$$

where  $We$  is the Weber number ( $D_1 V^2 \rho_l / \sigma_l$ );  $D_1$  is the diameter of the metal stream (flow tube diameter);  $v_m$  is the kinematic viscosity of the liquid;  $v_g$  is the kinematic viscosity of the gas;  $V$  is the velocity of the atomizing gas;  $\rho_l$  is the density of liquid metal;  $\sigma_l$  is the surface tension of the liquid metal;  $\dot{m}_1$  is the mass flow rate of the liquid;  $\dot{m}_g$  is the mass flow rate of the atomizing gas and  $K$  is a constant. All the groups in the above equation are dimensionless.

Kim and Marshall also considered atomization in terms of the following dimensionless groups:

- (1) the mass flow rate ratio,  $\dot{m}_g/\dot{m}_1$
- (2) the Weber number,  $D_1 V_{rel}^2 \rho_g / \sigma_l$
- (3) the Z number,  $\mu_l / (D_1 \rho_l \sigma_l)^{0.5}$  (where  $\mu_l$  is dynamic viscosity of liquid)
- (4) the ratio of liquid and gas kinematic viscosity,  $v_l/v_g$

## MASS FLOW RATIO

The mass flow ratio is probably the most important of the dimensionless groups in influencing particle size given a satisfactory nozzle geometry. Masters<sup>(8)</sup> has reviewed all atomization techniques and found that the mass flow rate ratio can vary between 0.1 and 10.0, a very wide range of values! Kim and Marshall<sup>(19)</sup> showed that as the mass flow rate ratio increases the drop size decreases as shown in Figure 1.6. Using this figure they proposed that the mass median diameter was proportional to  $[\dot{m}_g/\dot{m}_l]^{-0.5}$  for values of the mass flow rate ratio greater than 3, which is the same as in Lubanska's relationship, and proportional to  $[\dot{m}_g/\dot{m}_l]^{-1.0}$  for values less than 3. They obtained a mass median diameter of 20 microns for a gas/liquid mass flow rate ratio of 1.0. An increase in the mass flow rate ratio has been shown to give a finer particle size by many authors<sup>(7-9,14,19,20,22,23,35)</sup>.

The effect of mass flow rate ratio on the film thickness was investigated by Gretzinger and Marshall<sup>(23)</sup>. They estimated the film thickness,  $t$ , at the point where the gas meets the metal to be given by:

$$t = [3\mu_l \dot{m}_l / \rho_l^2 g \pi D]^{\frac{1}{3}}$$

where  $g$  = gravitational acceleration,  $m/s^2$

$D$  = diameter of liquid flow tube,  $m$

Thus as the mass flow rate ratio is decreased the film thickness increases and so as the film thickness increases the particle size increases. The film may even reach a thickness where sheets of metal are produced at the rim of the protrusion and break up to form ligaments and drops as described by Dombrowski<sup>(25)</sup>.

An increase in the pressure of the atomizing gas will also increase the mass flow rate of gas. This will result in an increase in the the mass flow rate ratio, if the liquid mass flow rate is kept constant, and so a decrease in the particle size produced. Increasing the atomization pressure has been reported to cause finer particles<sup>(12,20,24)</sup>. This finding contradicts the work done by Thompson<sup>(9)</sup>. He discovered that by increasing the

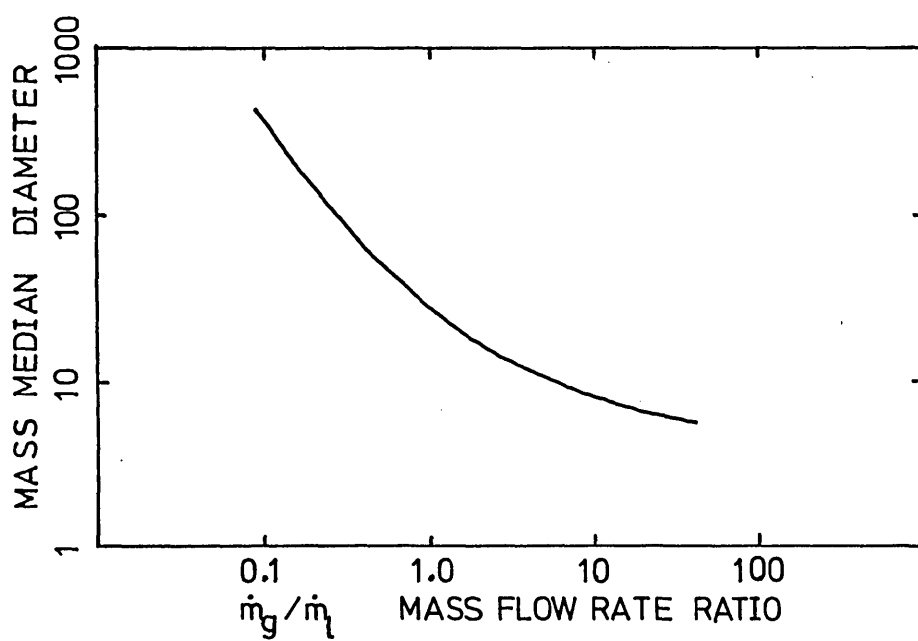


FIGURE 1.6

MASS MEDIAN DIAMETER  
VERSUS  
MASS FLOW RATE RATIO (19)

gas pressure there was little change in particle size. However Thompson did not effectively control the mass flow rate of metal in his experiments. The mass flow rate of metal increased as the gas pressure increased. This may have resulted in a constant mass flow rate ratio so no change in particle size would have occurred.

### WEBER NUMBER AND Z NUMBER

The Weber number measures the ratio of inertial (related to  $V^2\rho$ ) to surface tension forces. Lubanska uses  $\rho_1$  in her definition of the "Weber number" which is incorrect but she has shown, as have Kim and Marshall (who use  $\rho_g$  [which is correct]), that the inverse of the "Weber number" is proportional to particle size. This indicates that the particle size decreases with decreasing surface tension and with increasing velocity of the atomizing gas.

Kim and Marshall showed that an increase in the inertial force ( $V_{rel}^2\rho_g$ ) caused a decrease in particle size. This is consistent with Lubanska's results. In correlations of their data they showed that the mass median particle size was proportional to  $[1/(V_{rel}^2\rho_g)]^{0.57}$ . Fraser et al<sup>(7)</sup> have correlated the kinetic energy (proportional to the inertial force), with the Sauter mean diameter (SMD) at a constant mass flow ratio. They again found that increasing the inertial force leads to decreased particle size.

The effect of surface tension is poorly dealt with in the literature. Thompson<sup>(9)</sup>, in his work on the effect of temperature, stated that he thought that the finer powders he obtained with increased atomization temperature was due to a decrease in the surface tension although no measurements of surface tension were made.

Kim and Marshall<sup>(19)</sup> have defined the Z number as  $\mu_1/(D_1\rho_1\sigma_1)^{0.5}$ ; a ratio of the viscous and surface tension forces. They have shown that the Z number is proportional to the particle size and so a decrease in the Z number would be expected to cause a decrease in particle size. If the effect of viscosity on the Z number is considered then a decrease in the liquid metal

viscosity,  $\mu_1$  will cause a decrease in the Z number and so a decrease in particle size.

Work done on the effect of viscosity<sup>(7,8,19)</sup> has shown that a decrease in the viscosity causes an decrease in particle size. Masters<sup>(8)</sup> in a review of the literature gives the particle size proportional to  $[\mu_1]^n$  where  $n = 0.3-0.37$ . Kim and Marshall's<sup>(19)</sup> work on the effect of viscosity shows that the Mass Median Diameter is proportional to  $[\mu_1]^{0.32}$ . The study of the Weber number has shown that a decrease in surface tension will cause smaller particles. As the Z number increases (i.e. coarser particles) with decreasing surface tension there must be an optimum number at which there is a balance between surface tension and viscosity forces.

#### RATIO OF VISCOSITIES OF LIQUID AND GAS, $\nu_1/\nu_g$

It has already been established that a decrease in the liquid viscosity causes a decrease in particle size. If the viscosity ratio is proportional to particle size then a decrease in the viscosity ratio causes a decrease in particle size. This implies that a decrease in the gas viscosity will also cause an increase in particle size. However work carried out by Lewis et al<sup>(37)</sup> showed that decreasing gas viscosity resulted in a decreased particle size. This indicates that the effect of viscosity is probably not as simple as Lubanska suggests.

#### LIQUID SUPERHEATING

Liquid superheating is not dealt with in the dimensionless groups mentioned. It may affect the particle size in two ways; by changing the liquid properties and by causing premature solidification. The viscosity, surface tension and density are all decreased as the amount of superheating is increased, thereby tending to aid the metal break up and ease the formation of smaller particles. Higher temperatures are therefore expected to favour the production of finer particles.

Rao and Mehrotra<sup>(15)</sup> and Small and Bruce<sup>(12)</sup> have both produced slightly finer powders by increasing the superheating of the liquid. However in Thompson's<sup>(9)</sup> work there was a strong dependence of particle size on temperature. He also had a corresponding decrease in the flow rate of metal with increased superheat and the finer sized powder produced may well be a compound effect of temperature and metal flow rate. Johnson and See<sup>(10)</sup> found that superheating had no effect on particle size, but the proportion of ligaments was considerably less with superheating i.e. at low superheating the liquid break up was incomplete.

### 1.5.2 PARTICLE SIZE DISTRIBUTION

Although all the atomization variables are of interest the average particle size and the particle size distribution are of particular interest to the powder producer. The powders he sells are frequently subject to narrow specifications. It is not difficult to control the particle size, i.e. the MMD, to within a few microns, but it is quite difficult to change the particle size distribution as the very nature of the disintegration process, described earlier, tends to produce wide size distributions. In many cases the particle size distribution is an important property from both technical and economic points of view. Figures 1.7 and 1.8<sup>(14)</sup> illustrate this point very effectively showing the increase in yield that can be obtained by narrowing the size distribution of a powder. Klar and Schafer<sup>(14)</sup> report that for most powders produced the geometric standard deviation of the size distribution lies between 2 and 3. They say that narrow size distributions are favoured by concentric nozzle designs. Gretzinger et al<sup>(23)</sup> examined the effect of concentricity variations by atomizing water on one side of their nozzle only (they blocked one side of the gas annulus). They found that the size distribution was much wider than with a uniform gas flow in the annulus. The larger particles were formed on the side in which there was no gas flow. This shows the importance of a uniform gas flow. Kim and Marshall<sup>(19)</sup> agree that a uniform gas flow is important. Klar and Shafer<sup>(14)</sup> found that

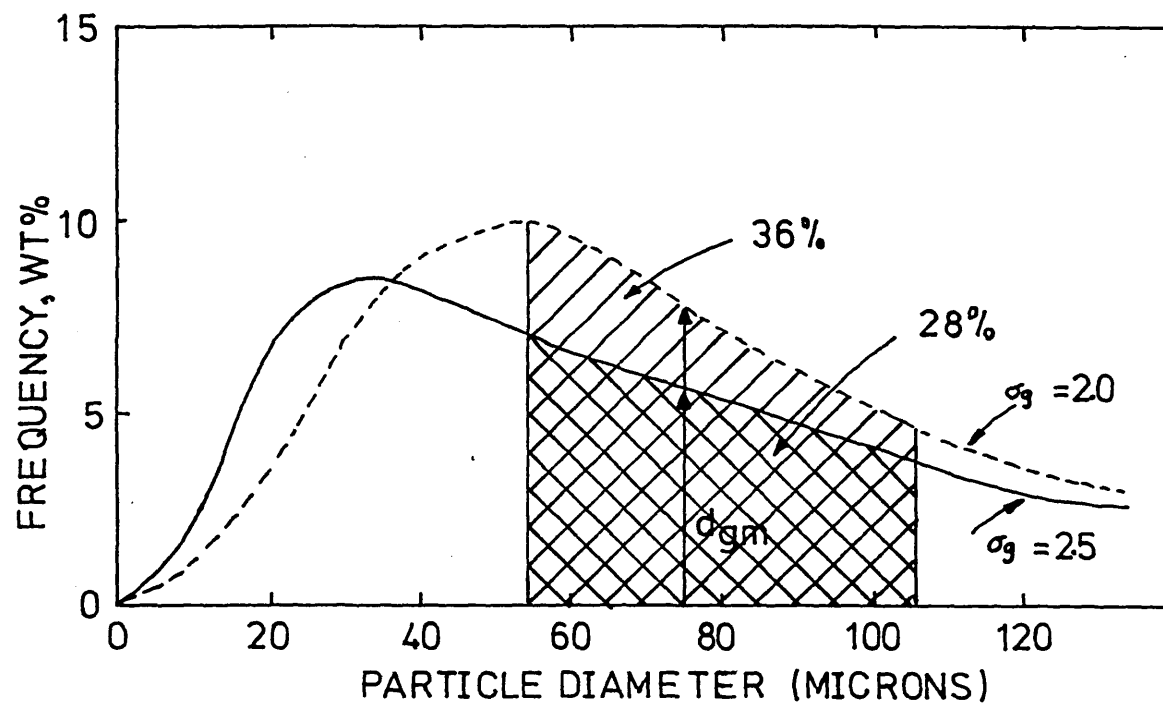


FIGURE 17      EFFECT OF DISPERSION ON YIELD (14)

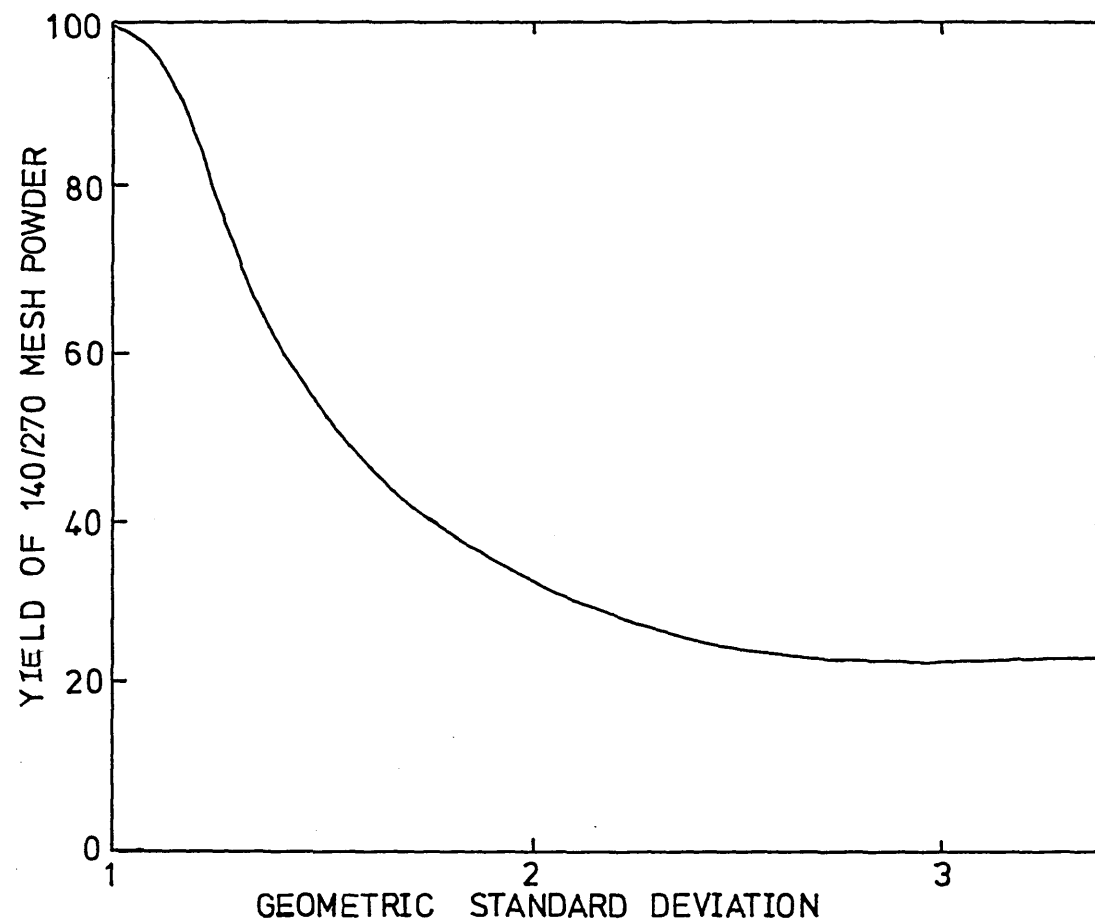


FIGURE 1.8 EFFECT OF DISPERSION ON YIELD (14)

the standard deviation increased as the metal stream diameter was increased.

Log-normal size distributions seem to be the most common type of size distribution used in the literature to represent the data on atomization<sup>(10,12,21,36,34)</sup>.

### 1.5.3 PARTICLE SHAPE

The final particle shape is an important consideration in almost all commercial uses of metal powders.

Particle shape is not easy to control and can vary from almost spherical to highly irregular. The processes that take place in the interval between disintegration of the liquid metal stream and the solidification of the drop (which depend on surface tension, viscosity, temperature, cooling rate and size of droplet) are critical to the final particle shape.

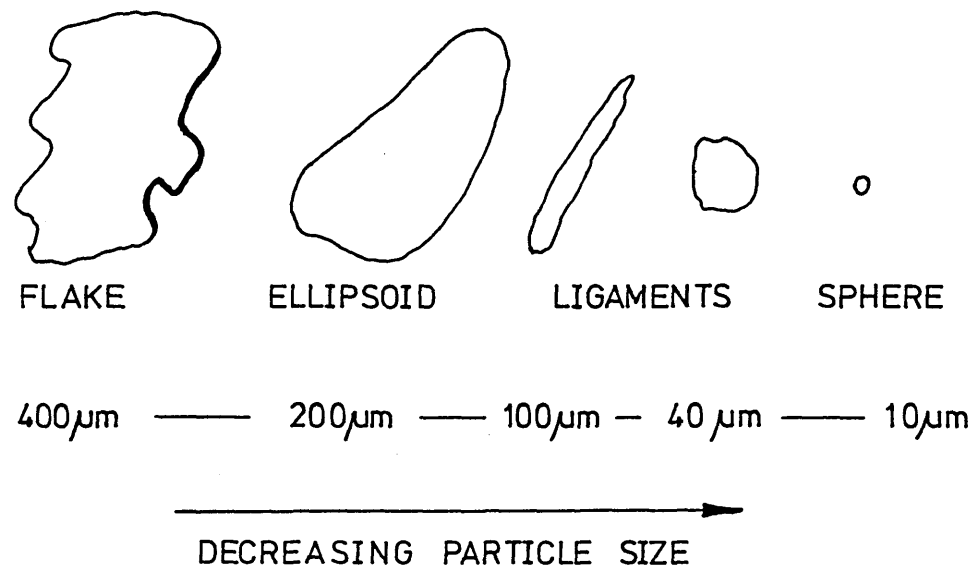
#### EFFECT OF SURFACE TENSION

The surface tension of liquid metals is high, and a droplet, once formed, tends to assume a spherical shape. Surface tension forces have less time to take effect when cooling rates are high and so irregular shapes are more likely to be formed.

In inert gas atomization it has been found that atomized powders are spherical regardless of superheating and mass flow ratio<sup>(4,12,20,24)</sup>. Small and Bruce<sup>(12)</sup> found that their gas atomized powders were spherical irrespective of their size, but Hugo and German<sup>(11)</sup> found that the shape of the powder was dependent upon size as illustrated in Figure 1.9 which schematically summarizes the shape changes with size. It shows that at particle sizes of approx 400 microns the particles form an ellipsoidal shape. This may be due to solidification occurring during the "flight" of the droplet. At progressively finer particle sizes the particle shape is mainly ligaments until a size of about 40 microns. With particle sizes below 100 microns there are often clusters of fine particles probably caused by

FIGURE 1.9

PARTICLE SHAPE VERSUS SIZE



turbulence and these clusters are often in the form of a particle with several satellites resulting from the collision between solidified finer particles and unsolidified larger particles<sup>(6)</sup>. The rate of cooling may well influence the amount of satelliting that occurs<sup>(8)</sup>. If the cooling rate is increased, the occurrence of satellites would diminish, since the powder particles would have solidified prior to collision.

Dixon<sup>(20)</sup> mentions work by Nichiporenko<sup>(38)</sup> who has investigated the rate at which metal particles, atomized in inert gas, become spherical after atomizing. He found that the time for transformation into a spherical shape is 2.5-3.5 orders of magnitude shorter than that needed for complete cooling of the particles.

The only obstacle to the formation of spheres is the formation of a protective oxide film which may help to preserve the initial as-atomized irregular shape. It has been found that atomization with helium produced more spherical powders than atomizing with air<sup>(18)</sup> because of the reduction in formation of oxide film.

#### **EFFECT OF SUPERHEATING**

The effect of superheating on particle shape has been investigated by many authors. Dixon<sup>(20)</sup> found a decrease in the surface tension of the molten metal with increased temperature. This favours the production of irregularly shaped particles but is balanced against a reduction in viscosity and a longer time for particles to form spheres on cooling. In inert gas atomization it has been found that with superheating of the melt, there remains enough superheat, regardless of high cooling rates, to allow surface tension forces, in many cases, to create spheroids.

#### **EFFECT OF ALLOYING ELEMENTS**

The shape of atomized particles can also be controlled, to some extent, by small additions of other elements. It is believed that the alloying elements hinder spheroidization and tend to produce irregularly shaped powders by reducing the surface tension of the melt or reacting with the oxygen to form stable

oxides on the powder particles at the instant of atomization.

#### 1.5.4 PARTICLE STRUCTURE AND CHEMICAL ANALYSIS

The particle structure is a function of the rate of solidification which depends upon two primary factors a high heat transfer rate at the metal droplet/atomizing gas interface and a small droplet size<sup>(22)</sup>. However the powder metallurgy is far more complex than this. The more rapid the cooling rate the finer the microstructure. The solidification rate can be determined by measuring the dendrite arm spacing using microstructural analysis<sup>(18)</sup> as shown in Figure 1.10<sup>(2)</sup>. Ro et al<sup>(18)</sup> determined cooling rates,  $U$ , in aluminium using an empirical relationship with secondary dendrite arm spacing,  $d$ :

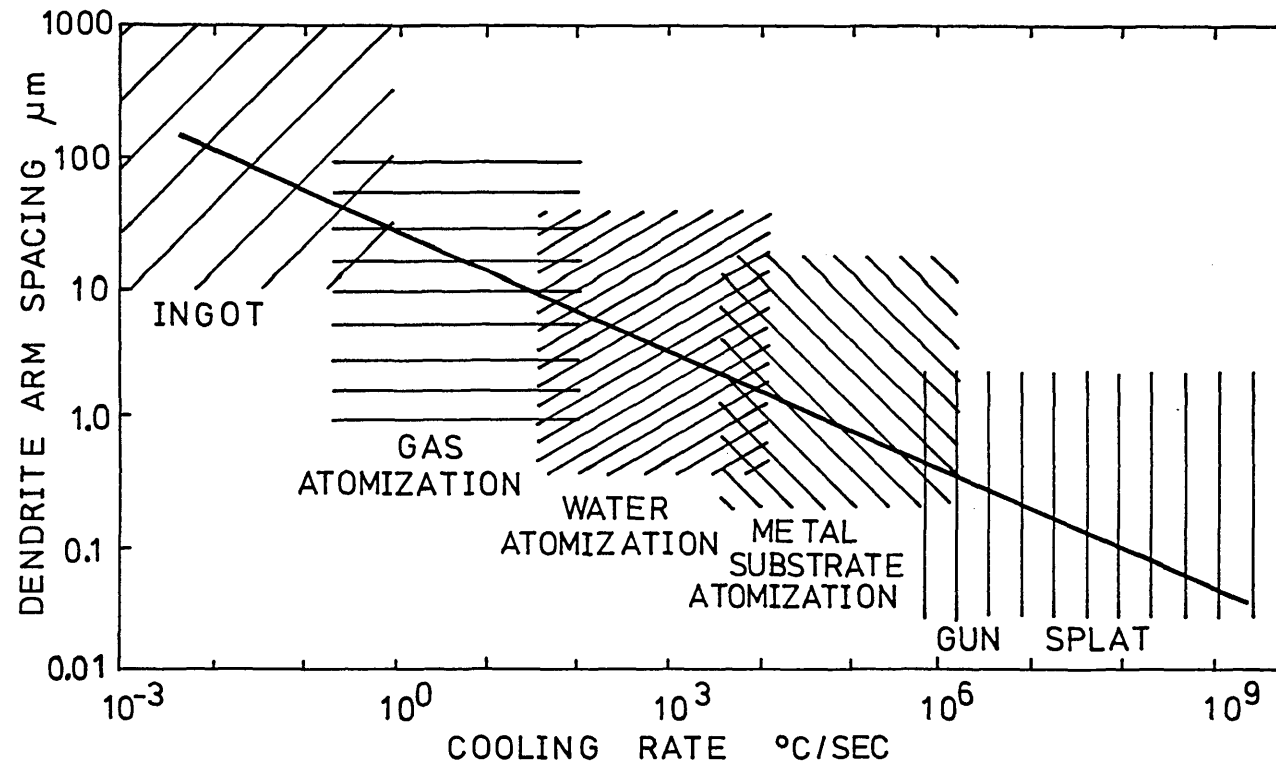
$$d^3 \times U = 10^5 \quad \mu\text{m}^3 \text{ K/sec}$$

The cooling rate is restricted primarily by the heat flow at the surface and so the higher the heat transfer coefficient,  $h$ , the faster the rate of heat loss<sup>(6)</sup>. Thus gases with a high heat conductivity are ideally suited to atomization e.g. helium. The rate of cooling could be increased by using helium instead of argon as the atomizing gas because the heat transfer coefficient of helium is an order of magnitude greater, for a 10 micron particle, than for argon<sup>(8)</sup>. Ro et al<sup>(18)</sup> found that the use of helium made no difference to the cooling rate. However Unal<sup>(39)</sup> has found that helium produces finer particles than argon or nitrogen suggesting that helium has two advantages; finer powders and higher cooling rates. Couper and Singer<sup>(22)</sup> found gas type had a minor effect.

Very closely related to the particle structure is the particle chemistry. The particle chemistry can be affected by alloy/metal reactions and by gas contamination. Research<sup>(4,12)</sup> has found that the chemical analysis is independent of particle size for inert gas systems. However, in non inert gas atomization, reactions take place more easily between the atomizing gas and liquid. The atomizing medium is then obviously

FIGURE 1.10

EFFECT OF COOLING RATE ON DENDRITE ARM  
SPACING



of great importance.

Small and Bruce<sup>(12)</sup> considered the subject of particle chemistry in some detail. They showed that particle chemical analysis was constant irrespective of the atomizing medium when using a cobalt alloy. However the amount of gas contamination was affected by the pouring temperature of the metal, the atomizing pressure and the final particle size. An increased pouring temperature caused the particles to be hotter after atomization and so the oxidation period was longer and more gas contamination resulted. Higher oxygen levels resulted with increased pressure and Small and Bruce explained this by saying that increased pressure merely supplied additional oxygen for pick-up. Size had the same effect on gas contamination regardless of the atomization medium; finer powders i.e. greater surface area per unit mass, gave a higher proportion of oxygen. This implied that oxygen was present as a result of a surface reaction.

Small and Bruce also showed that inert gas atomization produces powder with an order of magnitude less oxygen than that of air atomized powder.

## 1.6 THE BASIS ON WHICH THE PRESENT WORK WAS CONCEIVED

The possible benefits on powder metallurgical products of increasing the knowledge of atomization techniques was mentioned earlier in section 1.1. Powder atomization techniques are numerous and although gas atomization is the most widely used method the comment by Gummerson<sup>(7)</sup> -"the atomization process is somewhat of an art and not yet based on well recognised scientific principles"- is still true.

The aim of the project was to better understand the basic mechanisms in gas atomization, the most widely used atomization method, so that the final powder metallurgical product could be improved and made cheaper.

## NOZZLE DESIGN AND TESTING

The choice of basic nozzle type was obvious from reviewing the literature. The confined annular nozzle design is the most suitable for metal atomization as this causes pre-filming of the liquid to take place and this has been shown to favour finer particles. It was decided to run the nozzle vertically so that gravity aided the pre-filming process.

The basic design of the nozzle used in this project was based on the drawings available of Thompson's nozzle<sup>(9)</sup>, shown in figure 1.2, and Klar and Shafer's<sup>(14)</sup> nozzle which is shown in figure 1.1(b).

The work done by Thompson<sup>(9)</sup> has shown that nozzle design did not affect particle size. However Thompson's work was affected by poor control of the the metal flow rate and lack of detailed experimental work into the geometry of the atomization nozzle. As no detailed work had been done on:

i) how nozzle geometry affects the gas flow in nozzles

ii) or how the geometry can affect the particle size produced in atomization

it was therefore decided to look at this in some detail.

The velocity of the atomizing gas has been shown to effect powder properties<sup>(19,34)</sup>. So that the effect of velocity could be investigated the nozzles in this project were of a converging diverging type, with varying supersonic exit velocities, except for one convergent only nozzle with a sonic exit velocity.

As well as the nozzle geometry the effect of the process variables such as gas pressure and liquid flow rate were investigated.

## ATOMIZATION TESTS

Without carrying out a series of detailed atomization experiments, even with a detailed study of the gas flow, the project would be incomplete.

Wax was chosen by Kim and Marshall<sup>(19)</sup> as the liquid to be used in atomization tests instead of metal. Wax has a number of advantages over other substances which have been used in

atomization experiments in the past:

- i) it solidifies (unlike water) and so simulates metal
- ii) the powder can be easily sized as it is solid
- iii) it is molten at low temperatures

These advantages allow atomizations to be carried out with less complex melting facilities than those required for metal atomization and so was used to carry out the atomization test work.

The use of wax has an additional advantage it allows an investigation into the effect of liquid viscosity to be carried out as waxes can be blended to change the viscosity.

#### SUMMARY

In summary the project aimed to investigate:

- i) the effect of nozzle geometry on the gas flow
- ii) the effect of geometry on the particle size produced in atomization
- iii) the effect of process variables on particle size
- iv) the effect of gas flow on particle size

## CHAPTER TWO

### NOZZLE CONSTRUCTION AND TESTING

## 2.0 INTRODUCTION

This chapter will discuss the way in which the atomization nozzles used in this project were developed before the gas flow in atomization nozzles and the results of wax atomization tests are discussed. The problems encountered during the development of the atomization nozzle, from the initial design to that used in the atomization tests, and some of the methods used to identify and overcome the problems encountered will be discussed in this chapter.

Before discussing the different designs in detail the basic construction of the nozzle consisted of two shells which fit inside each other. In the centre of the nozzle is a liquid flow tube. The atomizing gas flows between the shells. The behaviour of gas flow in this channel is determined by inserts fitted into the two shells. The flow of gas causes an aspirating effect at the tip of the liquid flow tube which draws the liquid to be atomized up the tube.

### 2.1 INITIAL ALUMINIUM NOZZLE.

The initial aluminium nozzle was the first atomization nozzle built. This nozzle consisted of an inner and outer shell (Figure 2.1). The outer shell, into which fitted the outer insert, was surrounded by a gas manifold section into which were fitted the gas supply lines. The outer shell was attached to four bolts which were fitted through the periphery of the inner shell and then to a base plate. The design of the inserts evolved during the project and will be described later. The inner shell was free to travel up and down the bolts. The seal between the inner and outer shells was made with 'O' rings. The metal flow tube consisted of three sections - upper, middle and lower. All three sections screwed together to form a long tube. The protrusion, of the metal flow tube, could be altered by rotating the flow tube, in its threaded base, thereby lowering or raising the whole flow tube. Four threaded screws placed between the bottom of the inner shell and the base plate prevented the inner

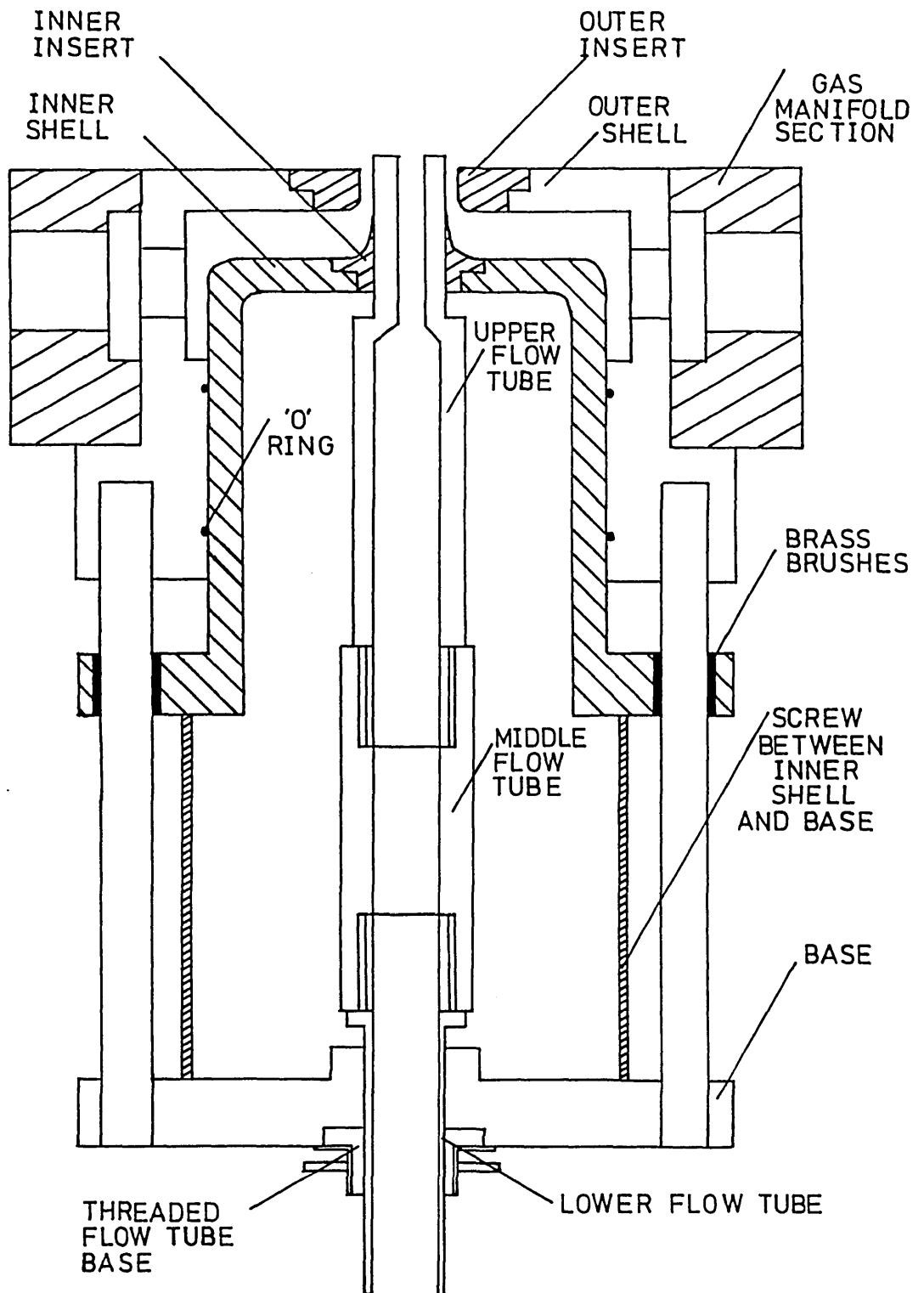


FIGURE 2.1  
INITIAL ALUMINIUM NOZZLE

shell from being pushed down the bolts by gas pressure. These were carefully adjusted and locked in place so that the distance between the bottom of the inner shell and the base plate was constant.

An initial problem encountered was that the gas flow was not uniform around the gas annulus. The method of measuring the gas flow is discussed later in this chapter. This unconcentric behaviour was obviously very undesirable as it would cause atomization to occur more on one side of the nozzle than the other. The consequent result would be powder produced of a poorer quality and of a wider size distribution. It was decided that this was a fault in the design. The fault was diagnosed as being the way in which the two shells fitted together.

Changes were made to the nozzle to ensure concentricity. It was decided to make it impossible for the inner and outer shells to move relative to each other. This was attempted by drilling holes in the outer insert and putting wire, of known thickness, through the holes. It was hoped that when the two shells were fitted together the wire would ensure a uniform spacing between the inserts and so ensure the concentricity of the nozzle. Figure 2.2 shows that this failed. It can be clearly seen that, even with the wires, the atomization taking place (of water) is not uniform around the annulus. The lack of wire of different suitable varieties of thickness was also a problem.

The design was further modified in an effort to ensure concentricity. Two attempts were made which involved the use of

(a) An Inner Insert Band

Discussions with the Mechanical Engineering Department led to a different method of ensuring the concentricity of the nozzle. It was decided to cut away a section from the upper half of the inner shell and heat shrink a ring of metal around this area. The band was intended to be a "push fit" into the outer shell thereby forcing concentricity between the two shells. This was a failure and the band was removed.

(b) Horizontal adjusting screws

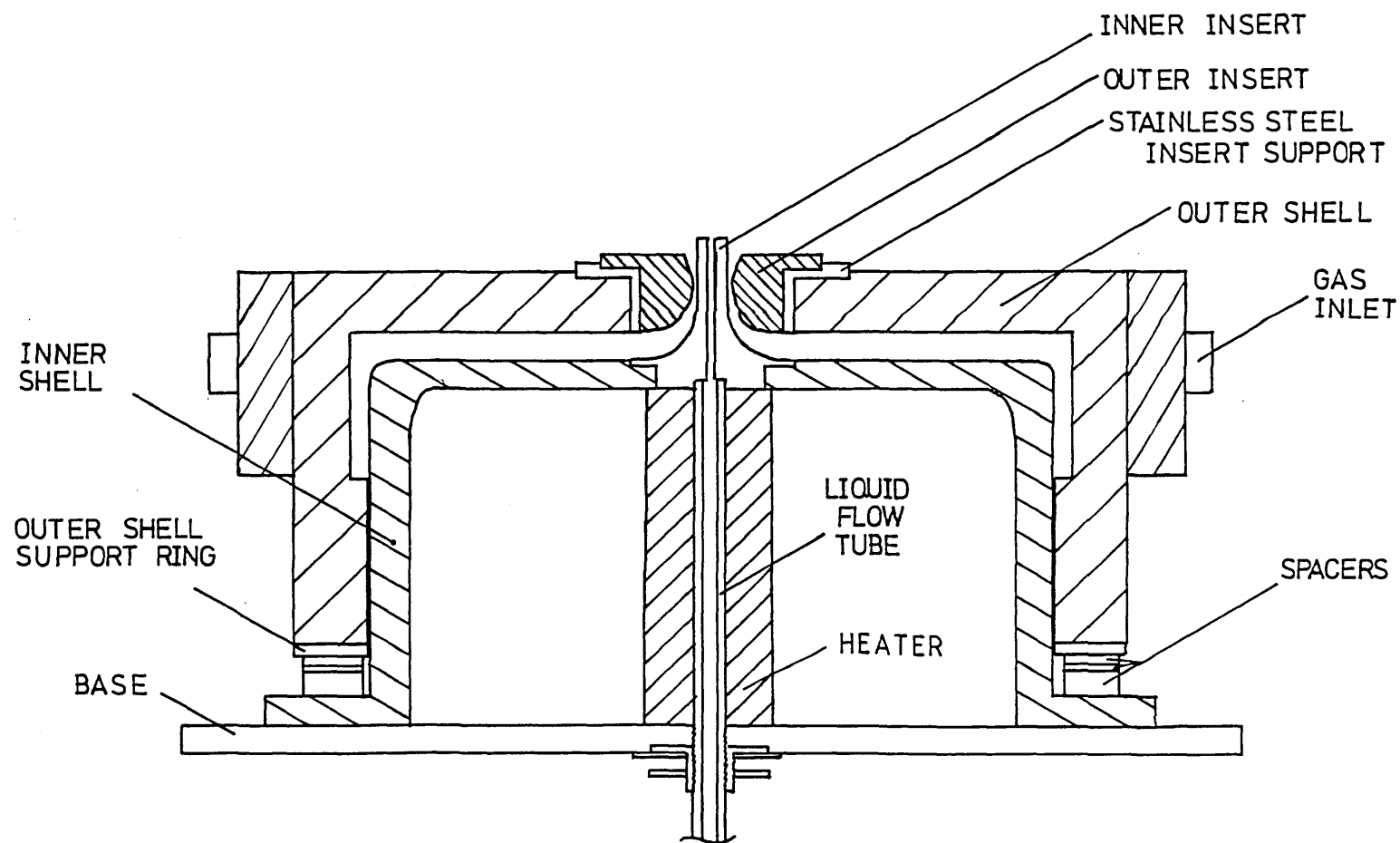
Earlier work by Gretzinger and Marshall<sup>(23)</sup> had noted that the concentricity of the nozzle was a problem and suggested that adjusting screws would solve the problem. This was attempted by



FIGURE 2.2

UNCONCENTRIC ATOMIZATION USING WIRE BETWEEN THE INSERTS

FIGURE 2.3     FINAL ALUMINIUM NOZZLE CONSTRUCTION



placing in the top of the outer shell of the nozzle, four screws with brass seats. These were simply adjusted by screwing them in towards the upper half of the inner shell thereby preventing the inner shell from moving. This was reasonably successful. It was found that by carefully adjusting the screws so that they were 'finger tight' it was possible to achieve good concentricity.

## 2.2 FINAL ALUMINIUM NOZZLE DESIGN

The aluminium nozzle was needed for wax atomizations. The changes in the initial design meant that it was now possible, by using the adjusting screws, to achieve a concentric nozzle. One major problem which still arose was that when the nozzle was reassembled, for example to place new inserts into the nozzle, there was no way in which the previously established concentricity could be retained and the whole, time consuming, adjusting procedure had to be repeated. This was obviously not acceptable as it was necessary to use a combination of perhaps three nozzle inserts in one day. The adjusting screws were therefore discarded, and a different approach to the problem was tried.

It was decided to re-machine the aluminium nozzle so that the holes in the outer and inner shells, into which the inserts fitted were concentric. This ensured that the inner and outer inserts, which were made to fit in these holes, were also concentric.

In the re-machining operation a plate was placed on the bottom of the outer shell and machined to achieve a tight fit between the inner and the outer shells. The hole in the outer shell into which the inserts are fixed was then enlarged and a stainless steel section screwed into place. This acted as the seating for the outer insert. To minimize the possibility of the two shells being unconcentric the two shells were then fixed together and the holes for the inner and outer insert were machined at the same time without removing the assembly from the lathe. The holes were machined so that, with the outer insert removed, the inner insert could be changed without dismantling the nozzle.

Thus the assembly was designed in such a way that the holes in the inner and outer shells would always be concentric. It is this nozzle assembly which has been used in all the wax atomizations and is shown in Figure 2.3. Note the presence of a heater, in the body of the nozzle, which was used to prevent the wax from freezing in the nozzle flow tube.

## 2.3 INSERTS

As mentioned in the introduction the behaviour of the gas flow in the nozzle is determined by the inserts. They are therefore the most important parts of an atomization nozzle. The inserts consist of two parts, the inner insert and the outer insert, and fit inside the main body of the atomizer. The shape of the inserts were based on the nozzle drawings in Klar<sup>(14)</sup> and Thompson<sup>(9)</sup> (see figures 1.1 and 1.2 in Chapter 1). The insert design went through two phases.

### 2.3.1 Initial Insert Design

Here the outer insert was a parallel sided tube with no converging diverging section. The converging diverging nature of the nozzle was achieved with the inner insert (see inserts in Figure 2.1). The throat area, using these inserts, was dependent upon the distance between the two shells - a disadvantage as the distance was difficult to determine accurately. The flow tube fitted through the inner insert and height of the flow tube, protruding above the nozzle exit plane, was adjusted as described earlier.

### 2.3.2 Final Insert Design

In the final design the converging diverging nature of the nozzle was achieved with the outer insert and the inner insert was a simple tube into the bottom of which the liquid flow tube was fitted. This design had the advantage, which the early inserts did not, of allowing the throat area to be independent of

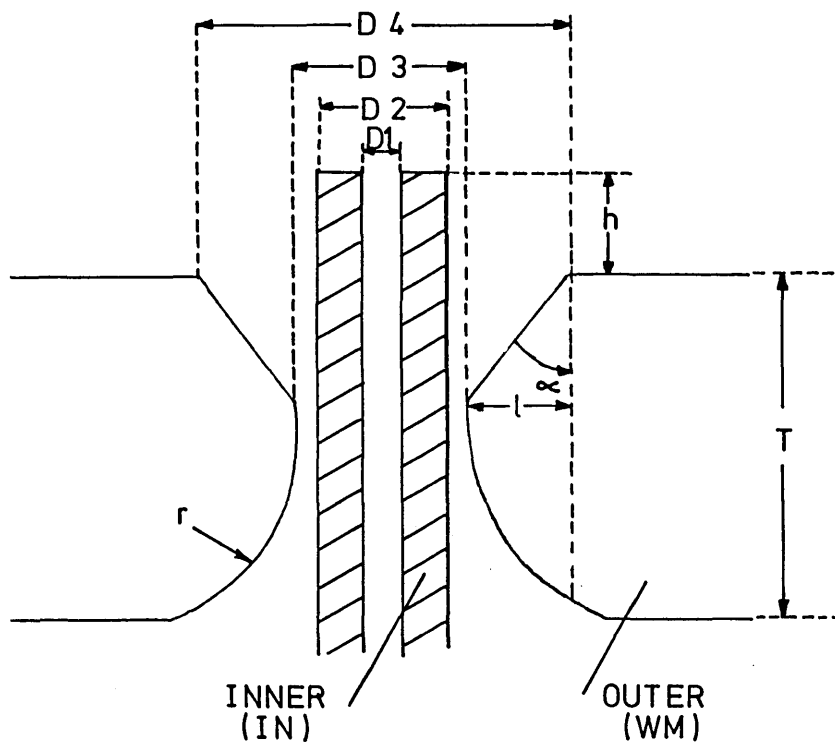


FIGURE 2.4a CONVERGENT DIVERGENT NOZZLE

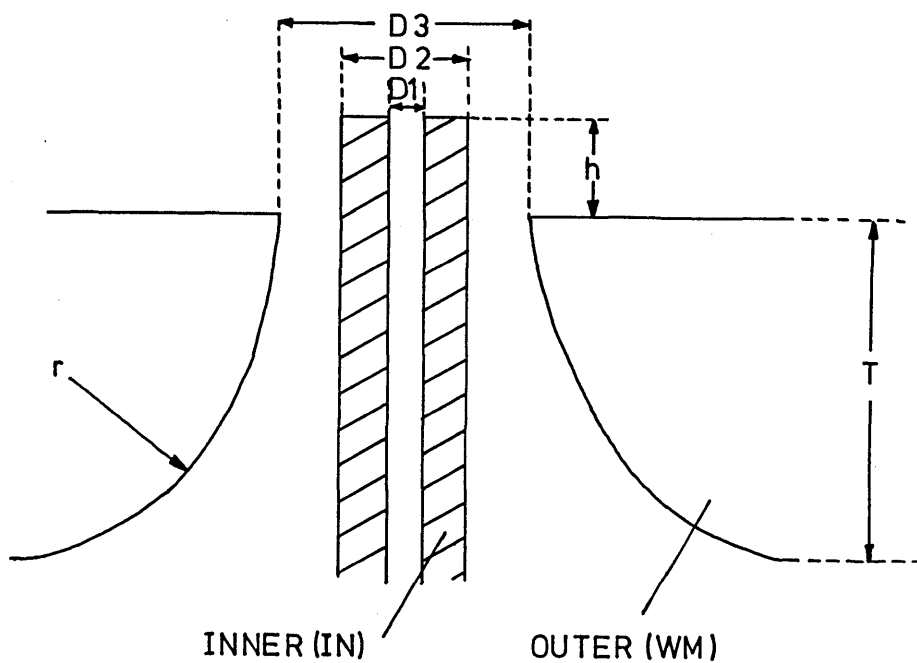


FIGURE 2.4 b CONVERGENT ONLY NOZZLE

**TABLE 2.1**  
**NOZZLE INSERT DIMENSIONS**

| NOZZLE<br>INSERT | A*<br>mm <sup>2</sup> | A <sub>e</sub><br>mm <sup>2</sup> | A <sub>e</sub> /A* | P<br>bar(a) | Mach<br>No | h<br>mm | D <sub>1</sub><br>mm | D <sub>2</sub><br>mm | D <sub>3</sub><br>mm | D <sub>4</sub><br>mm | α     | l<br>mm | T<br>mm | r<br>mm |
|------------------|-----------------------|-----------------------------------|--------------------|-------------|------------|---------|----------------------|----------------------|----------------------|----------------------|-------|---------|---------|---------|
| IN2/NN2          | 122.52                | 71.03                             | 1.725              | 8.07        | 2.02       | 0-6     | 4.0                  | 10.0                 | 13.80                | 16.00                | ----- | -----   | -----   | -----   |
| IN3/WM1          | -----                 | 75.40                             | -----              | -----       | 1.00       | 0-6     | 4.0                  | 10.0                 | 14.00                | -----                | ----- | -----   | 12.35   | 12.35   |
| IN3/WM2          | 14.43                 | 38.45                             | 2.665              | 17.35       | 2.51       | 0-6     | 4.0                  | 10.0                 | 10.88                | 12.205               | 13.10 | 0.663   | 12.35   | 9.50    |
| IN3/WM3          | -----                 | 17.36                             | -----              | -----       | 1.00       | 0-6     | 4.0                  | 10.0                 | 11.05                | -----                | ----- | -----   | 12.35   | 12.35   |
| IN3/WM4          | 15.63                 | 28.06                             | 1.80               | 8.84        | 2.08       | 0-6     | 4.0                  | 10.0                 | 10.95                | 11.65                | 7.30  | 0.365   | 12.35   | 9.50    |
| IN3/WM5          | 15.63                 | 55.22                             | 3.53               | 27.56       | 2.81       | 0-6     | 4.0                  | 10.0                 | 10.95                | 13.05                | 20.86 | 1.09    | 12.35   | 9.50    |
| IN4/WM7          | 14.77                 | 36.99                             | 2.50               | 15.81       | 2.45       | 0-6     | 4.0                  | 8.0                  | 9.10                 | 10.54                | 14.18 | 0.72    | 12.35   | 9.50    |
| IN5/WM8          | 13.17                 | 35.45                             | 2.69               | 17.62       | 2.52       | 0-6     | 4.0                  | 12.18                | 12.83                | 13.91                | 10.73 | 0.54    | 12.35   | 9.50    |
| IN6/WM2          | 14.43                 | 38.45                             | 2.665              | 17.36       | 2.51       | 6-12    | 4.0                  | 10.0                 | 10.88                | 12.205               | 13.1  | 0.663   | 12.35   | 9.50    |

the distance between the two shells. In order for the inserts to be easily machined the converging diverging shape of the nozzle was not theoretically perfect. The combination of inner and outer insert enable a great number of gas flow sections, of nearly any shape, to be made. Nozzles used in this project are referred to by their insert combinations. They are abbreviated by 'IN n' for an inner insert and by 'WM n' for an outer insert, 'n' being the number of the insert e.g. IN3/WM2 (The only exception to this rule is the inserts which were used for concentricity work IN2/NN2).

The inserts were chosen so that the gas flow sections were convergent divergent or convergent only. The characteristics of the gas flow and geometry can be summarized by referring to Figures 2.4a and 2.4b in conjunction with Table 2.1.

For example consider the insert combination IN3/WM2.

(a) inner insert (IN3).

This inner insert (see figure 2.5a) consists of a base which tapers into a parallel sided flow tube, of outside diameter, 10.0 mm ( $D_2$ ) and bore of 4.0 mm ( $D_1$ ). The height which the liquid flow tube protrudes above the exit plane of the outer insert ( $h$ ) is known as the protrusion. In IN3/WM2 it can vary from 0.0-6.0 mm. The protrusion is varied by using different combinations of 'spacers', which fit between the inner and outer shells (see figure 2.3 for position of spacers), so altering the position of the outer insert relative to the inner insert.

(b) outer insert (WM2).

This outer insert (see figure 2.5b) consists of a convergent divergent tube which fits over the inner insert. The tube has a throat diameter ( $D_3$ ) of 10.88 mm and exit diameter ( $D_4$ ) 12.205 mm. The angle,  $\alpha$  of taper of the divergent section is  $13.1^\circ$ . The radius,  $r$ , equals 9.5 mm and was chosen to allow the gas to flow as smoothly as possible through the nozzle. The insert depth,  $T$ , is 12.35 mm.

The exit area,  $A_e$ , is calculated from the above figures as  $38.45 \text{ mm}^2$  and the throat area,  $A_*$ , as  $14.43 \text{ mm}^2$ . Thus the value of the ratio  $A_e/A_* = 2.665$ . From the equations of isentropic gas flow (Chapter 3) for isentropic expansion in a round nozzle,

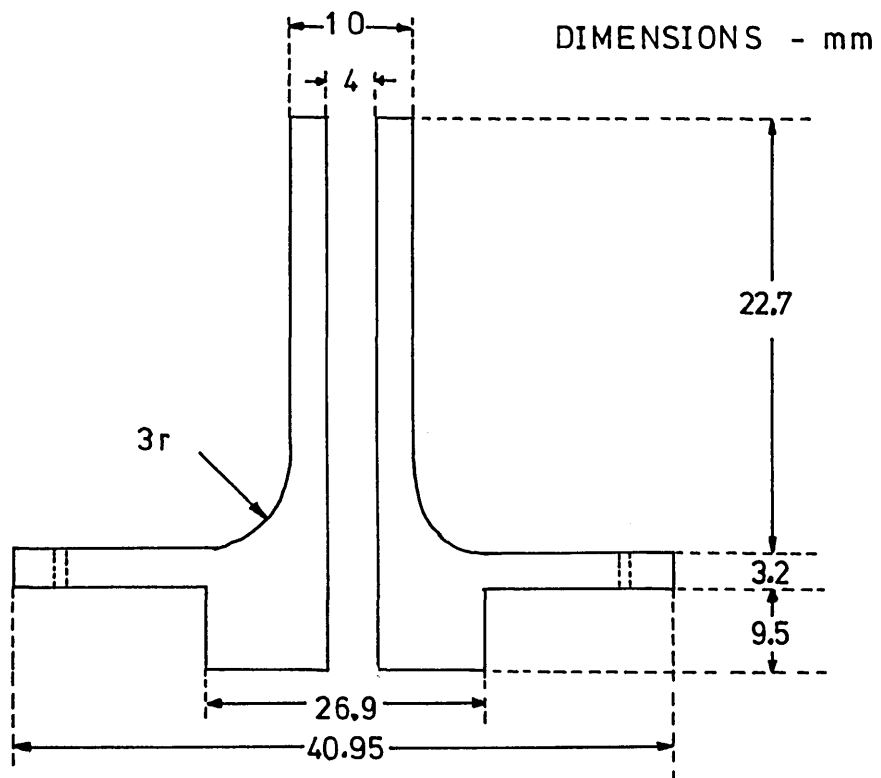


FIGURE 2.5 a

INSERT IN3

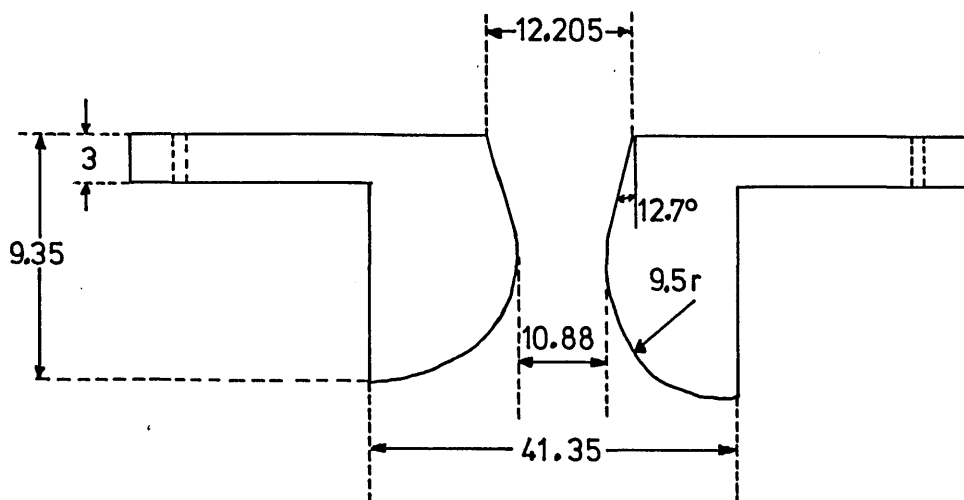


FIGURE 2.5 b

INSERT WM2

MATERIAL : BRASS

whose throat and exit areas are the same as IN3/WM2, the pressure ratio across the nozzle must be 0.05762 and the Mach number produced by the nozzle will be 2.51.

## 2.4 CONCENTRICITY

The concentricity of nozzles was found by Gretzinger and Marshall<sup>(23)</sup> to be of great importance. They found that when the gas annulus and liquid flow tube were eccentric they obtained nonreproducible results and larger drop sizes. Therefore considerable effort was spent in this project to ensure that the nozzles used were concentric.

### 2.4.1 EXPERIMENTAL INVESTIGATION OF CONCENTRICITY

The concentricity was investigated by traversing a pitot tube across the nozzle top (while the nozzle was running on the laboratory airline) at the exit plane. This was accomplished by connecting the pitot to an XYZ traverse rig. The traverse rig was connected to three linear voltage displacement transducers (LVDT's), for accurate positioning of the pitot. The pitot was connected to a pressure transducer. The output from the pressure transducer and the LVDT, in the direction of the traverse, was recorded on an XY recorder. The experimental apparatus is discussed further in Chapter 4. By carrying out a series of traverses above the nozzle in one horizontal direction, and moving the pitot a small amount in the orthogonal horizontal direction a picture of the gas flow above the nozzle was produced.

By plotting the stagnation pressure recorded by the pitot tube, on a circle corresponding to the annular position of the traverse, a picture, or 'rosette', which shows the areas of maximum and minimum gas flow, can be drawn.

Figures 2.6 and 2.7 show two such rosettes, for IN2/NN2. Figure 2.6 shows a case where the gas flow seems to be 'blocked' in the nozzle. Figure 2.7 shows a case where the nozzle seems to be running concentrically with very little difference in the gas flow anywhere around the annulus.

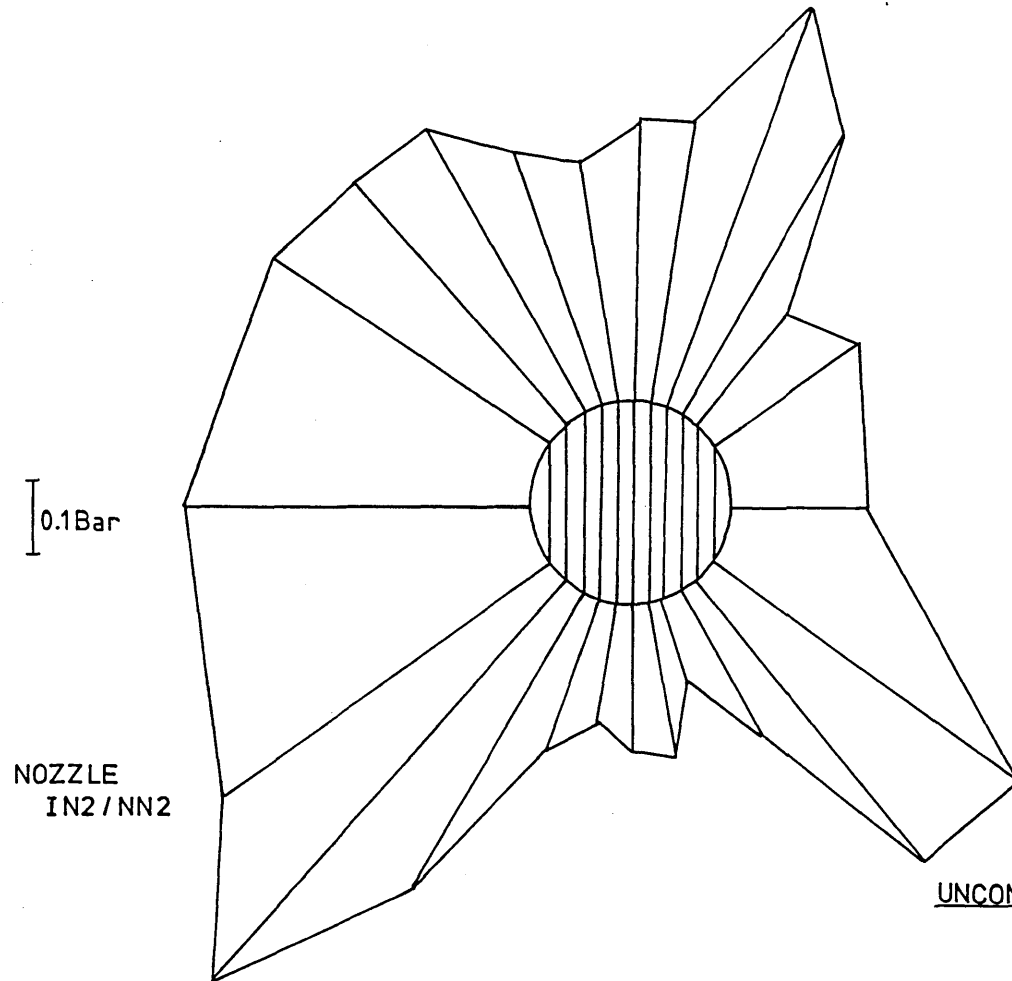


FIGURE 2.6  
UNCONCENTRIC TRAVERSE  
ROSETTE

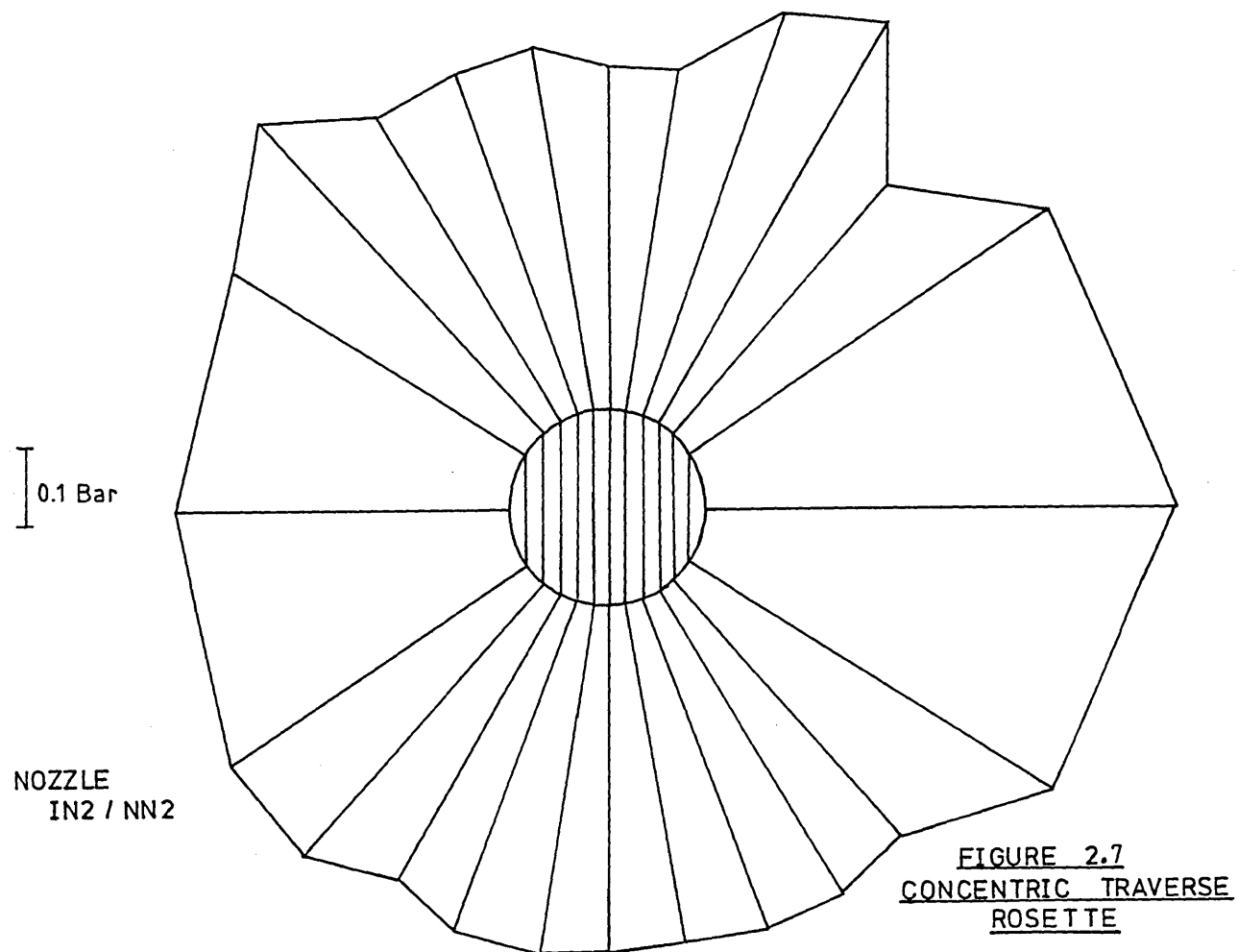


Figure 2.8 to 2.9 show some examples of individual traverses. The traverses were carried out with 0.00 mm protrusion at 1.00 mm above the nozzle exit plane. The traverses were carried out at a driving pressure of 4.5 bars (absolute).

Figure 2.8 best illustrates a concentric traverse. The stagnation pressure peaks which are obtained are of almost identical height. The variation of pressure above the flow tube is well defined and is always below ambient. The 'secondary' peak in the centre of the traverse corresponds to the bore of the flow tube and is caused by gas flowing up the flow tube, the bottom of which was open to atmosphere. (This gas flow is due to the entrainment effect of the gas jet above the nozzle.) The diagram also includes the nozzle exit dimensions which are given in Table 2.1 of IN2/NN2.

Figure 2.9 shows two stagnation pressure peaks of different heights. This illustrates non-concentric behaviour.

Subsequent understanding of the nature of the gas flow in the nozzle has shown us that the chances of unconcentric behaviour being measured, at the experimental pressure used, were considerable. The pressure at which the concentricity tests were carried out meant that very often shock waves were situated in or just outside the exit of the nozzle. Theoretically the IN2/NN2 nozzle would choke at the exit at a pressure of 1.75 bars absolute. As the experimental pressure was just above this the stagnation pressure measured by the pitot tube in many cases could be either side of shock waves occurring outside the nozzle.

For example minor variations in the nozzle dimensions could cause the situation illustrated in Figure 2.10 where the traverse on one side of the nozzle was across an oblique shock wave and on the other side of the traverse was downstream of a normal shock wave still in the divergent portion of the nozzle. This would result in the stagnation pressure measured by the pitot tube, on the side of the oblique shock being greater than the pressure measured on the other side.

It was found that when operating at higher pressures the concentricity of the nozzle was not nearly such a problem as had been initially feared because the pressure of the shock waves around the nozzle exit is not nearly so crucial at higher

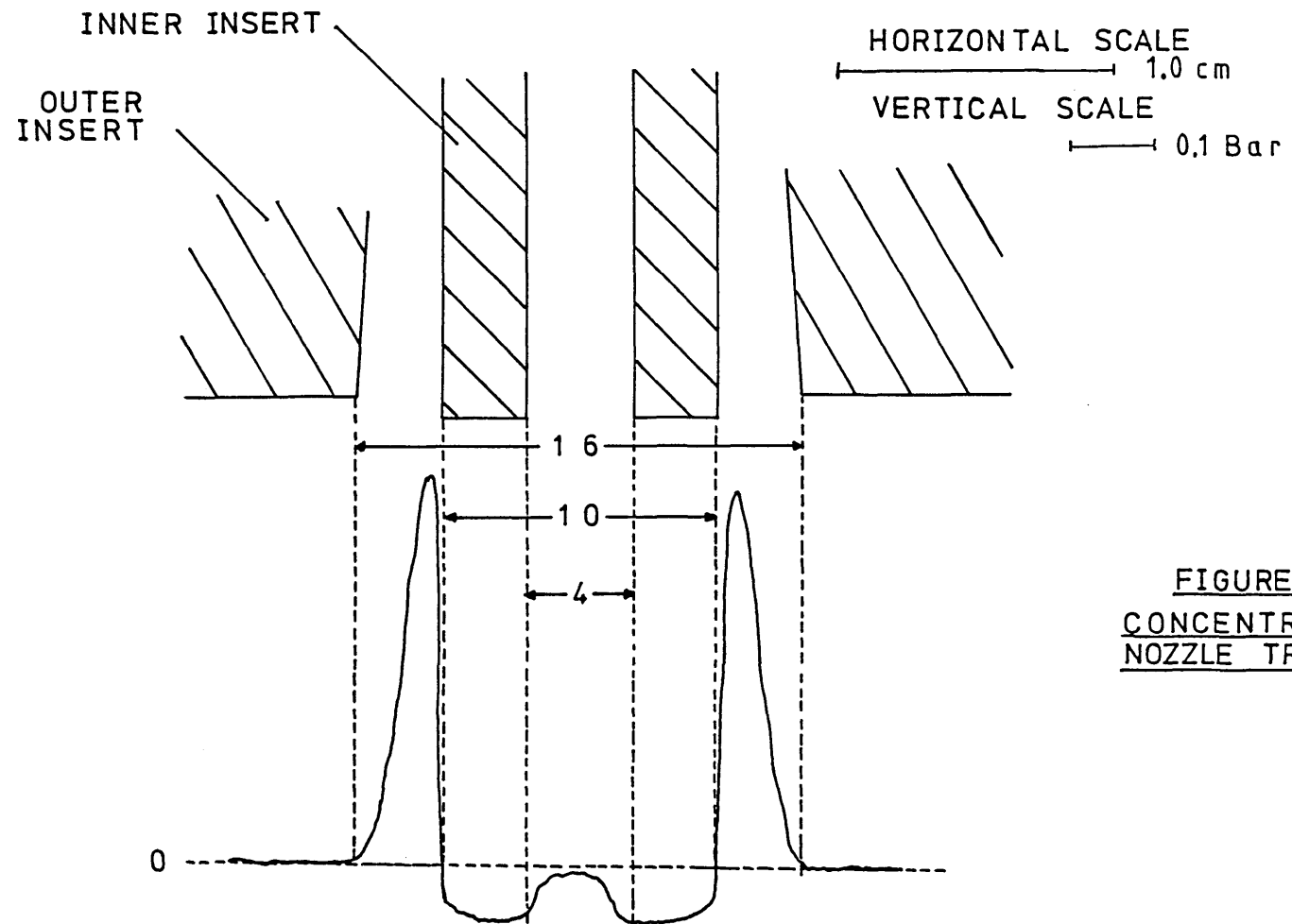


FIGURE 2.8  
CONCENTRIC  
NOZZLE TRAVERSE

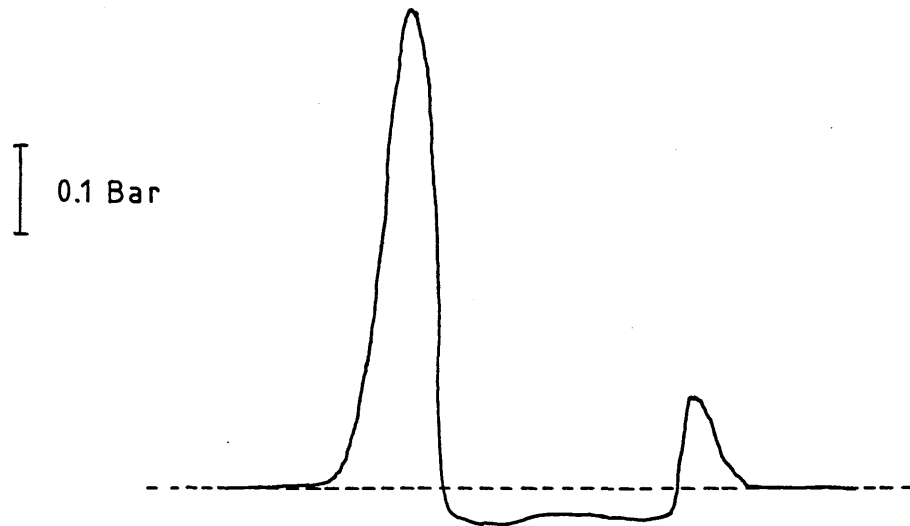
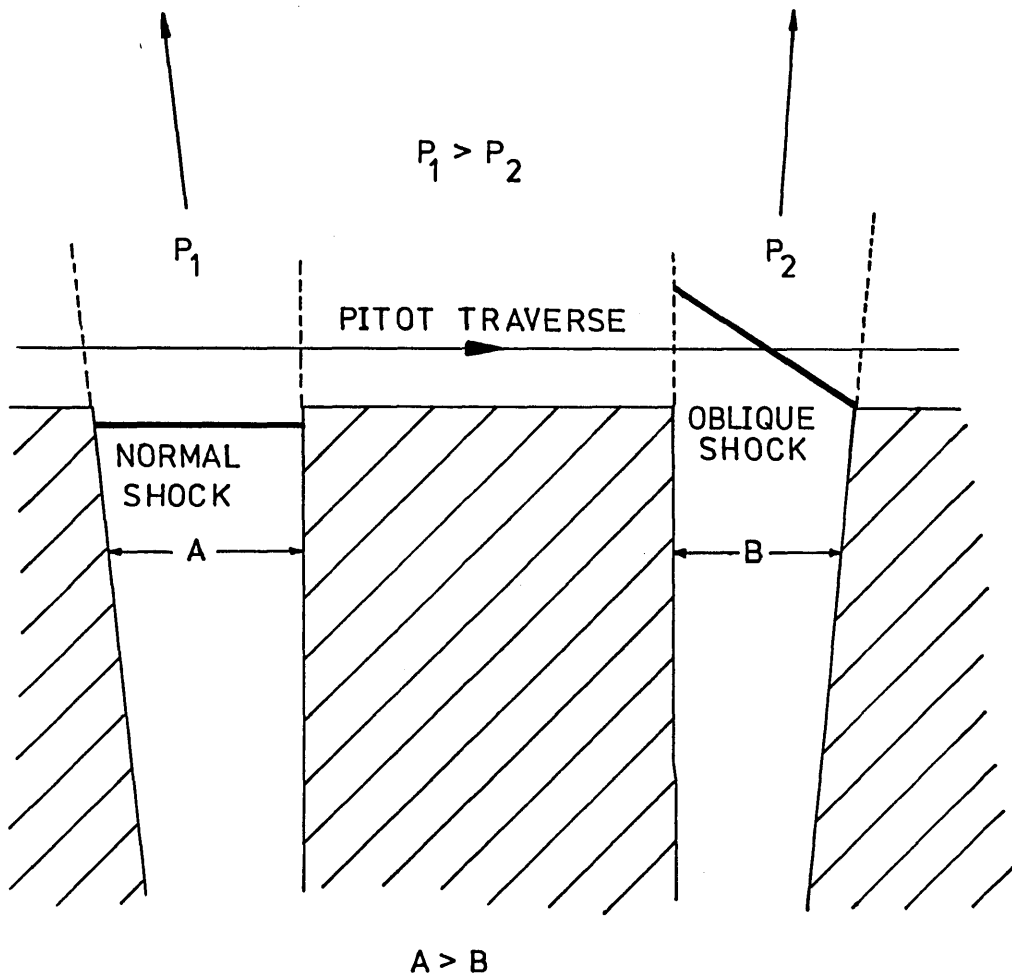


FIGURE 2.9  
UNCONCENTRIC TRAVERSE

**FIGURE 2.10**  
**POSSIBLE SHOCK WAVE CONFIGURATION**  
**FOR UNCONCENTRIC OPERATION**



pressures. When operating at higher pressures the likelihood of measuring unconcentric behaviour decreases. This is because the normal shocks will no longer sit in the diverging section of the nozzle and oblique shock waves will not be present on both sides of a pitot traverse. For this reason operating pressures which cause normal shock waves at the nozzle exit should not be considered. The following chapter describes the gas flow and development of shock waves, in the nozzles used, in much greater detail.

## **CHAPTER THREE**

### **GAS FLOW IN NOZZLES**

### 3.1 INTRODUCTION

This chapter will show a series of sample gas flow calculations on the nozzle IN3/WM2. However in order to do this it will be necessary to introduce the basic compressible gas flow equations and derive the relationships which can be used to describe the gas flow in convergent as well as convergent divergent nozzles. The chapter contains the following sections:

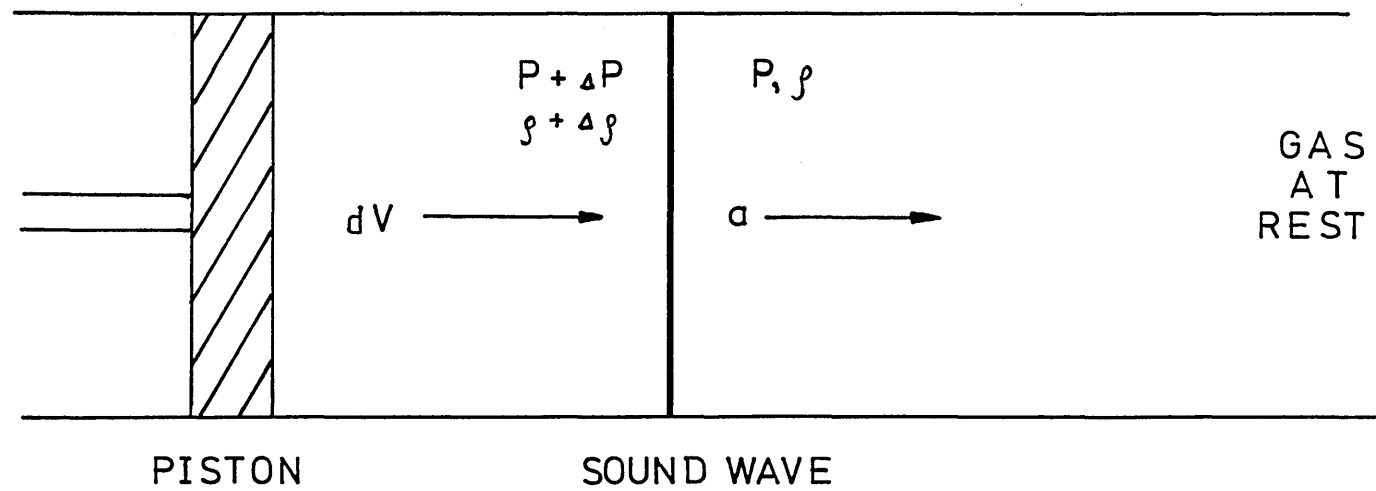
- (1) Velocity of Sound
- (2) Mach Number Relationships for Compressible Flow
- (3) Isentropic Flow through a Varying Area Channel
- (4) Dependence of the Mach Number on Area Variation
- (5) Converging Diverging Nozzles
- (6) Under Expanded and Over Expanded Nozzles
- (7) Gas Mass Flow Rate
- (8) Convergent Nozzles
- (9) Normal Shock Waves
- (10) Example Calculation using IN3/WM2
- (11) Oblique Shock Wave and Expansion Wave Behaviour in IN3/WM2

The calculations assume that the nozzle is a slit and that the gas is ideal, compressible and isentropic. The nozzle can be assumed to be a slit as the nozzle has a small exit gap and a large diameter relative to the exit gap.

### 3.2 VELOCITY OF SOUND.

An expression for the velocity of sound can be derived by considering a piston in a tube moving at infinitesimal velocity  $dV$  causing a compression of the gas in the tube as in Figure 3.1. This creates a sound wave of velocity  $a$ . Then considering a control volume around the sound wave moving through the gas: the mass balance for steady flow is:

FIGURE 3.1  
SOUND WAVE



$$(\rho + d\rho)(a - dV)A - \rho aA = 0$$

where

$A$  = cross sectional area of the control volume

$\rho$  = density of gas

$V$  = velocity of gas

which when simplified and the second order terms are dropped gives:

$$a d\rho - \rho dV = 0 \quad (3.1)$$

The momentum balance for steady flow gives:

$$PA - (P + dP)A = [(a - dV) - a] \rho Aa$$

where  $P$  = pressure

which on simplifying gives:

$$dP = \rho a dV \quad (3.2)$$

combining the above two equations 3.1 and 3.2 gives:

$$dP = a^2 d\rho$$

or

$$a^2 = \partial P / \partial \rho \quad (3.3)$$

Since a sound wave produces infinitesimal changes in the pressure and density, the sound wave can be considered to be reversible and as it travels at high speeds it can also be considered to be adiabatic. A reversible adiabatic process is an isentropic process; thus, the expression for the speed of sound can be written as:

$$a^2 = [\partial P / \partial \rho]_S$$

If we consider the piston causing an expansion rather than a compression then using the same control volume around the sound wave and using the equation of adiabatic change for a perfect gas<sup>(41)</sup>:

$$p / \rho^k = \text{constant} \quad (3.4)$$

where  $k$  the ratio of specific heats is defined as:

$$k = c_p / c_v.$$

where

$c_p$  = specific heat of the gas at constant pressure.

$c_v$  = specific heat of the gas at constant

volume.

Then for a perfect gas:

$$(\partial P / \partial \rho) = kP / \rho$$

and

$$a = (kP / \rho)^{0.5}$$

For a perfect gas the equation of state is<sup>(41)</sup>:

$$P / \rho = RT \quad (3.5)$$

where

R = gas constant

T = absolute temperature

and so:

$$a = (kRT)^{0.5} \quad (3.6)$$

The Mach number of a gas is defined by:

$$M = V / a \quad (3.7)$$

### 3.3 MACH NUMBER RELATIONSHIPS FOR COMPRESSIBLE FLOW

Consider the flow in Figure 3.2 in which a control volume is bounded by two streamlines in steady compressible flow. Applying the energy equation and neglecting any potential energy terms gives, for adiabatic flow:

$$\dot{m}_1 (h_1 + V_1^2 / 2) = \dot{m}_2 (h_2 + V_2^2 / 2)$$

where  $\dot{m}$  = The mass flow rate of gas

as the mass flow rate must be constant:

$$(h_1 + V_1^2 / 2) = (h_2 + V_2^2 / 2)$$

and since points 1 and 2 are arbitrary points on the same streamline:

$$h + V^2 / 2 = \text{constant} \quad (3.8)$$

where the constant is equal to the total enthalpy,  $h_t$ .

The enthalpy of an ideal gas can be written as:

$$h = c_p T$$

Substituting this equation into 3.8 and dividing by  $c_p T$  gives:

$$1 + (V^2 / 2c_p T) = T_t / T \quad (3.9)$$

where  $T_t$  is the total temperature.

given that

$$R = c_p - c_v$$

therefore:

$$c_p = kR / (k-1)$$

substituting back into 3.9 gives:

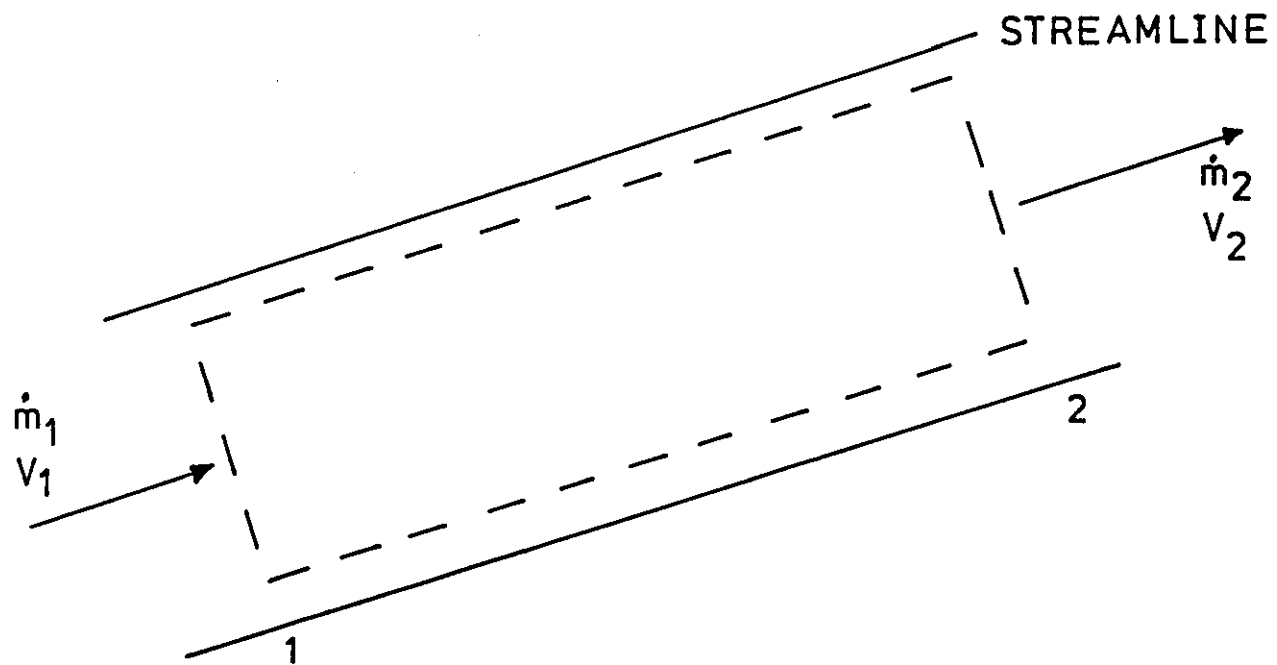


FIGURE 3.2  
STEADY COMPRESSIBLE FLOW

$$T_t/T = [1 + (k-1)M^2/2] \quad (3.10)$$

If flow is isentropic, then the following relationship can be obtained from equation 3.4 for temperature and pressure between two points along a streamline<sup>(41)</sup>:

$$P_1/P_2 = (T_1/T_2)^{k/(k-1)} \quad (3.11)$$

Also if flow is isentropic then the total temperature,  $T_t$ , is constant along the streamline:

$$T_t = T_1[1 + (k-1)M_1^2/2] = T_2[1 + (k-1)M_2^2/2]$$

The total pressure in an isentropic compressible flow is:

$$P_t = P_1[1 + (k-1)M^2/2]^{k/(k-1)} \quad (3.12)$$

Density can be obtained similarly to pressure and is given by:

$$\rho_t = \rho_1[1 + (k-1)M^2/2]^{1/(k-1)} \quad (3.13)$$

### 3.4 ISENTROPIC FLOW THROUGH A VARYING AREA CHANNEL

Consider a control volume of the gas flow through a duct of varying cross section, as illustrated in Figure 3.3. By carrying out a mass, momentum and energy balance the effect of varying area on velocity can be determined:

#### Mass balance

The mass flow of the duct is given by:

$$\dot{m}_g = \rho AV \quad (3.14)$$

Since the mass flow along the duct is constant:

$$(\rho + d\rho)(A + dA)(V + dV) - (\rho AV) = 0 \quad (3.15)$$

Equation 3.15 can be written as:

$$d\rho/\rho + dA/A + dV/V = 0 \quad (3.16)$$

#### Momentum balance

The rate of change in the in going and out going momentum is equal to the forces exerted on the control volume. If the assumption is made that the mean pressure exerted by the walls of the duct on the control volume are  $(P + dP/2)$  then:

$$\dot{m}_g [(V + dV) - V] = PA - (P + dP)(A + dA) + (P + dP/2)dA_s \sin\theta$$

neglecting second order terms and putting  $dA = dA_s \sin\theta$  then:

$$(\rho VA)dV = -AdP$$

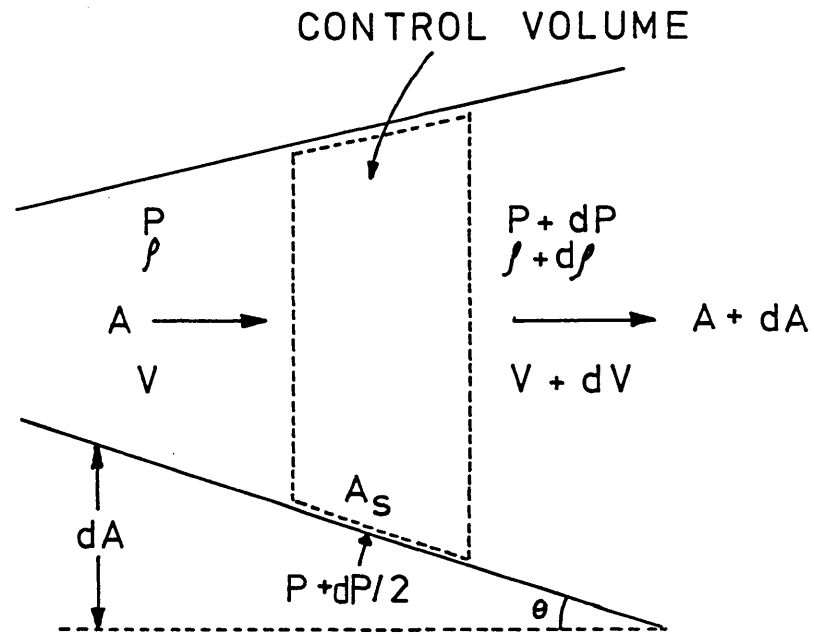


FIGURE 3.3  
VARYING AREA FLOW

or

$$dP + \rho V dV = 0 \quad (3.17)$$

Energy Equation:

The enthalpy of a system,  $h$ , is equal to the sum of the internal energy,  $u$ , and the flow energy of a gas,  $P/\rho$  :

$$h = u + P/\rho \quad (3.18)$$

With no external heat transfer and no work done, for steady one dimensional flow, equation 3.8 can be written as:

$$dh + dV^2/2 = 0 \quad (3.19)$$

The second law of thermodynamics states a reversible process is one that can be reversed to its initial state without changing the system or surrounding. From the second law the entropy,  $s$ , of a system is defined as:

$$ds = \partial Q/T$$

where  $Q$  = heat in the system

and so from the first and second laws of thermodynamics:

$$Tds = dh - dP/\rho$$

For isentropic flow ( $Tds=0$ ):

$$dh = dp/\rho$$

Combining with 3.19

$$dP + \rho V dV = 0 \quad (3.17)$$

which is the same as equation 3.17

Combining the mass balance and momentum balance equations for isentropic flow equations 3.16 and 3.17 then:

$$dP + \rho V^2 (-d\rho/\rho - dA/A) = 0 \quad (3.20)$$

But:

$$(\partial P/\partial \rho) = a^2 \quad (3.3)$$

Therefore for isentropic flow:

$$dP + V^2 (-dP/\rho a^2 - dA/A) = 0$$

therefore:

$$dP(1-M^2) = V^2 dA/A \quad (3.21)$$

### 3.5 DEPENDENCE OF THE MACH NUMBER ON AREA VARIATION.

In convergent and convergent divergent nozzles the effect of change of area is the most dominant factor on the resulting flow. For isentropic flow we have shown that:

$$dP(1 - M^2) = V^2 dA/A \quad (3.21)$$

Equation 3.21 demonstrates the influence of Mach number on the flow. For an  $M < 1$ , subsonic flow, the term  $(1 - M^2)$  is positive. Therefore an increase in area results in an increase in pressure and a decrease in velocity as shown in equation 3.17. Likewise, a decrease in area results in a decrease in pressure and an increase in velocity. For supersonic flow,  $M > 1$ , the term  $(1 - M^2)$  in equation 3.21 is negative, and opposite variations occur.

Thus subsonic flow cannot be accelerated to a velocity greater than the velocity of sound in a converging nozzle. This is true irrespective of the pressure difference imposed on the flow through the nozzle. If it is desired to accelerate a stream to supersonic velocity, a convergent divergent channel must be used.

If we now look at the flow in a convergent divergent nozzle and a convergent only nozzle the way in which pressure and Mach number vary can be examined in more detail.

### 3.6 CONVERGENT DIVERGENT NOZZLE

Equation 3.21 can be expressed as a relation between area and Mach number only.

If equation 3.6,  $a = (kRT)^{0.5}$ , is differentiated then:

$$da/a = dM/M + dT/2T \quad (3.22)$$

If equation 3.10, the temperature form of the energy equation, is also differentiated then:

$$\begin{aligned} dT/T &= [-(k-1)M dM] / [1 + (k-1)M^2/2] \\ &= [ \{-(k-1)M^2\} / \{1 + (k-1)M^2/2\} ] dM/M \end{aligned} \quad (3.23)$$

If equations 3.22 and 3.23 are substituted into 3.21 then:

$$dA/A = [ (M^2-1) / \{1 + (k-1)M^2/2\} ] dM/M \quad (3.24)$$

Thus in a convergent divergent nozzle the ratio of area of cross section of the exit to the area of cross section at the throat,  $A/A_*$ , to produce a given Mach number can be obtained by integrating equation 3.24 giving:

$$A/A_* = 1/M \left[ \{1 + (k-1)M^2/2\} / \{(k+1)/2\} \right]^{(k+1)/2(k-1)} \quad (3.25)$$

### 3.7 UNDEREXPANDED AND OVEREXPANDED NOZZLES

As mentioned earlier equation 3.21 indicates that for  $M > 1$  the velocity will increase with increase of nozzle area after sonic conditions have been established at the throat. This increase in velocity requires that the pressure difference along the length of the nozzle increases. In the case where the nozzle is running into air at a pressure of  $P_a$  (1 bar(a)) the pressure difference across the nozzle increases as the driving pressure,  $P_d$ , is increased.

Figure 3.4 shows some different operating conditions of the convergent divergent nozzle for different values of the driving pressure. As  $P_d$  is increased from the "no flow" condition gas is accelerated towards the throat. If  $M < 1$  at the throat then the divergent portion of the nozzle acts as a diffuser increasing the pressure and reducing the velocity of the gas.

At the critical throat condition, the nozzle is choked at the throat and  $M = 1$ . From equation 3.12

$$P_t = P_1 (1 + (k-1)M^2/2)^{k/(k-1)} \quad (3.12)$$

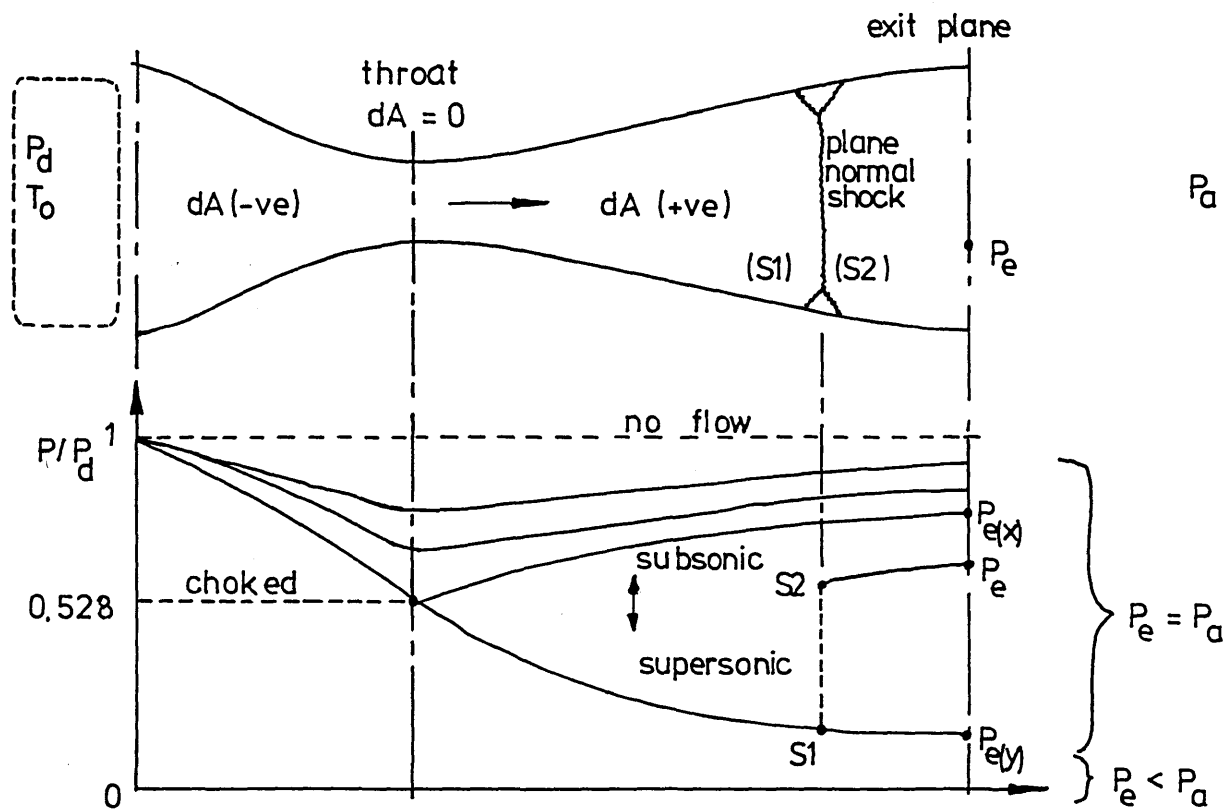
the critical pressure ratio at the throat can be calculated by substituting  $M = 1$  giving:

$$P_*/P_d = (2/(k+1))^{k/(k-1)} \quad (3.26)$$

which for air is

$$P_*/P_d = 0.528$$

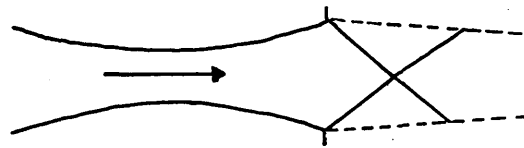
FIGURE 34 PRESSURE DISTRIBUTION FOR COMPRESSIBLE FLOW THROUGH  
A CONVERGENT DIVERGENT NOZZLE



where  $P_*$  is the pressure at the throat

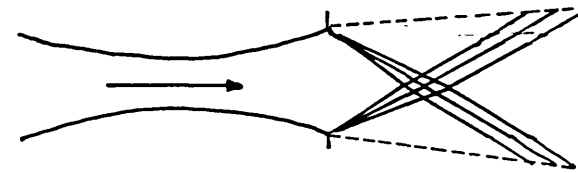
Under ideal conditions, by solving equation 3.25, there are two values for the nozzle exit pressure,  $P_e$ , corresponding to two values of Mach number for a given area ratio. The higher value of exit pressure  $P_{e(x)}$  corresponds to subsonic isentropic flow in the divergent portion of the nozzle while the lower value  $P_{e(y)}$  corresponds to supersonic isentropic flow. In both cases the nozzle exit pressure is the same as the pressure into which the nozzle is exhausting,  $P_a$ , and the Mach number at the throat is unity. The nozzle in the subsonic case has just reached the critical pressure ratio at the throat. The nozzle in the supersonic case is said to be ideally expanded. The value of the pressure ratio across the nozzle which gives ideally expanded flow,  $P_{ideal}$ , and the critical pressure ratio across the nozzle can also be calculated from equation 3.12 by substituting the value of the Mach numbers obtained by solving equation 3.25.

However if the value of  $P_e$  is not equal to  $P_a$  then the nozzle flow becomes increasingly complex. If  $P_d > P_{ideal}$  the exit pressure,  $P_e$ , is larger than  $P_a$  and the nozzle is behaving in an underexpanded mode because the flow could have expanded further. The flow at the exit of the nozzle then must go through a series of expansion waves to bring the exit pressure to  $P_a$ . A nozzle for which the exit pressure is less than  $P_a$ , i.e.  $P_d < P_{ideal}$ , is behaving in the overexpanded mode because the flow has been expanded below  $P_a$ . Oblique shock waves occur at the exit if  $P_e$  is slightly less than  $P_a$ , raising the pressure back to  $P_a$ . If however the value of  $P_e$  is too small for the oblique shock to raise the pressure a normal shock will occur in the nozzle, (as illustrated in Figure 3.4 -  $S_1, S_2$ ) the flow will become subsonic and decelerate in the remaining portion of the diverging section. The flow outside the jet in the ideal, overexpanded and underexpanded modes is illustrated in Figure 3.5.



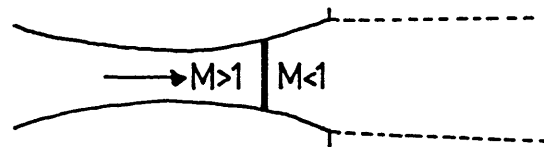
OVER EXPANDED  
(oblique shock waves)

$$P_d < P_{ideal}$$



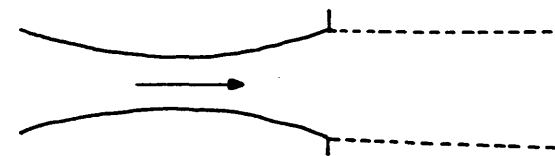
UNDER EXPANDED  
(expansion waves)

$$P_d > P_{ideal}$$



NORMAL SHOCK

$$P_d \ll P_{ideal}$$



IDEAL

$$P_d = P_{ideal}$$

FIGURE 3.5

NOZZLE OPERATING MODES

### 3.8 GAS MASS FLOW RATE

The easiest place at which to calculate the gas mass flow rate is at the throat of the nozzle where the Mach number is unity. Combining equations 3.6 and 3.14 for flow at the throat then:

$$\dot{m}_g = \rho_* A_* (kRT_*)^{0.5} \quad (3.27)$$

If the flow at the throat is expressed in terms of the total conditions then from 3.10

$$T_*/T_t = [2/(k+1)] \quad (3.28)$$

and from 3.13

$$\rho_*/\rho_t = [2/(k+1)]^{1/(k-1)} \quad (3.29)$$

Substituting 3.28 and 3.29 into 3.27 gives

$$\dot{m} = \rho_t (kRT_t)^{0.5} A_* [2/(k+1)]^{(k+1)/2(k-1)} \quad (3.30)$$

Using the equation of state 3.5 to eliminate  $\rho_t$  gives:

$$\dot{m} = P_t A_* / (T_t)^{0.5} [k/R\{2/(k+1)\}^{(k+1)/(k-1)}]^{0.5} \quad (3.31)$$

For gases with a ratio of specific heats,  $k$ , = 1.4, such as nitrogen and air:

$$\dot{m} = 0.685 P_t A_* / (RT_t)^{0.5}$$

### 3.9 CONVERGENT ONLY NOZZLE

The flow in a convergent only nozzle is equivalent to that in a convergent divergent nozzle cut off at the throat. As stated earlier the exit Mach number cannot exceed 1.

The mass flow rate through the nozzle can be calculated the same way as for a convergent divergent nozzle provided the nozzle is choked. i.e  $P_d/P_d > 0.528$  for gas with  $k=1.4$ . The situation for an unchoked nozzle is more complex but as the situation does not arise in this project it will not be discussed.

When the value of  $P_d$  is increased above the critical value the pressure at the exit is above  $P_a$  and the nozzle achieves pressure equilibrium after the exit through a series of expansion waves.

### 3.10 NORMAL SHOCK WAVES

As explained earlier normal shock waves can occur in the nozzle. The effect of the normal shock wave on mach number can be explained by considering a control volume around a normal shock wave as shown in Figure 3.6.

The mass balance gives:

$$-\rho_1 V_1 A + \rho_2 V_2 A = 0$$

Equating pressure forces to net momentum gives:

$$\rho_1 V_1 A (-V_1 + V_2) = (P_1 - P_2) A$$

and  $T_{t1} = T_{t2}$  for adiabatic conditions

Using equation 3.6 and 3.5 the mass balance can be rewritten as:

$$P_1 / (RT_1) M_1 (kRT_1)^{0.5} = P_2 / (RT_2) M_2 (kRT_2)^{0.5} \quad (3.32)$$

The Mach number can be introduced into the momentum equation in the following way:

$$\begin{aligned} \rho_2 V_2^2 - \rho_1 V_1^2 &= P_1 - P_2 \\ P_1 + P_1 / (RT_1) V_1^2 &= P_2 + P_2 / (RT_2) V_2^2 \\ P_1 (1 + kM_1^2) &= P_2 (1 + kM_2^2) \end{aligned}$$

rearranging gives the static pressure ratio across a normal shock

$$P_2 / P_1 = (1 + kM_1^2) / (1 + kM_2^2) \quad (3.33)$$

because  $M_1 > 1$  and  $M_2 < 1$ ; then  $P_2 > P_1$ , which shows that static pressure increases across a shock wave.

Substituting  $T_{t1} = T_{t2}$  into equation 3.10 gives

$$T_2 / T_1 = [1 + (k-1)M_1^2 / 2] / [1 + (k-1)M_2^2 / 2] \quad (3.34)$$

The ratio  $T_2 / T_1 > 1.0$

Substituting 3.33 and 3.34 into 3.32 and solving for  $M_2$  as a function of  $M_1$  gives:

$$M_2^2 = [(k-1)M_1^2 + 2] / [2kM_1^2 - (k-1)] \quad (3.35)$$

Thus across a shock wave pressure temperature and density all increase and the Mach number decreases.

### 3.11 EXAMPLE CALCULATIONS FOR IN3/WM2 - A/A\* = 2.665

The basic gas flow equations, which are necessary to do a calculation, have now been discussed. It is now possible to apply these equations to a convergent and a convergent divergent nozzle.

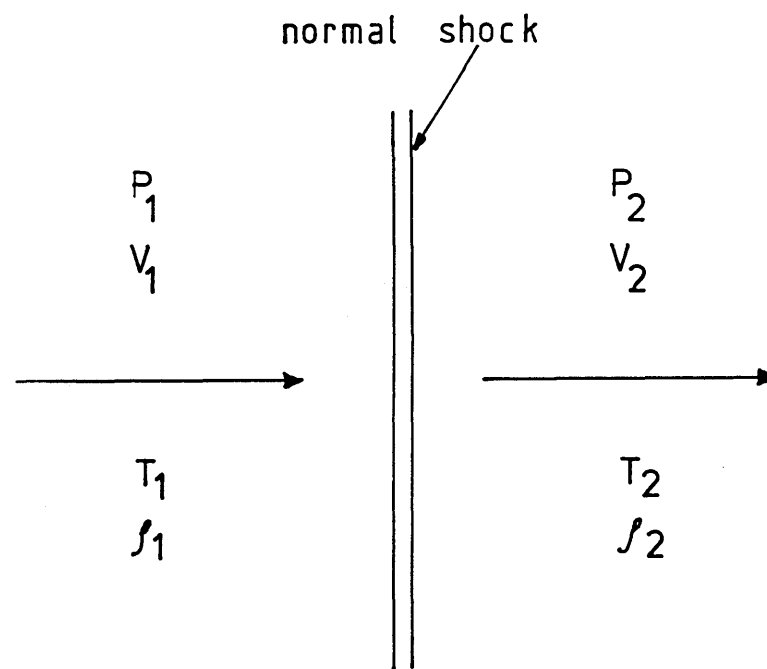


FIGURE 3.6  
NORMAL SHOCK

In all the calculations the following assumptions have been made:

- i) the gas flow is ideal
- ii) the flow is isentropic
- iii) the nozzle is a slit
- iv) the exiting gas does not entrain gas from the surroundings

The first example calculation will use IN3/WM2. This nozzle has a  $A/A_* = 2.665$  (the exit area/throat area ratio). In all calculations pressure is in bars absolute.

Substituting  $A/A_*$  into equation 3.25 and solving for the Mach number gives  $M = 2.51$  for a supersonic isentropic expansion or  $M = 0.225$  for a subsonic isentropic expansion.

The critical pressure ratio across the nozzle from equation 3.12 with  $M = 0.225$  is:

$$P_e/P_d = 0.9414$$

Thus as  $P_e = 1.0$  bars(a),  $P_d = 1.062$  bars(a)

The ideal operating pressure,  $P_{ideal}$ , is calculated the same way by substituting  $M = 2.51$  into equation 3.12 and so:

$$P_e/P_{ideal} = 0.0576$$

Thus as  $P_e = 1.0$  bars,  $P_{ideal} = 17.35$  bars

So when the nozzle is operating above 17.35 bars driving pressure it is underexpanded and expansion waves occur at the exit.

When the nozzle is running below 17.35 bars it is overexpanded and oblique shocks form at the exit. It is possible to calculate at what pressure ratio the normal shock, which can occur in the diverging portion of the nozzle, sits at the exit of the nozzle.

When  $M_1 = 2.51$  then from 3.35 and 3.33, the pressure ratio across the normal shock,  $P_2/P_1 = 7.183$ . Thus the pressure ratio across the nozzle,  $P_e/P_d$ , (0.0576) increases to  $7.183 \times 0.0576 = 0.4137$ . And so for a  $P_e = 1.0$  bars,  $P_d = 2.417$  bars. Thus the normal shock sits at the exit of IN3/WM2 at a driving pressure of 2.417 bars(a).

The gas mass flow rate can be calculated from equation 3.31 and for air with  $k = 1.4$ ,  $R = 287 \text{ J/kgK}$ ,  $A_* = 14.43 \times 10^{-6} \text{ m}^2$  and taking  $T = 265^\circ\text{K}$  (see Chapter 4 on mass flow rate measurements for an explanation of why  $T = 265^\circ\text{K}$ ) the gas mass flow rate is:

$$\dot{m}_g = P_d (3.5829 \times 10^{-8})$$

where  $P_d$  is in Pa.

### 3.12 OBLIQUE SHOCK WAVE AND EXPANSION WAVE BEHAVIOUR IN A CONVERGING DIVERGING ANNULAR NOZZLE

In order to describe the action of shock waves in the converging diverging nozzles used in this project IN3/WM2 will be used as an example to demonstrate the calculation of shock wave location. This will be done for an overexpanded as well as an underexpanded case.

Reference is made to readily available tables<sup>(41,42,43)</sup> of isentropic flow, flow through normal shock waves, Prandtl Meyer flow, and flow through an oblique shock.

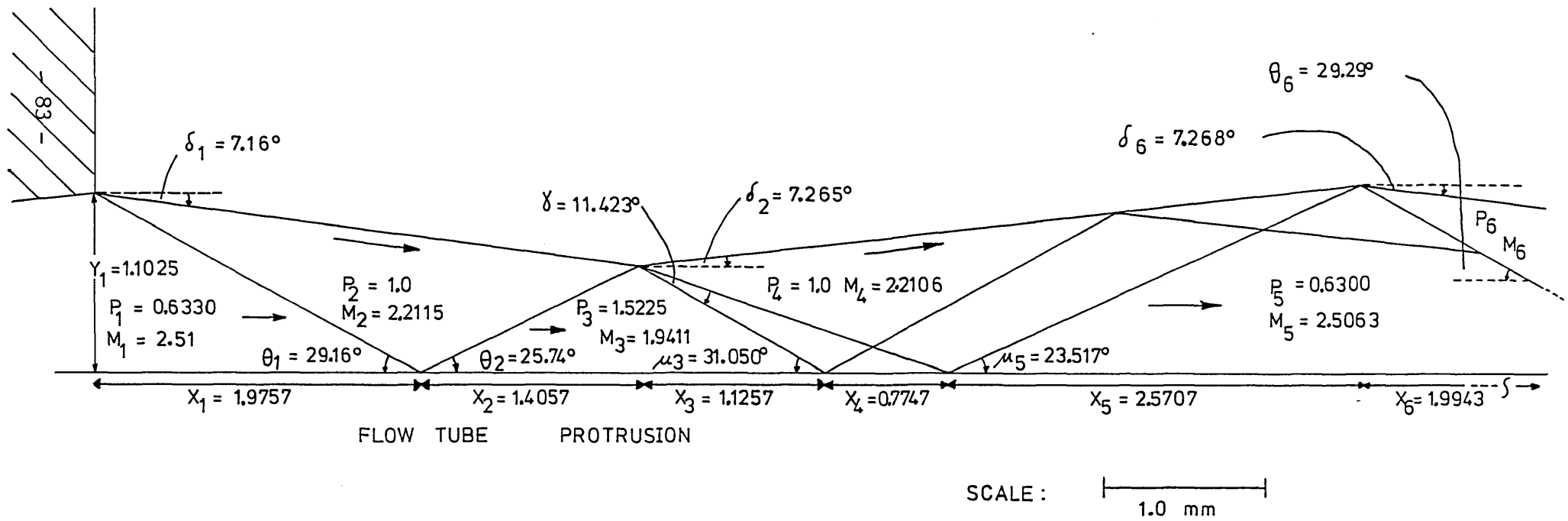
Later in Chapter 4 we will introduce Schlieren photography which was used to photograph the shock wave behaviour in the nozzles. The calculations are an important tool in evaluating those photographs.

#### 3.12.1 OVEREXPANDED BEHAVIOUR

We have already shown in section 3.11 that gas will ideally expand through IN3/WM2 when the pressure ratio across the nozzle is 0.05762, and the Mach number of the exiting gas will be 2.51. Thus as the nozzle discharges into the atmosphere, of pressure  $P_a$  (1.0 bar), the corresponding upstream or driving pressure must be 17.36 bars absolute for ideal expansion.

If we consider, as our example, the expansion which occurs when the driving pressure is 11.0 bars (the pressure at which many of the experimental atomizations were carried out) then the gas passing through the nozzle will overexpand and the pressure at the exit will be below ambient. A compression wave then occurs outside the nozzle exit which raises the pressure at the exit of the nozzle to ambient. This compression involves the formation of

**FIGURE 3.7**  
**OVER EXPANDED BEHAVIOUR IN IN3/WM2 AT 11.0 BARS PRESSURE**



an oblique shock wave, which also changes the direction of gas flow towards the flow tube protrusion. A sketch of the behaviour downstream of the oblique shock is shown in Figure 3.7. The presence of a flow tube protrusion is equivalent to bisecting the flow sketched in Figure 3.5. For the purposes of the diagram the flow tube protrusion is assumed to be infinitely long. In all the calculations so that the pressure differences caused by suction at the flow tube tip do not influence the shock wave behaviour along the flow tube protrusion. It is also assumed that there is no entrainment of gas from the surrounding atmosphere.

The details of the calculations are contained in Appendix 1. A summary of the calculations are contained in Table 3.12.1.

When the oblique shock hits the flow tube it reflects as an oblique shock. The reflected oblique shock must be positioned so as to make the flow parallel to the protrusion side after the shock i.e. the deflection angle is  $12.7^\circ$ .

The flow having passed through the reflected oblique shock is now above ambient pressure and in order to return to ambient the gas must go through an expansion fan from 1.5225 bars to 1.0 bar. The expansion takes the form of a series of expansion waves which make up an expansion fan. The expansion also changes the direction of gas flow away from the flow tube protrusion.

The expansion fan now reflects from the flow tube protrusion and the gas goes through a further expansion. In order for the gas flow to return parallel to the flow tube protrusion side the flow must turn through an angle equal to the flow deflection,  $\delta_2$ .

The expansion fan reflection now in turn reflects from the free pressure boundary as a series of compression waves which compress together to form an oblique shock.

The following equations can be used to calculate the distances, from the nozzle exit, at which the oblique shock reflection, the expansion fan, and the expansion fan reflection occur (see Figure 3.7). The value of  $Y_1$  can be obtained from Table 2.1 giving the dimensions for the inserts.

TABLE 3.12.1

RESULTS OF CALCULATION OF OVEREXPANDED BEHAVIOUR

PRESSURE : 11.0 BARS ABSOLUTE

NOZZLE : IN3/WM2.

$$\begin{aligned}P_1 &= 0.6330 \\M_1 &= 2.51 \\\delta_1 &= 7.16^\circ \\Y_1 &= 1.1025 \\x_1 &= 1.9757 \text{ mm} \\\theta_1 &= 29.61^\circ \\P_2 &= 1.0 \\M_2 &= 2.2115 \\\theta_2 &= 25.74^\circ \\x_2 &= 1.4057 \text{ mm} \\P_3 &= 1.5225 \\M_3 &= 1.9411 \\\mu_3 &= 31.050^\circ \\\gamma &= 11.423^\circ \\x_3 &= 1.1257 \text{ mm} \\P_4 &= 1.0 \\M_4 &= 2.2106 \\\delta_2 &= 7.265^\circ \\x_4 &= 0.7747 \text{ mm} \\P_5 &= 0.6300 \\M_5 &= 2.5063 \\\mu_5 &= 23.517^\circ \\x_5 &= 2.5707 \text{ mm} \\\delta_6 &= 7.268^\circ \\\theta_6 &= 29.29^\circ \\x_6 &= 1.9943 \text{ mm}\end{aligned}$$

$$\begin{aligned}
x_1 &= Y_1 / \tan \theta_1 \\
K &= (Y_1 - \tan \delta_1 x_1) / (1 + \tan \delta_1 / \tan \theta_2) \\
x_2 &= K / \tan \theta_2 \\
x_3 &= K / \tan \mu_3 \\
x_4 &= K (1 / \tan (\mu_3 - \gamma) - 1 / \tan \mu_3) \\
x_5 &= (\tan \delta_2 (\tan \mu_3 / K) + K) / (\tan \mu_5 - \tan \delta_2) \\
x_6 &= x_5 \tan \mu_5 / \tan \theta_6
\end{aligned}$$

thus at 11.0 bar driving pressure in IN3/WM2:

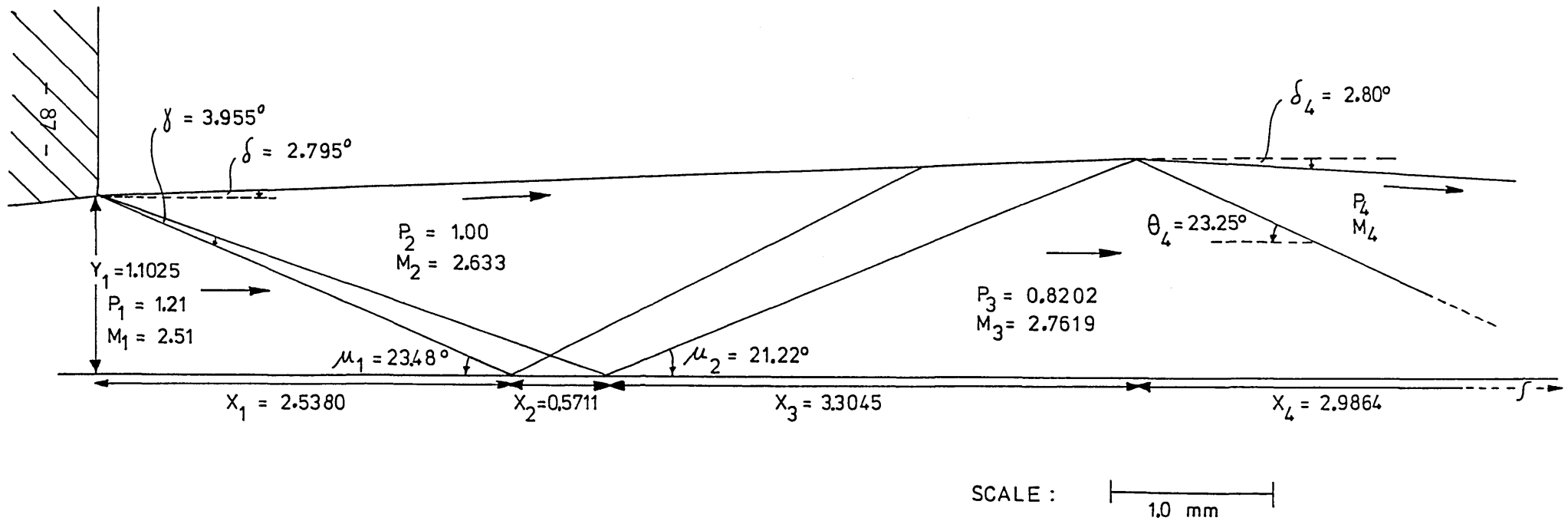
$$\begin{aligned}
Y_1 &= 1.1025 \text{ mm} \\
x_1 &= 1.9759 \text{ mm} \\
K &= 0.6777 \\
x_2 &= 1.4057 \text{ mm} \\
x_3 &= 1.1257 \text{ mm} \\
x_4 &= 0.7747 \text{ mm} \\
x_5 &= 2.5707 \text{ mm} \\
x_6 &= 1.9943 \text{ mm}
\end{aligned}$$

### 3.12.2 UNDEREXPANDED BEHAVIOUR

The underexpanded behaviour is very similar to that of the overexpanded behaviour in terms of the expansion wave.

If we consider the expansion through the nozzle when the driving pressure is 21.0 bars absolute then the gas passing through the nozzle will underexpand and the pressure at the exit will be above ambient. An expansion then occurs which lowers the pressure at the exit of the nozzle to ambient. The expansion involves the formation of a series of expansion waves which make up an expansion fan. The presence of a flow tube protrusion is equivalent to bisecting the flow sketched in Figure 3.5 so that the expansion fan does not reflect from itself but from the flow tube side. As with the overexpanded example the nozzle flow tube protrusion will be assumed to be infinitely long. A sketch of the behaviour is given in Figure 3.8.

**FIGURE 3.8**  
UNDER EXPANDED BEHAVIOUR IN IN3/WM2 AT 21.0 BARS PRESSURE



The details of the calculations which result in figure 3.8 are contained in appendix 2. A summary of the calculations are given in table 3.12.2.

The angle the beginning of the expansion fan makes with the flow tube protrusion is equal to  $\mu_1 = 23.48^\circ$ .

The angle the end of the fan makes with the flow tube protrusion is equal to  $\mu_1 - \gamma_1 = 19.525^\circ$ .

The expansion fan now reflects from the flow tube protrusion and the gas goes through a further expansion. In order for the gas flow to return parallel to the flow tube protrusion tube the flow must turn through an angle equal to the flow deflection,  $\delta_1$ .

The expansion fan reflection now in turn reflects the free pressure boundary as a series of compression waves which compress together to form an oblique shock.

The following equations can be used to calculate the distances from the nozzle exit, at which the expansion fan, and the expansion fan reflection occur (see Figure 3.8). They are very similar to those used for overexpanded behaviour. The value of  $Y_1$  can be obtained from Table 2.1 giving the dimensions for the inserts.

$$\begin{aligned}x_1 &= Y_1 / \tan \mu_1 \\x_2 &= Y_1 (1 / \tan (\mu_1 - \gamma_1) - 1 / \tan \mu_1) \\x_3 &= (\tan \delta_1 (\tan \mu_1 / Y_1) + Y_1) / (\tan \mu_3 - \tan \delta_1) \\x_4 &= x_3 \tan \mu_3 / \tan \theta_4\end{aligned}$$

thus for IN3/WM2 running with 21.0 bars driving pressure:

$$\begin{aligned}x_1 &= 2.5380 \text{ mm} \\x_2 &= 0.5711 \text{ mm} \\x_3 &= 3.3045 \text{ mm} \\x_4 &= 2.9864 \text{ mm}\end{aligned}$$

TABLE 3.12.2

RESULTS OF CALCULATION OF UNDEREXPANDED BEHAVIOUR

PRESSURE : 21.0 BARS ABSOLUTE

NOZZLE : IN3/WM2.

$$P_1 = 1.21$$

$$M_1 = 2.51$$

$$\delta_1 = 2.795^\circ$$

$$Y_1 = 1.1025$$

$$x_1 = 2.5380 \text{ mm}$$

$$\mu_1 = 23.48^\circ$$

$$\gamma = 3.955^\circ$$

$$P_2 = 1.0$$

$$M_2 = 2.633$$

$$x_2 = 0.5711 \text{ mm}$$

$$P_3 = 0.8202$$

$$M_3 = 2.7619$$

$$\mu_2 = 21.22^\circ$$

$$x_3 = 3.3045 \text{ mm}$$

$$P_4 = 1.0$$

$$\delta_4 = 2.80^\circ$$

$$x_4 = 2.9864 \text{ mm}$$

## **CHAPTER FOUR**

### **EXPERIMENTAL PROCEDURES**

## 4.1 EXPERIMENTAL APPROACH

The purpose of the experiments was to determine the characteristics of an annular twin fluid atomizing nozzle, operating vertically upwards, using wax. The design and gas flow in atomizing nozzles has been described earlier in Chapters 2 and 3.

The experiments investigated the effects of varying:

- (a) atomizing gas driving pressure
- (b) nozzle geometry
- (c) wax flow rate

on the gas flow in the nozzle and the particle size of wax powder produced by the nozzle.

The atomizing gas mass flow rate, the gas flow characteristics in the nozzle, and the suction developed at the tip of the liquid flow tube protrusion are all affected by the driving pressure.

The nozzle geometry was varied so the effect of Mach number and liquid flow tube protrusion could be investigated.

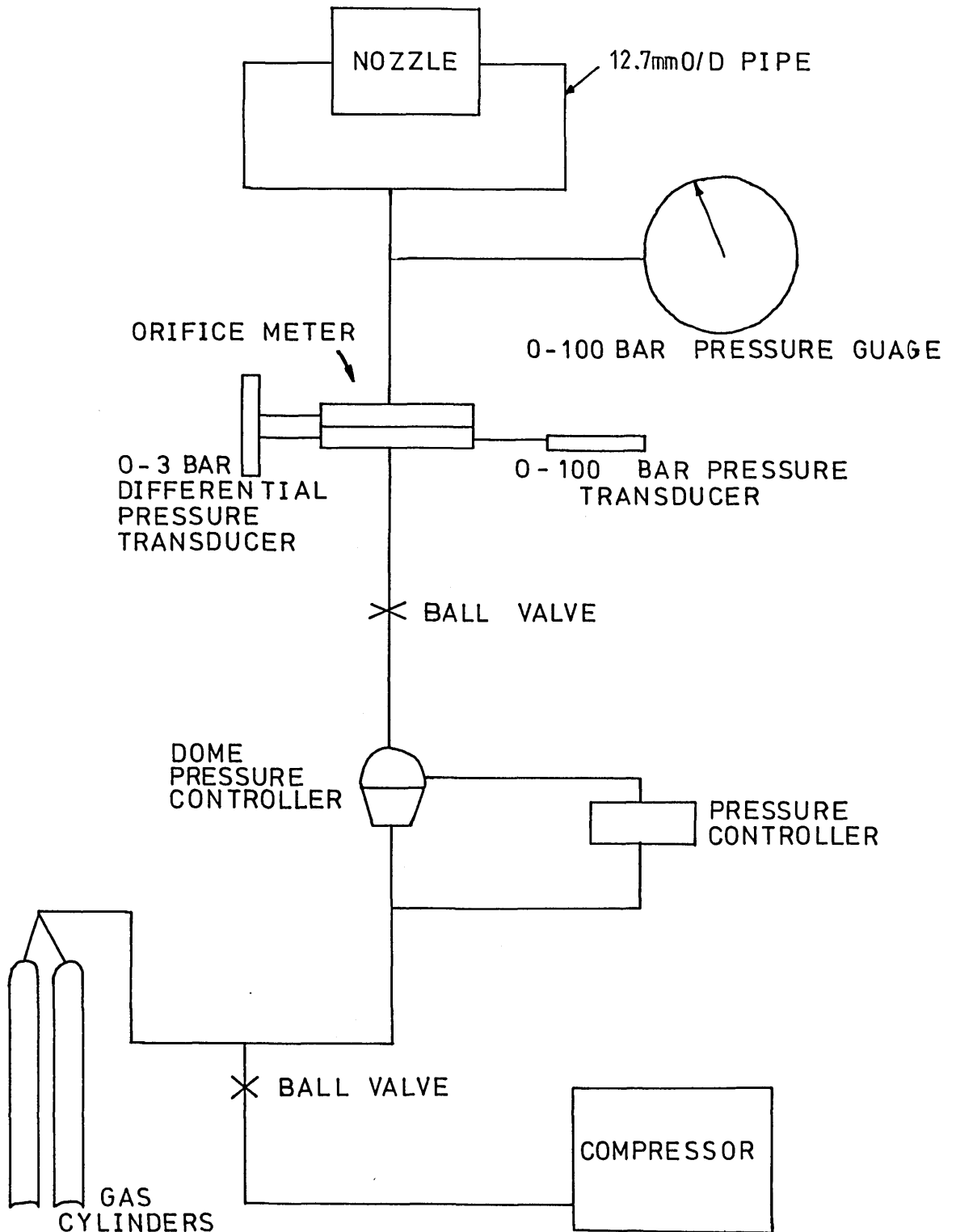
The liquid wax flow rate in the experiments was controlled. Thus its effect on particle size was determined independently of driving pressure and nozzle suction.

## 4.2 EXPERIMENTAL APPARATUS

### 4.2.1 GAS SUPPLY SYSTEM

The gas supply apparatus is schematically shown in Figure 4.1. The gas was supplied from two large gas cylinders connected to a central manifold. The cylinders were filled with air using a compressor. A half inch outer diameter pipeline connects the pallet of cylinders to a dome type pressure controller. By adjusting the pressure in the dome of the pressure controller the pressure of the gas to the rest of the apparatus can be controlled. This pressure adjustment is achieved by tapping the main line from the cylinders and feeding this, via a regulator, to the dome. The pipeline downstream of the dome controller is half inch outer diameter and runs to the nozzle via a ball valve,

FIGURE 4.1  
GAS SUPPLY SYSTEM



an orifice meter and a pressure gauge. All the pipework was supported by a metal frame.

[Note: Many early problems were encountered in the project because the original pipe diameter used for the majority of the high pressure lines was only one quarter inch outer diameter. This resulted in the gas, at the flow rates required for the nozzle, choking in the pipeline and so the gas flow rate was dependent, not on the nozzle throat area, but on the pipe diameter. Appendix 3 shows some more detailed calculations on choking in pipelines.]

#### 4.2.2 GAS MASS FLOW RATE MEASUREMENT USING AN ORIFICE METER

When gas passes through an orifice meter placed in a pipeline the flow rate of the gas can be determined using the equation (see Appendix 4 for derivation):

$$\dot{m} = CYA_* (2dP/\rho)^{0.5} \quad (4.1)$$

where

C = coefficient of discharge (dimensionless)

Y = expansion factor (dimensionless)

A<sub>\*</sub> = area of orifice in meter

ρ = density of gas at orifice

dP = pressure drop across orifice

The density can be calculated for an ideal gas using equation 3.5,  $P/\rho = RT$  and therefore density,  $\rho = P/RT$

where P = gas pressure before the orifice

T = gas temperature at the orifice

and are measured at the orifice.

From Vennard and Street<sup>(44)</sup>:

$$Y = 1 - \{(1-r)/k(0.41 + 0.35\beta^4)\} \quad (4.2)$$

β = ratio of orifice diameter to pipe diameter

r = ratio of pressure downstream of orifice to pressure upstream

k = ratio of specific heats

FIGURE 4.2 a  
ORIFICE METER

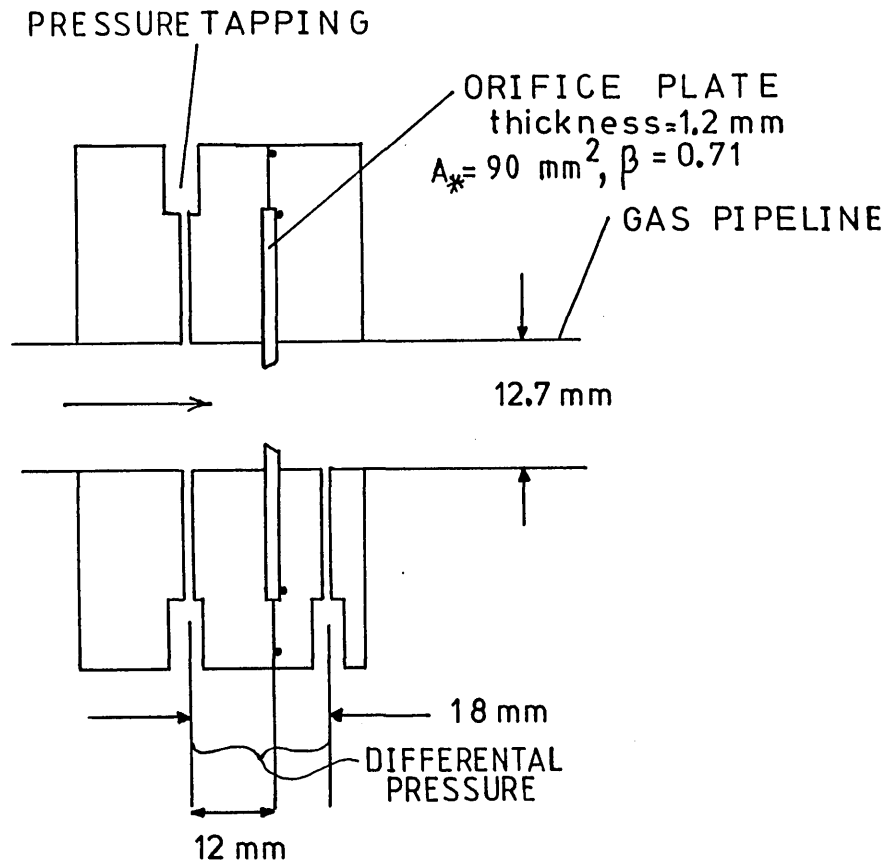


FIGURE 4.2 b  
PITOT TUBE

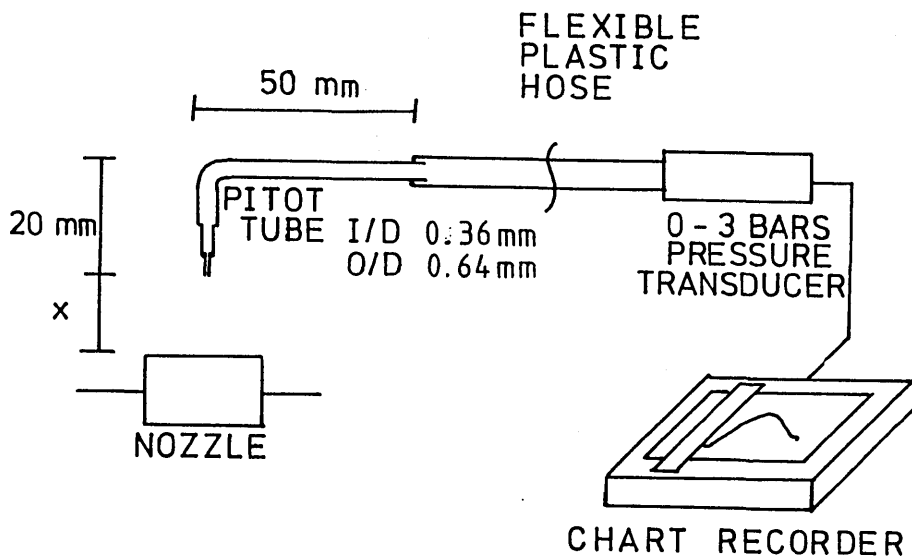


Figure 4.2a illustrates the orifice meter used in this project. The temperature of the gas was measured just before the orifice meter with a iron/constantan thermocouple and was found in all cases to be  $265^{\circ}\text{K} \pm 5^{\circ}$ . The pressure before the orifice was measured using a 0-100 bars (full scale) pressure transducer and the differential pressure was measured with a differential pressure transducer. The output of the pressure transducers and the thermocouple were recorded on a chart recorder. [note: the section of pipe into which the orifice meter is fitted has an inner diameter of 12.7 mm]

#### **4.2.3 NOZZLE SUCTION MEASUREMENTS**

As mentioned earlier the gas flow in the nozzle causes an aspirating effect at the exit of the flow tube. The suction created at the tip was measured by recording the output of a 0-3 bars (full scale) pressure transducer, connected to the bottom of the nozzle liquid flow tube, and the output of the orifice meter pressure transducer, on a chart recorder.

#### **4.2.4 PITOT TUBE CONCENTRICITY AND MACH NUMBER MEASUREMENTS**

The pitot tube, illustrated in Figure 4.2b, was used to measure the concentricity of the nozzle (as described in Chapter 2, section 2.4) and the exit Mach number of atomizing gas. The pitot tube was fixed to an XYZ traverse rig, which enabled the pitot tube to be precisely located above the nozzle. The pitot tube had an inner diameter of 0.3556 mm and an outer diameter of 0.6350 mm. The pitot tube stagnation pressure was determined by recording the output of a pressure transducer connected to the pitot tube (via a flexible plastic hose), and the output of the orifice meter pressure transducer, on a chart recorder.

#### **4.2.5 ADJUSTMENT OF NOZZLE FLOW TUBE PROTRUSION**

As mentioned earlier the protrusion of the liquid flow tube above the exit plane was adjustable. This was done by using spacers of precise thicknesses which adjusted the distance between the two shells and so controlled the height of the protrusion (see figure 2.3). Thus the protrusion could be increased by decreasing the thickness of spacers. The following

spacer sizes were available: 5.44, 4.75, 2.39, 2.00, 1.65, 1.12 mm. The nozzle was designed so that given a spacer of 9.30 mm thickness, the protrusion of the inner insert would be 0 mm [except in the case of IN3/WM6 which was designed for higher protrusions]. Thus a variety of different protrusion could be achieved.

#### 4.3 WAX ATOMIZATION EXPERIMENTAL PROCEDURE

In order to carry out wax atomization tests it was necessary to design a system in which the atomized wax powder could be collected. The final design had two major components, the wax supply system and the wax collection system.

##### 4.3.1 Wax supply system.

In order to accurately control the wax flow rate during atomization a copper tank, of 750 cm<sup>3</sup> capacity was constructed. Heating tapes wrapped around the outside of the tank enabled the temperature of the wax to be accurately controlled. The wax flow rate to the nozzle was controlled by passing a known volume of gas into the top of the tank resulting in the same volume flow rate of wax out of the bottom of the tank and so to the nozzle. The gas flowing into the top of the tank was supplied from the laboratory airline connected to the top of the wax tank via an on/off valve, a rotameter and a calibrated needle valve (see Figure 4.3a). As air is compressible the wax tank was refilled after each atomization, thereby preventing the delay in the wax flow from the bottom which would occur, as the pressure in the tank increased to that of the gas supply pressure, in a partially filled tank. The wax tank was so placed, as to ensure that when the tank was full, the level of wax in the nozzle liquid flow tube was about 2 cm below the top of the nozzle. Tests using water (see Appendix 5 on calibrations) showed the time taken to reach a steady liquid flow rate during an atomization to be negligible.

##### 4.3.2 Wax collection system

The atomized wax powder was collected in a large plastic bag. The bottom of the bag was folded around a metal ring which was pushed into the top of a collection bin and held fast with

FIGURE 4.3a  
WAX SUPPLY SYSTEM

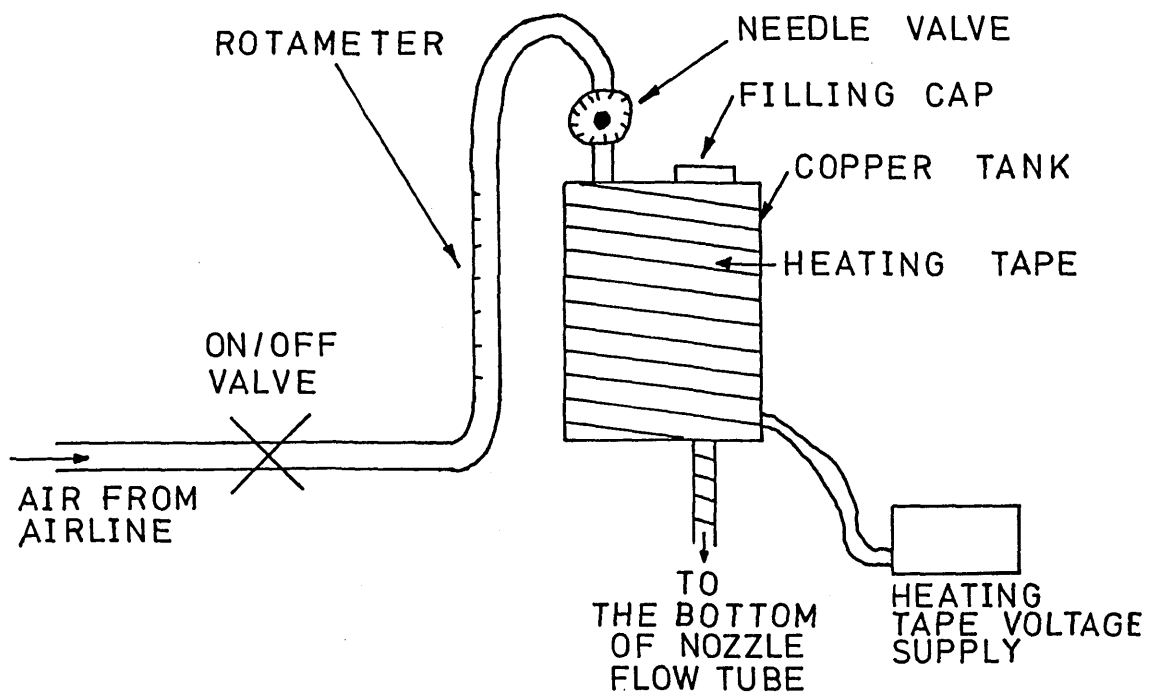
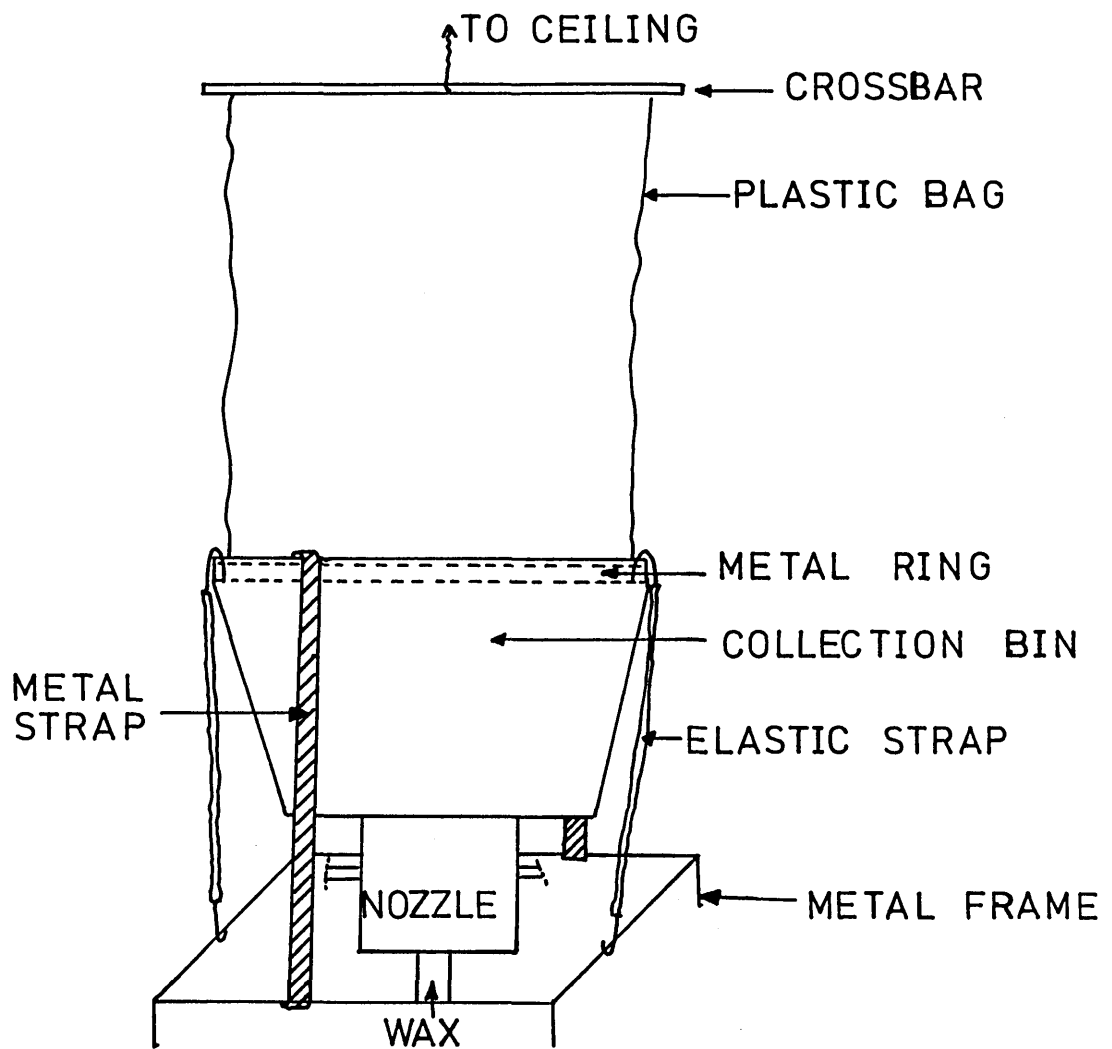


FIGURE 4.3b  
WAX COLLECTION SYSTEM



two elastic straps. The top of the bag was attached to a metal crossbar suspended from the ceiling. The bin was attached to the top of the nozzle with metal straps (see Figure 4.3b). During an atomization test the bag inflated with gas and atomized wax powder. The run was deemed complete when the bag was fully inflated (this took between 10 and 15 seconds). The collection bin and plastic bag were then removed from the nozzle, the plastic bag shaken and the resulting wax powder was carefully removed from the collection bin. In an early test run the wax powder produced was weighed and this showed that the weight of powder collected was close to the calculated value with only small losses occurring as some powder was left in the plastic bag. A new plastic bag was used for each run. The procedure for an atomization run could be summarized as follows:

1. the wax flow rate for the atomization test is selected by setting the gas flow to the tank using the needle value.
2. the wax tank is filled and the temperature of wax allowed to come to equilibrium.
3. the wax collection bin and associated plastic bag are attached to the top of the nozzle.
4. the atomizing gas pressure is set.
5. the ball valve allowing gas to flow and the on/off valve allowing wax to flow are turned on simultaneously.
6. when the bag is fully inflated the wax and gas are turned off.
7. the bag and collection bin are removed and the wax carefully collected.
8. particle size analysis is carried out on the wax.

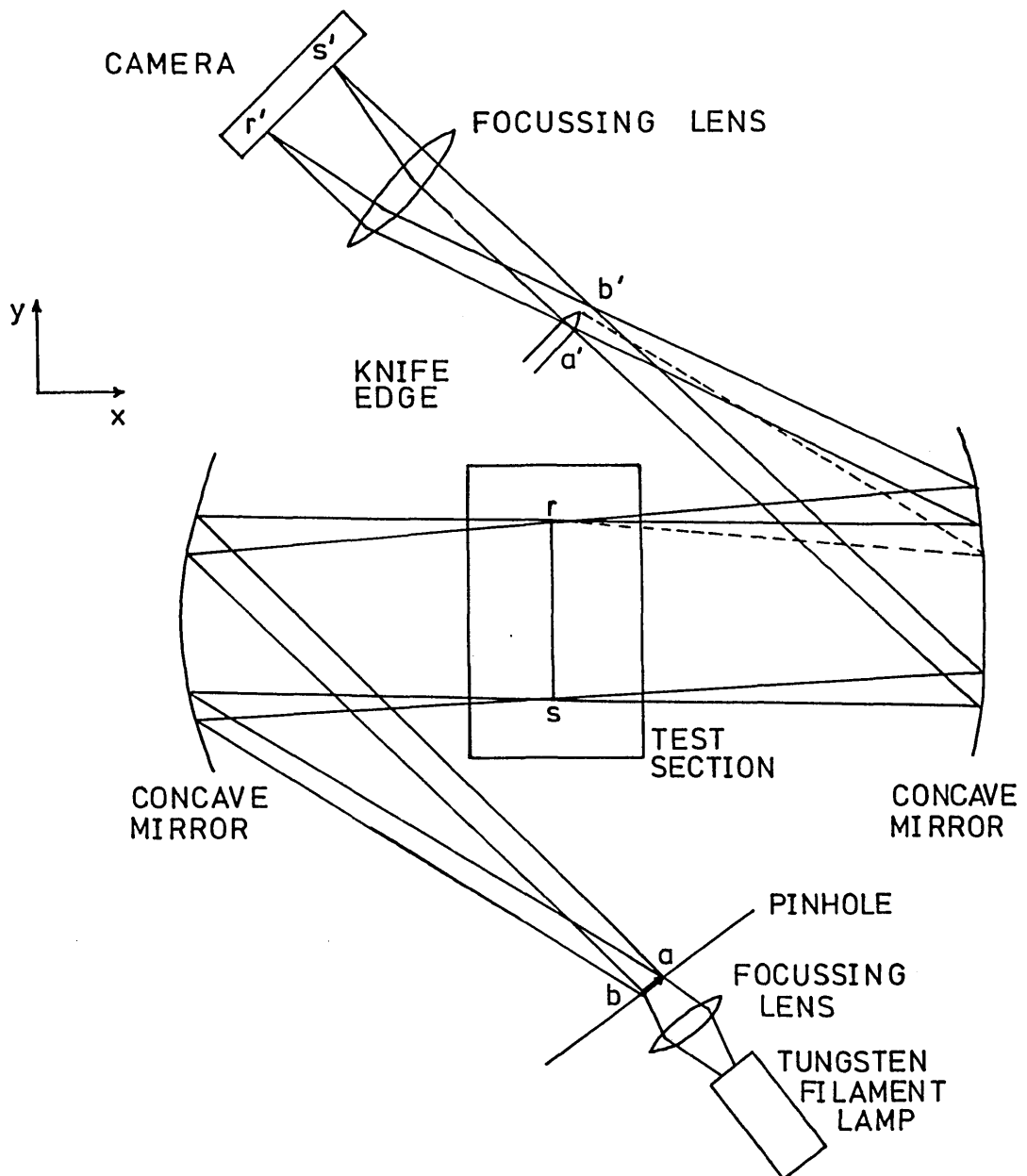
#### 4.4 SCHLIEREN PHOTOGRAPHY

As mentioned earlier, in Chapter 3, Schlieren photography was used to picture the shock wave behaviour of the atomization nozzles. Schlieren photography will show the position of the shock waves and by carefully examining the photographs a better understanding of the behavior of the nozzles gained.

The Schlieren system used in this project is shown schematically in figure 4.4. Light from a tungsten filament source is focused through a pin hole. This acts as the light source. The light reflects from a concave spherical mirror, placed a distance equal to the focal length of the mirror, producing a parallel beam of light which then reflects from a second concave mirror. The parallel beam of light acts as the test section into which the nozzle is placed. A knife edge is placed at a distance equal to the focal length of the second mirror so that it blocks out approximately half of the light. The remaining light then passes through a focusing lens and the image is focused on the back of a camera.

By considering the light waves in the Schlieren system it is possible to describe how it operates. By placing the knife edge so that it blocks out half of the light the image formed on the camera back will be darker than before but still uniformly illuminated. If we consider two extreme light waves, a and b, from the pinhole as illustrated in Figure 4.4 then the rays reflect from the first concave mirror and pass as parallel rays through the test section. They then reflect from the second mirror and form an image of the light source, a' and b'. If a knife edge is placed at a'b', so that the image is on the plane of the knife edge, then the ray rb'r' will reach the screen, but the ray ra'r' will not, so the image of point r will actually appear only half as bright as it would without the knife edge. The Schlieren technique is sensitive to the first differential of density i.e.  $\delta\rho/\delta x$  and light bends towards the denser medium. Thus if there is a density gradient within the test section in the plane of r (same constant y coordinate as r) the rays from r will be deflected so that, for example, the ray rb'r' will be displaced downwards, as shown, to the dashed line. Now this ray will be intercepted by the knife edge, so the image of r on the screen will be darker than the rest of the image of the test section. If the density gradient had the opposite sign, the rays from r would be displaced upwards, so that some rays which had been previously obstructed by the knife edge would now pass over it and give a brighter image of r on the screen. Thus it is possible to use a Schlieren optical system to visualize, for

FIGURE 4.4  
SCHLIEREN SYSTEM



example, a shock wave by observing the light and dark areas on the image produced.

In the system used in this project the knife edge was placed so that it blocked the light that was deflected downwards (as illustrated).

#### 4.5 PARTICLE SIZE ANALYSIS

##### INTRODUCTION

The powder particles produced in atomization tests were sized using a Malvern 3600D Laser Particle Sizer with a 100 mm focal length lens (range 1.9 to 188 microns). A unit cell system was used with ethyl alcohol as the dispersion medium. The samples were of about 0.25 g in weight and were ultrasonically stirred, before measurements were made, to help break up any agglomerated wax particles.

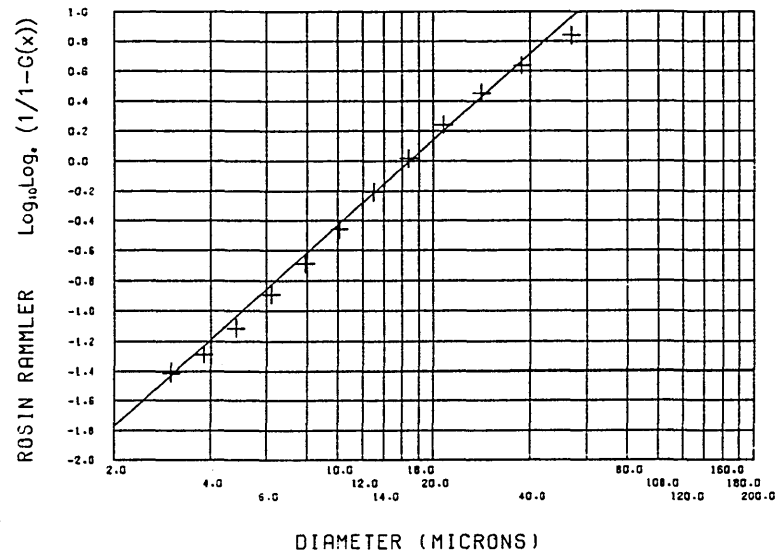
Weight in size band data obtained from the Malvern laser was analysed using a computer program to fit the size distribution data to log-normal and Rosin Rammler laws. In all cases the Rosin Rammler fit was better than the log-normal fit. The computer program was used to calculate the Mass Median Diameter (MMD), the point below which 90 % (D-90), and 10 % (D-10), of the powder lies, the Sauter Mean Diameter (SMD), the Volume Mean Diameter (VMD), the Rosin Rammler Mean (RRM), The Rosin Rammler distribution parameter (RRP) and the variances of the mass median diameter ( $x_{mmd}$ ) and the Rosin Rammler mean ( $x_{rrm}$ ). A typical output is shown in Figure 4.5 for run 108. Figure 4.6 shows the log-normal output for the same run.

##### DESCRIPTION OF THE DISTRIBUTIONS

#### 4.5.1 ROSIN RAMMLER DISTRIBUTION

The Rosin Rammler Distribution was developed by Rosin and Rammler<sup>(46)</sup> and initially used to describe the distributions resulting in powdered coal.

RUN 108



REGRESSION DONE ON ALL DATA

D-90% =  $26.02\mu$  D-50% =  $13.90\mu$  D-10% =  $5.19\mu$

SMD =  $9.14\mu$  VMD =  $14.98\mu$

ROSIN-RAMMLER MEAN =  $16.83\mu$

ROSIN-RAMMLER DISTRIBUTION PARAMETER = 1.91

VARIANCE (RRM) = 1.74 VARIANCE (MMD) = 2.06

RESULTS

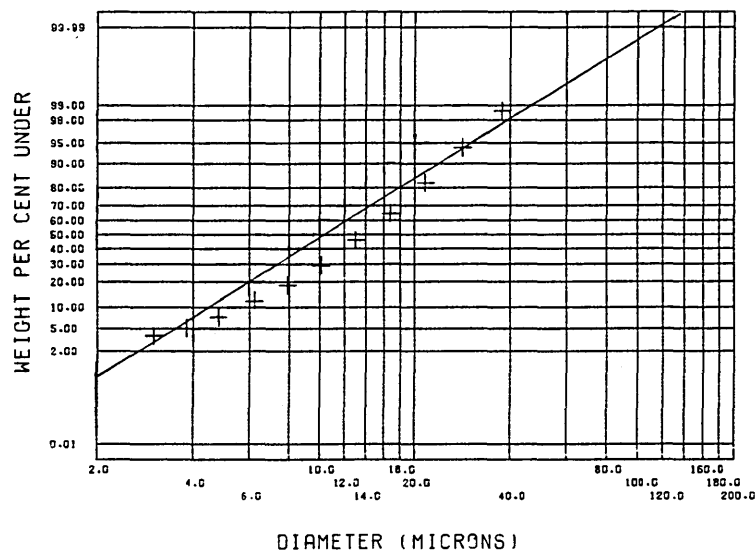
LOG ERROR = 2.93  
SAMPLE CONC = 0.0073  
BEAM OBSCURATION = 0.28

| DIAM (MICRONS) | WEIGHT % UNDER |
|----------------|----------------|
| 188.0          | 100.0          |
| 87.2           | 100.0          |
| 53.5           | 99.9           |
| 37.6           | 98.7           |
| 28.1           | 94.2           |
| 21.5           | 82.5           |
| 16.7           | 64.8           |
| 13.0           | 46.2           |
| 10.1           | 29.3           |
| 7.9            | 18.5           |
| 6.2            | 12.1           |
| 4.8            | 7.4            |
| 3.3            | 5.0            |
| 3.0            | 3.8            |
| 2.4            | 2.8            |
| 1.9            | 1.9            |

ROSIN - RAMMLER DISTRIBUTION

FIGURE 4.5

RUN 108



REGRESSION DONE ON ALL DATA

D-90% =  $16.11 \mu$  D-50% =  $9.52 \mu$  D-10% =  $5.62 \mu$

SMD =  $9.14 \mu$  VMD =  $14.98 \mu$

VARIANCE ( $\sigma_y$ ) = 0.01044  $\sigma_y$  = 1.64

VARIANCE ( $\sigma_z$ ) = 0.00388  $\sigma_z$  = 0.50

VARIANCE (MMD) = 16.21

RESULTS

LOG ERROR = 2.99  
SAMPLE CONC = 0.0J73  
BEAM OBSCURATION = 0.23

| DIAM (MICRONS) | WEIGHT % UNDER |
|----------------|----------------|
| 188.3          | 100.0          |
| 87.2           | 100.0          |
| 53.5           | 99.9           |
| 37.6           | 98.7           |
| 28.1           | 94.2           |
| 21.5           | 82.5           |
| 16.7           | 64.8           |
| 13.0           | 46.2           |
| 10.1           | 29.3           |
| 7.9            | 18.5           |
| 6.2            | 12.1           |
| 4.8            | 7.4            |
| 3.8            | 5.0            |
| 3.0            | 3.8            |
| 2.4            | 2.8            |
| 1.9            | 1.0            |

LOG - NORMAL DISTRIBUTION

FIGURE 4.6

This distribution is given by the following equation

$$G(x) = 1 - \exp(-x/x_{rrm})^n \quad (4.3)$$

where  $G(x)$  is the fractional weight per cent undersize,  $n$  is the Rosin Rammler distribution parameter,  $x$  the drop size and  $x_{rrm}$  is the 'Rosin Rammler mean'. Equation 4.3 can be rearranged as:

$$\log \ln \{1/[1 - G(x)]\} = n \log x - n \log x_{rrm} \quad (4.4)$$

or with  $X = \log x$ ,  $Y = \log \ln \{1/[1 - G(x)]\}$ ;  $Y = nX - n \log x_{rrm}$   
or:

$$Y = bX + a \quad (4.5)$$

where  $b = n$  and  $a = -n \log x_{rrm}$ , it follows that

$$x_{rrm} = 10^{(-a/b)} \quad (4.6)$$

(see Appendix 6 for derivation taken from Bayvel<sup>(47)</sup>).

The variance of the intercept  $a$ ,  $\text{var}(a)$ , of equation 4.5, and the variance of the slope  $b$ ,  $\text{var}(b)$ , are obtained from straight line regression analysis. The variance of the mean  $x$  (see Appendix 6 for derivation) is given by:

$$\text{var}(x_{rrm}) = 5.3(10^{-2a/b})/b^2 \{ \text{var}(a) + a^2 \text{var}(b)/b^2 \} \quad (4.7)$$

Thus, given a distribution function  $G(x)$ , as in equation 4.3, the parameters  $a$ ,  $b$  and their variances are obtained from the linear regression analysis of equation 4.5, and the Rosin Rammler mean and its variance are obtained from equations 4.6 and 4.7 respectively.

#### 4.5.2 LOG-NORMAL DISTRIBUTION

The log-normal distribution is defined in the following equation:

$$G(x) = \frac{1}{(\sigma_z [2\pi])^{0.5}} \int_{-\infty}^{\ln x} \exp[(\ln x - \ln x_{mmd})^2 / (2\sigma_z^2)] d(\ln x) \quad (4.8)$$

where  $\sigma_z$  is the geometric standard deviation and  $x_{mmd}$  is the mass median dia. size. For a linear regression analysis to be carried out the relevant straight line (see Appendix 6 for derivation) is

$$Y = bX + a \quad (4.9)$$

where

$$Y = (\ln x - \ln x_{\text{mmd}})/\sigma_z \quad \text{and} \quad X = \ln x$$

The mass mean diameter  $x_{\text{mmd}}$  is obtained at the point where  $G(x) = 0.5$  or analytically

$$\ln x_{\text{mmd}} = - (a/b) \quad (4.10)$$

the standard deviation is given by

$$\sigma_z = 1/b \quad (4.11)$$

and

$$\text{var}(x_{\text{mmd}}) = x_{\text{mmd}}^2/b^2 [ \text{var}(a) + a^2\text{var}(b)/b^2 ] \quad (4.12)$$

#### 4.5.3 COMPUTER ANALYSIS

The computer program carried out a linear regression on the size analysis data from the Malvern and gave the slope(b) and intercept(a) of the regression obtained. The program also calculated the variance of the slope, var(b), and the variance of the intercept, var(a).

(1) MMD - the MMD is the size corresponding to  $G(x) = 0.5$  and is calculated from the linear regression (equation 4.10 for the log normal or equation 4.7 for the Rosin Rammler distribution). The 10 % and 90 % cut off point are calculated in the same way putting  $G(x) = 0.1$  and  $0.9$  respectively.

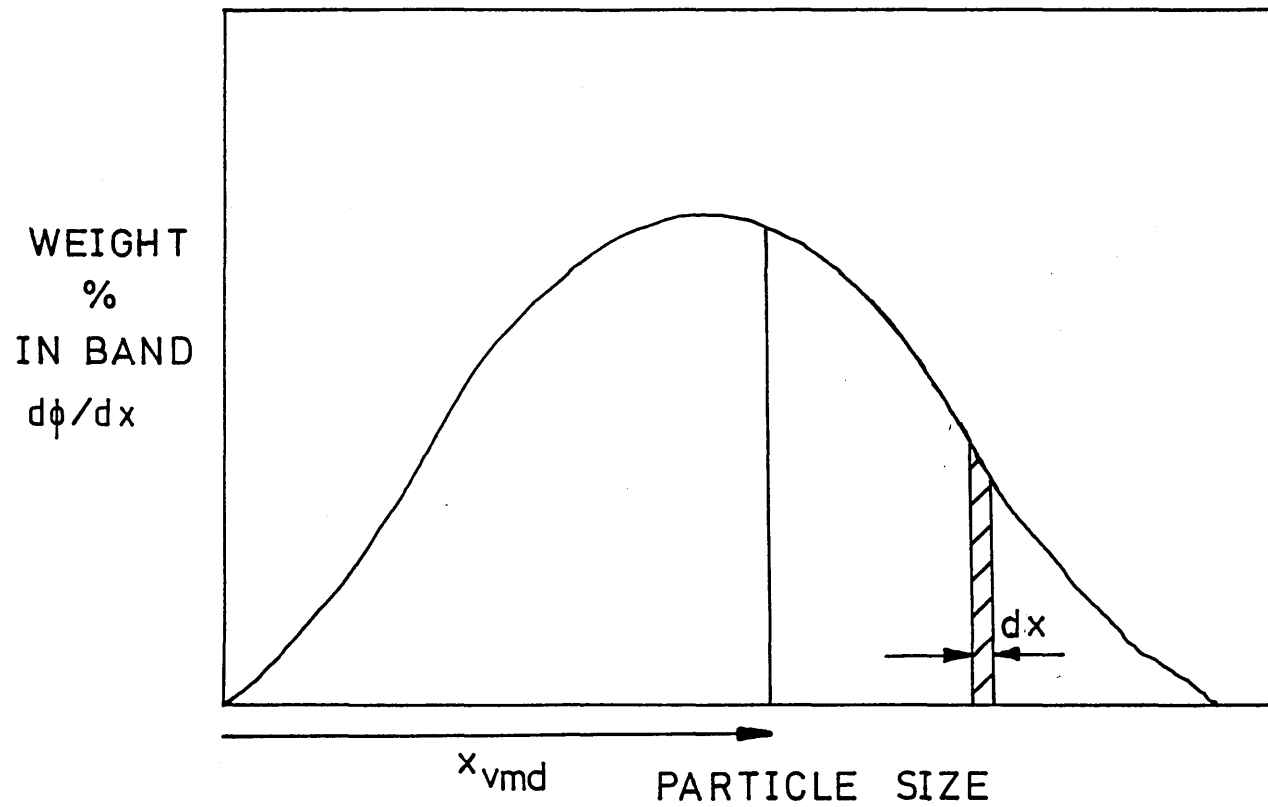
(2) SMD - the SMD is the droplet size having the same surface-to-volume ratio as the entire spray or powder sample. In the calculation of SMD the particles are assumed to be spherical. SMD was calculated using the following equation:

$$\text{SMD} = (\sum x^3 dN) / (\sum x^2 dN) = 100 / (\sum d\phi/x)$$

where  $d\phi$  = weight percent in band,  $x$  = average size of band,  $dN$  = number frequency in band

(3) VMD - the VMD is best explained with reference to Figure 4.7 of a distribution. The VMD is the size which corresponds to the centre of gravity of a sheet of uniform thickness and density cut to the size of the distribution. Hence, for the VMD, the moment sum of all the elementary areas of thickness  $dx$  about the ordinate  $x_{\text{mmd}}$  multiplied by total area.

FIGURE 4.7  
VOLUME MEAN DIAMETER



$$x_{VMD} \Sigma d\phi / dx \delta x = \Sigma x d\phi / dx \delta x$$

where  $dx$  = width of size band, hence

$$x_{VMD} = \Sigma x d\phi / \Sigma d\phi$$

and for a weight distribution  $d\phi = x^3 dN$   
therefore

$$VMD = (\Sigma x^4 dN) / (\Sigma x^3 dN) = (\Sigma x d\phi) / 100$$

(4) RRM - the RRM is determined as described above from equation 4.4

(5) RRP - the RRP is the value of  $n$  from equation 4.3 and is the slope of the linear regression. Thus an infinite value of RRP signifies that all the particles are the same size.

(6)  $[\sigma_g, \sigma_z]$  -  $\sigma_g$  is the value of the geometric standard deviation for a plot of  $\log_{10} x$  versus  $G(x)$ .  $\sigma_z$  is the value of the geometric standard deviation for a plot of  $\ln x$  versus  $G(x)$ . A value of 1 signifies that all the particles are the same size. The variances of  $\sigma_g$  and  $\sigma_z$  were calculated as shown in Appendix 6.  $G(x)$  is plotted on a log normal probability scale.

## CHAPTER FIVE

### CHARACTERIZATION OF GAS FLOW IN ATOMIZATION NOZZLES

## 5.0 INTRODUCTION

This chapter discusses the investigations carried out to characterise the flow in the nozzles used and it begins by discussing the variation of gas mass flow rate in the nozzles with driving pressure. Schlieren photography, the main tool used to experimentally investigate shock waves, is then discussed. The second part of the chapter discusses the results obtained using pitot tubes and shows how they can be related to the gas flow calculations carried out in Chapter 3, and then describes the results of the investigation into nozzle suction.

## 5.1 NOZZLE GAS MASS FLOW RATE

The gas mass flow rate,  $\dot{m}_g$ , was measured for all the nozzles using an orifice plate meter as described in the Chapter 4. Figure 5.1 shows the variation of the mass flow rate of gas with driving pressure for the nozzle IN3/WM2. The figure also gives the curve for the theoretical mass flow rate of gas. All measured gas mass flowrates showed similar behaviour.

### 5.1.1 CALCULATION OF ACTUAL AND THEORETICAL GAS MASS FLOW RATE

#### Calculation of Actual Gas Mass Flow Rate

For orifice meters the mass flow rate can be calculated using equation 4.1:

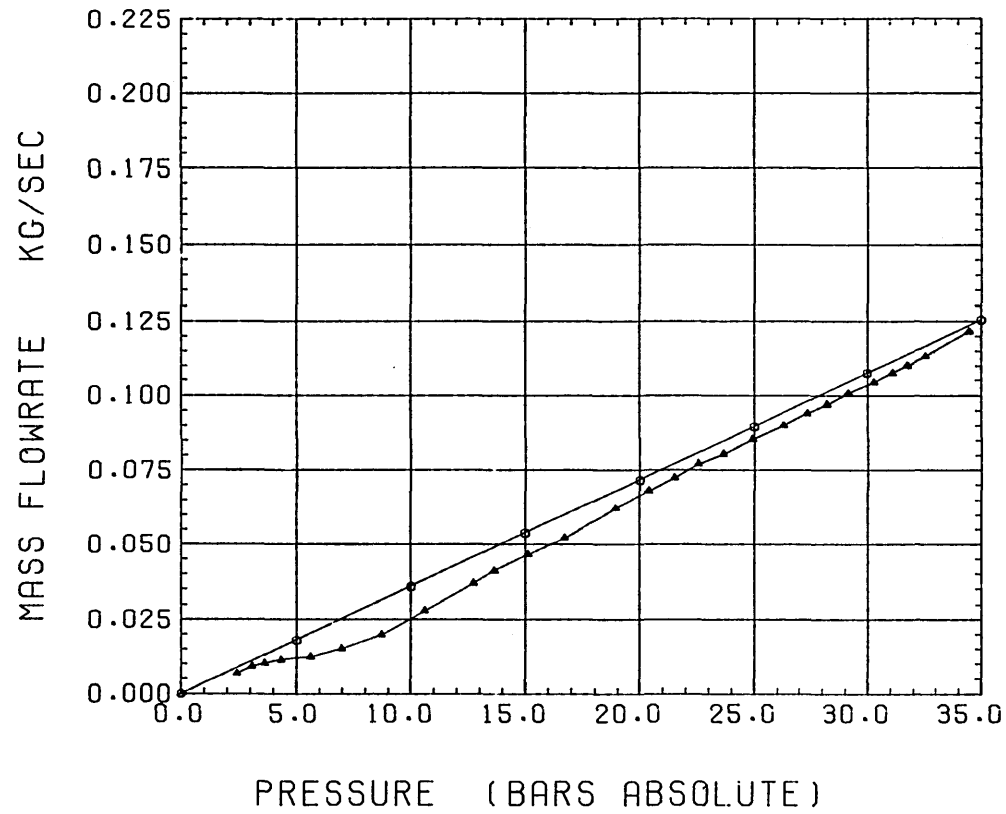
$$\dot{m} = C Y A_* (2dP/\rho)^{0.5} \quad (4.1)$$

#### Sample calculation for IN3/WM2

A computer program was written to calculate the mass flow rate of gas. This used the following data:

The orifice diameter - 9 mm

GAS MASS FLOW RATE CURVE



| NOZZLE<br>NAME | SYMBOL |        |
|----------------|--------|--------|
| IN3/WM2        | ⊙      | THEORY |
| IN3/WM2        | △      | 2.54mm |

FIGURE 5.1

The pipe diameter - 12.7 mm.

The orifice temperature, T, is as shown in Table 5.1.1 of the results. The coefficient of discharge,  $C = 0.705_{(45)}$  and  $\beta = 0.7087$ .

Thus solving equation 4.1:

$$\dot{m} = 0.705(63.62 \times 10^{-6}) Y (2PdP / 287.0 * T)^{0.5}$$

Thus when  $P = 34.46$  bars(a),  $dP = 0.839$  bars,  $R = 287$  J/kgK,  $k = 1.4$  and  $T = 275.0$  K, the mass flow rate of gas  $\dot{m}_g = 0.12156$  kg/sec

#### Calculation of Theoretical Gas Mass Flow Rate

The theoretical mass flow rate is calculated using the throat area,  $A_*$ , from Table 2.1 and equation 3.31:

$$\dot{m}_g = A_* P_d / (T_t)^{0.5} [k/R \{ (2/k+1)^{(k+1)/(k-1)} \}]^{0.5} \quad (3.31)$$

where:

$A_*$  = throat area  $m^2$

$P_d$  = driving pressure Pa

$T_t$  = total temperature  $^{\circ}K$

therefore with  $P_d = 34.46 \times 10^5$  Pa,  $A_* = 14.43 \times 10^{-6} m^2$ ,  $k = 1.4$ ,  $T_t = 265K$ , then  $\dot{m} = 0.1235$  kg/sec.

#### **5.1.2 COMPARISON BETWEEN MEASURED AND THEORETICAL GAS MASS FLOW RATES**

It can be seen from Figure 5.1 that the theoretical gas mass flow rate is greater than the experimentally determined mass flow rate but the variation from the theoretically predicted gas mass flow rate is not large. The variation can be explained in terms of boundary layer growth.

The thickness of the boundary layer that would be needed at the throat to account for the difference between the theoretical mass flow rate and the actual mass flow rate can be calculated<sup>(48)</sup>. This distance is known as the displacement boundary layer thickness,  $\delta_1$ .

TABLE 5.1.1RESULTS OF CALCULATION OF MASS FLOW RATE

| DRIVING<br>PRESSURE<br>(bars(a)) | DIFFERENTIAL<br>PRESSURE<br>(bars) | TEMPERATURE<br>°K | MASS FLOW<br>RATE (measured)<br>kg/sec |
|----------------------------------|------------------------------------|-------------------|----------------------------------------|
| 34.46                            | 0.839                              | 275.0             | 0.1216                                 |
| 32.54                            | 0.767                              | 273.5             | 0.1133                                 |
| 31.74                            | 0.735                              | 271.5             | 0.1102                                 |
| 31.08                            | 0.715                              | 270.5             | 0.1075                                 |
| 30.28                            | 0.688                              | 269.5             | 0.1043                                 |
| 29.16                            | 0.633                              | 268.5             | 0.1006                                 |
| 28.23                            | 0.633                              | 268.0             | 0.0968                                 |
| 27.35                            | 0.612                              | 267.0             | 0.0940                                 |
| 26.29                            | 0.582                              | 266.5             | 0.0899                                 |
| 24.90                            | 0.522                              | 266.0             | 0.0853                                 |
| 23.62                            | 0.516                              | 265.5             | 0.0804                                 |
| 22.53                            | 0.497                              | 265.0             | 0.0771                                 |
| 21.50                            | 0.458                              | 265.0             | 0.0724                                 |
| 20.38                            | 0.426                              | 265.0             | 0.0679                                 |
| 18.91                            | 0.383                              | 264.5             | 0.0621                                 |
| 16.70                            | 0.302                              | 264.0             | 0.0516                                 |
| 15.11                            | 0.267                              | 264.0             | 0.0465                                 |
| 13.64                            | 0.232                              | 264.0             | 0.0411                                 |
| 12.71                            | 0.119                              | 263.5             | 0.0369                                 |
| 10.58                            | 0.135                              | 263.5             | 0.0277                                 |
| 8.72                             | 0.083                              | 263.5             | 0.0197                                 |
| 6.99                             | 0.060                              | 263.5             | 0.0151                                 |
| 5.60                             | 0.050                              | 264.0             | 0.0123                                 |
| 4.33                             | 0.055                              | 264.0             | 0.0113                                 |
| 3.61                             | 0.052                              | 264.0             | 0.0101                                 |
| 3.05                             | 0.050                              | 264.5             | 0.0091                                 |
| 2.41                             | 0.035                              | 265.0             | 0.0067                                 |

$$\delta_1 = (\dot{m}_{\text{theory}} - \dot{m}_{\text{actual}}) / (\dot{m}_{\text{theory}}) (A_*/U) \quad (5.1)$$

where:

U = the 'wetted perimeter' of the nozzle (outer insert circumference at the throat + inner insert circumference at the throat), m

Using equation 5.1 given that  $U = (0.01 + 0.01088)\pi$  (see Table 2.1 for source of dimensions) the displacement thickness in IN3/WM2 can be calculated for a given driving pressure as given in table 5.1.2:

Table 5.1.2

| Pressure<br>bars(a) | $\dot{m}_{\text{theory}}$<br>kg/sec | $\dot{m}_{\text{actual}}$<br>kg/sec | $\delta_1$<br>mm |
|---------------------|-------------------------------------|-------------------------------------|------------------|
| 5.0                 | 0.0179                              | 0.012                               | 0.0725           |
| 10.0                | 0.0358                              | 0.025                               | 0.0664           |
| 15.0                | 0.0538                              | 0.046                               | 0.0319           |
| 20.0                | 0.0717                              | 0.062                               | 0.0298           |
| 25.0                | 0.0896                              | 0.086                               | 0.0088           |

The Reynolds Number, Re, at the throat can be calculated and used to determine if the flow was laminar or turbulent.

The Reynolds number is defined as  $\rho Vd/\mu$ .

where

$\mu$  = dynamic viscosity of gas, kg/ms

d = diameter of pipe or nozzle, m

V = velocity m/s

$\rho$  = density kg/m<sup>3</sup>

As above the density can be calculated using equation 3.5 ( $P/\rho = RT$ ). The dynamic viscosity for air at 293° K,  $\mu_{293} = 18.1 \times 10^{-6}$  kg/ms (from Plint and Boswith<sup>(48)</sup>  $\mu_T = \mu_{293}(1 + 0.005(T - 293))$ ). The wetted perimeter, U, in an annular nozzle can be used for the value of d. V can be calculated using equation 3.6 ( $V = (kRT)^{0.5}$ ).

Therefore for air with  $T = 265 \text{ K}$

$Re = (1.82 \times 10^6) P_d$  (where  $P_d$  is driving pressure in bars(a))

Laminar boundary layer flow can occur with Reynolds numbers up to between  $1 \times 10^5$  and  $3 \times 10^6$  (48) and so the boundary layer, in the nozzle IN3/WM2, was almost certainly laminar at low pressures but turbulent at higher pressures.

Although it is beyond the scope of this discussion to determine exactly how the boundary layer grows in the nozzle it is possible to describe the growth quantitatively with increasing driving pressure.

The text book discussion of boundary layers (48) describes the growth along a flat plate placed in an air stream of constant velocity. If the velocity is  $V_i$  then for laminar boundary layers the displacement thickness,  $\delta_1$ , is given by  $1.73(vx/V_i)^{0.5}$  and for turbulent boundary layers by  $0.01738 (Re)_x^{0.861} v/V_i$ , where  $x$  is the distance from the beginning of the plate and  $v$  is the kinematic viscosity. By putting numbers into the above equations it can be shown that for a given distance down the plate the boundary layer thickness decreases with increasing velocity,  $V_i$ . It can also be shown that at a given distance down the plate the turbulent boundary layer is thinner than the laminar boundary layer.

Thus in Figure 5.1 the boundary layer is initially laminar up to about 5 bars driving pressure. There is rapid laminar boundary layer growth and so the mass flow is less than theoretical. As the driving pressure is increased above 5 bars the boundary layer becomes turbulent. The boundary layer thickness at the throat therefore decreases and the experimental gas mass flow rate starts to approach the theoretical value. With further increases in driving pressure the boundary layer thickness decreases yet further and the mass flow rate becomes closer to the theoretical value. The discharge coefficient for the nozzle can be defined as  $\dot{m}_{\text{actual}}/\dot{m}_{\text{theoretical}}$  and for turbulent flow in the nozzle this is approx. 90%, showing that the gas flow in the nozzle is very close to the theoretical value.

Hence the departure of the gas mass flow rate from theoretically predicted values increases rapidly at low driving pressures. However as driving pressure increases the departure from theory decreases.

## 5.2 SCHLIEREN PHOTOGRAPHY

### 5.2.0 INTRODUCTION

In order to investigate the behaviour of the shock waves above the nozzle exit in greater detail it was decided to take a series of Schlieren photographs. The effect of pressure, protrusion, Mach number, and flow tube diameter were investigated.

Photographs were taken for IN3/WM2, IN3/WM3, IN3/WM4, IN3/WM5, IN4/WM7 and IN5/WM8. Table 5.2.1 summarizes all the photographs taken.

### 5.2.1 EFFECT OF DRIVING PRESSURE

The effect of driving pressure is illustrated in Figures 5.2 to 5.6 of IN3/WM2. A number of features can be seen to change as the driving pressure is increased:

#### Direction of Flow of Outer Surface of Jet

The outside surface of the jet exiting at 11 bars (Figure 5.2) is nearly vertical but as the driving pressure is increased above this (Figures 5.3 and 5.4) the exiting gas is expanding and leaving the nozzle at an angle similar to the angle of the diverging section of the nozzle.

The direction of the flow pattern on the outer surface of the jet is an indication of whether the jet is operating in the over or under expanded mode, i.e whether the jet is contracting or expanding at the exit of the nozzle. Figure 5.2 shows the nozzle operating in the over expanded mode and Figure 5.4 shows the nozzle operating in the under expanded mode. The expansion outside the nozzle can be clearly seen in 5.4.

TABLE 5.2.1

SUMMARY OF SCHLIEREN PHOTOGRAPHS

| FIGURE NO. | NOZZLE<br>INSERTS | PRESSURE<br>BARS (a) | PROTRUSION<br>mm |
|------------|-------------------|----------------------|------------------|
| 5.2        | IN3/WM2           | 11.00                | 4.90             |
| 5.3        | IN3/WM2           | 16.00                | 4.90             |
| 5.4        | IN3/WM2           | 26.00                | 4.90             |
| 5.5        | IN3/WM2           | 11.00                | 0.00             |
| 5.6        | IN3/WM2           | 26.00                | 0.00             |
| 5.7        | IN3/WM4           | 16.00                | 4.90             |
| 5.8        | IN3/WM5           | 16.00                | 4.90             |
| 5.9        | IN3/WM3           | 16.00                | 4.90             |
| 5.10       | IN3/WM3           | 26.00                | 0.00             |
| 5.11       | IN4/WM7           | 16.00                | 0.00             |
| 5.12       | IN5/WM8           | 16.00                | 0.00             |

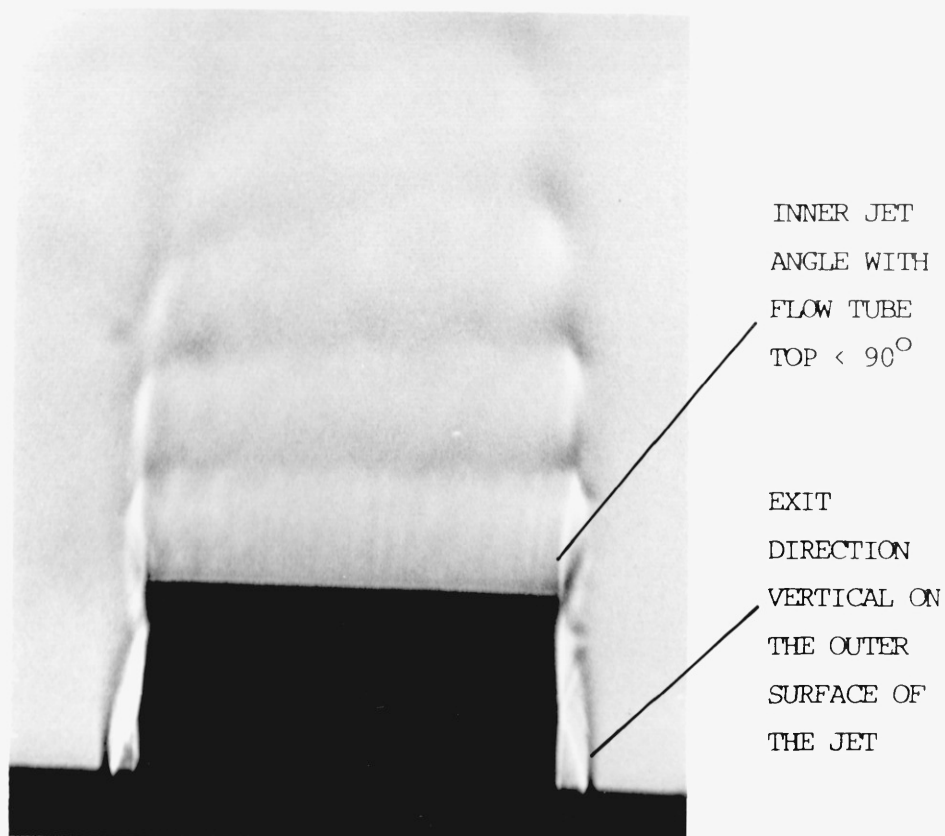
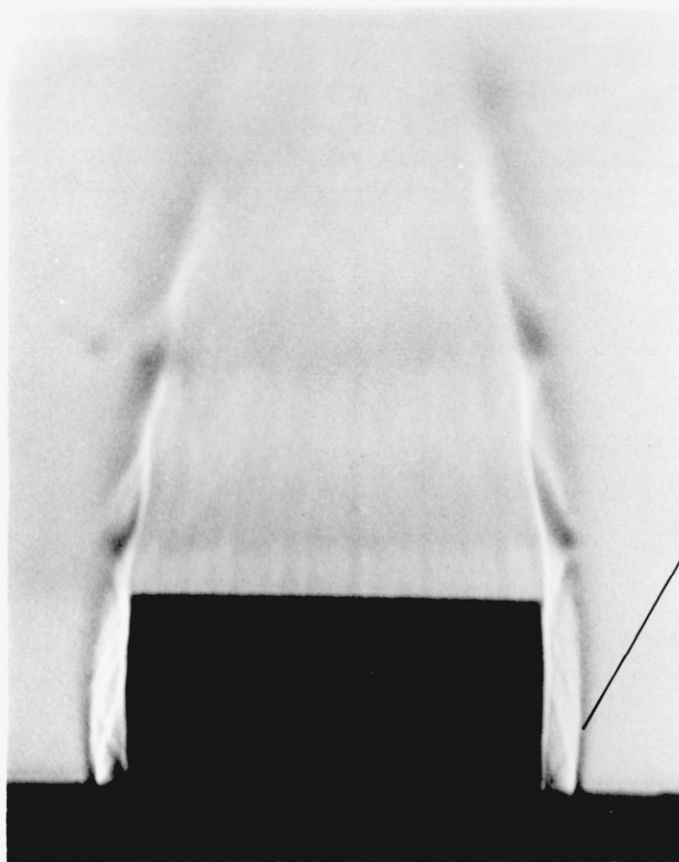


FIGURE 5.2

NOZZLE IN3/WM2 - 11.00 BARS DRIVING PRESSURE (OVEREXPANDED)



NON  
VERTICAL  
EXIT  
DIRECTION  
ON OUTER  
SURFACE OF  
THE JET

FIGURE 5.3

NOZZLE - IN3/WM2    16.00 BARS DRIVING PRESSURE

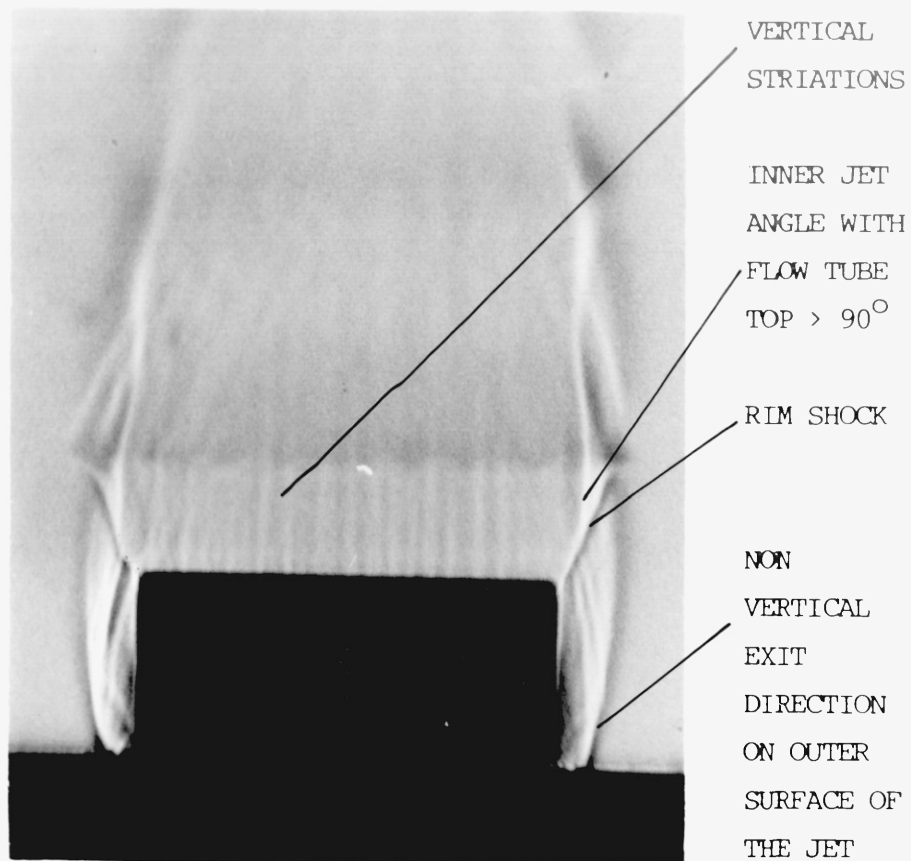


FIGURE 5.4

NOZZLE - IN3/WM2 26.00 BARS DRIVING PRESSURE (UNDER EXPANDED)

### Direction of Flow of Inner Surface of Jet

The inner surface of the jet at the tip changes direction as the driving pressure changes. With 4.9 mm protrusion (Figure 5.2-5.4) the direction of the jet is inclined at an angle less than  $90^{\circ}$  to the protrusion top at 11 bars pressure. As the pressure increases the angle increases to greater than  $90^{\circ}$ .

The direction of flow on the inner surface of the jet is determined by the difference in the pressure at the tip of the flow tube protrusion (suction) and the static pressure in the jet. In Figure 5.2 it can be seen that the direction of flow is slightly towards the protruding flow tube wall. Thus the pressure in the jet must be less than that at the tip. The direction of flow in Figure 5.4 at 26.0 bars is away from the flow tube wall. Thus the pressure at the tip is less than the pressure in the jet.

### Shock Wave Pattern

As the driving pressure is increased the size of the cells created by the shock wave pattern increases. This is well illustrated by Figures 5.5 and 5.6 where there is no protrusion. The area between the jets contains very well defined bands running across the area above the nozzle exit. These correspond to the end of the cells and occur because the flow is cylindrical. The size of the cells in the shock wave pattern can be shown by calculation to increase as the driving pressure in the nozzle increases. This is very clearly illustrated when Figures 5.5 and 5.6 are compared.

### Rim Shock

The presence of a rim shock is best illustrated in Figure 5.4 where it is well defined. It is present at 21 bars but the presence of the shock is not very well defined at 11 and 16 bars. The rim shock (Figure 5.4) is the result of the turning of the gas flow on the outside of the jet so that a constant pressure boundary is maintained. This occurs, as a result of the nozzle not being a theoretical supersonic contour, when the nozzle is running under expanded and gas expansion occurs at the exit of the nozzle. The expanding gas flow is compressed by the ambient pressure as it moves away from the exit of the nozzle and the compression continues until a shock wave forms. This shock wave

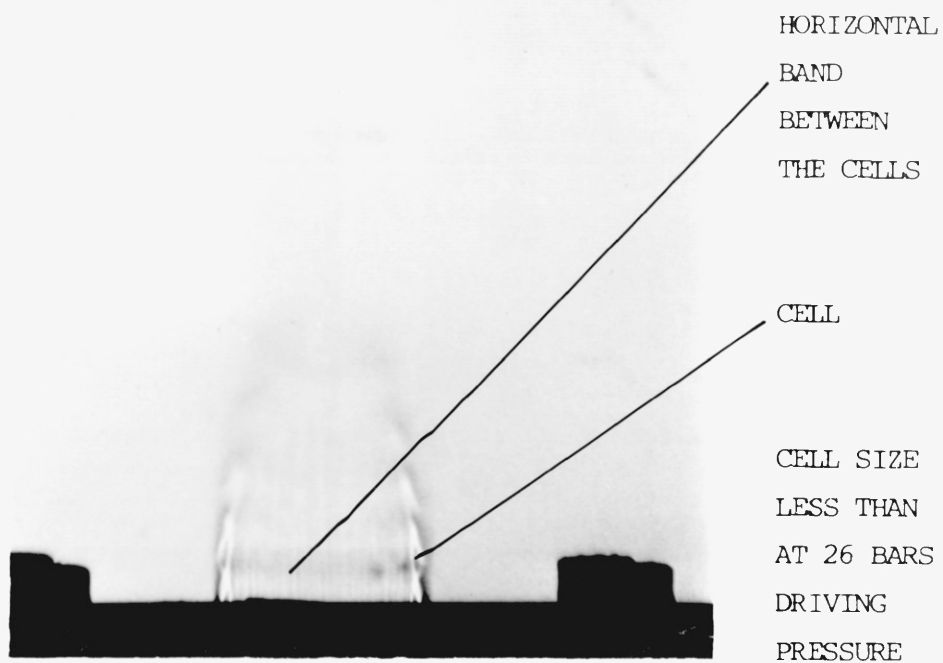


FIGURE 5.5

NOZZLE - IN3/WM2    11.00 BARS DRIVING PRESSURE  
0 mm FLOW TUBE PROTRUSION

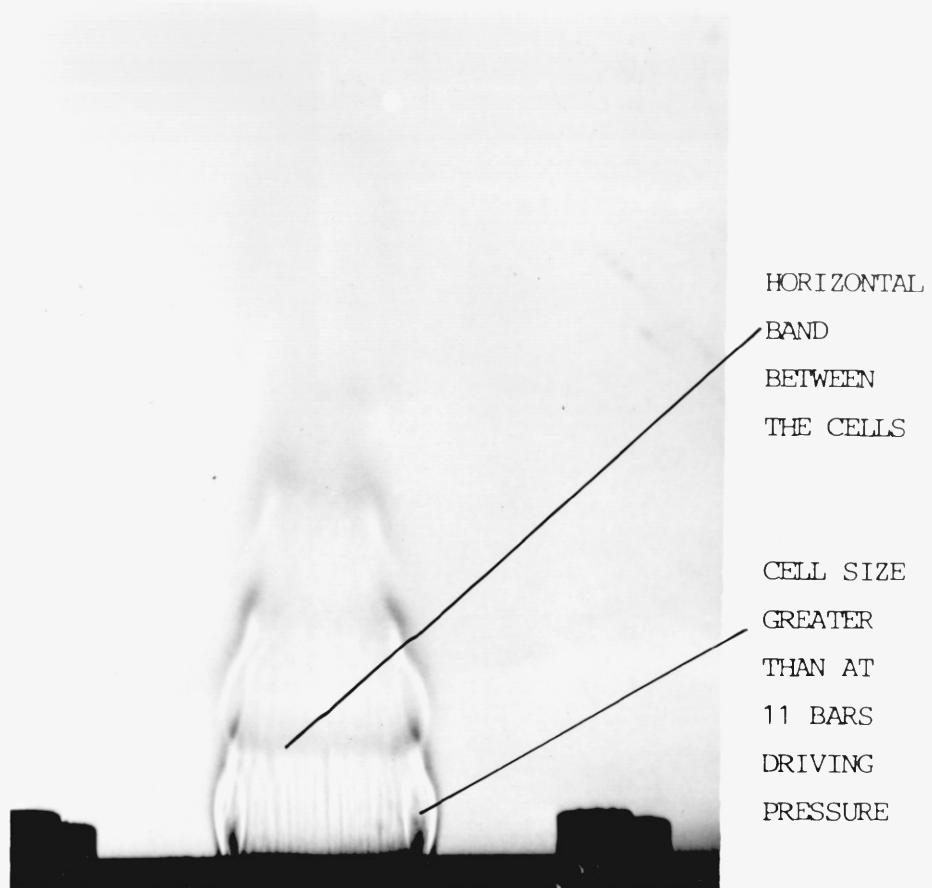


FIGURE 5.6

NOZZLE - IN3/WM2 26.00 BARS DRIVING PRESSURE

0 mm FLOW TUBE PROTRUSION

will attach itself to the nearest point of discontinuity available; the rim of the top of the protrusion. Hence the term rim shock.

#### Vertical Striations

Vertical striations can be seen, well defined in figure 5.4, in the region above the protrusion. The vertical striations are caused by very small vortices forming in the gas flow. The vortices formed are thought to be caused by rotational flow in the exiting gas.

### **5.2.2 EFFECT OF FLOW TUBE PROTRUSION**

By comparing the flow with and without a flow tube protrusion it is possible to see that the direction of flow of the outer surface of the jet is unaffected by the protrusion. However the change in the direction of flow of the inner surface of the jet with increasing driving pressure (Figures 5.5-5.6) is the opposite to that described earlier when there is a protrusion. The flow direction is approximately  $90^\circ$  to the protrusion top at 11 bars but as the driving pressure is increased the direction changes to less than  $90^\circ$ . This is not caused by the suction at the tip changing but is caused by the jet behaving in a similar manner to a converging diverging slit as described in Chapter 3. The presence of the protrusion changes the flow characteristics and the flow behaves like a bisected convergent divergent nozzle with the oblique shock waves and the expansion waves reflecting from the protrusion rather than from the centreline of the slit (see Figure 3.5).

The rim shock is not present when there is no protrusion.

### **5.2.3 EFFECT OF MACH NUMBER**

The characteristics of nozzle used are as follows:

|                          |                       |            |
|--------------------------|-----------------------|------------|
| IN3/WM4 - $A/A_* = 1.80$ | $P_{ideal} = 8.84$    | $M = 2.08$ |
| IN3/WM2 - $A/A_* = 2.67$ | $P_{ideal} = 17.35$   | $M = 2.51$ |
| IN3/WM5 - $A/A_* = 3.53$ | $P_{ideal} = 27.56$   | $M = 2.81$ |
| IN3/WM3 -----            | CONVERGENT ONLY ----- | $M = 1.00$ |

Figures 5.7 to 5.9 illustrate IN3/WM4, IN3/WM5 and IN3/WM3 respectively.

IN3/WM4 at 16 bars theoretically should run under expanded (Figure 5.7). There is a rim shock on one side of the nozzle confirming that the nozzle is running under expanded and indicating that the ideal driving pressure is below 16 bars. IN3/WM5 at 16 bars theoretically should run over expanded (Figure 5.8). The presence of an oblique shock at the exit is clear. The nozzle appears to some extent to be ignoring the presence of the protrusion and the intersecting shocks are similar to those illustrated in Figure 3.5. Thus the Schlieren photographs can be used to help determine whether a nozzle is operating in the over expanded, under expanded or ideal mode.

The flow in the convergent only nozzle cannot be compared to IN3/WM4 and IN3/WM5 as the expansion occurring at the exit makes interpretation of the flow difficult. Convergent only nozzles have an exit mach number of 1.00 and the gas flow has to undergo a considerable expansion at the exit which decreases the exit pressure from  $0.528 \times$  the driving pressure (see equation 3.26) to 1 bar. There is a very strong shock wave occurring just over half way up the protrusion. (Figure 5.9 showing IN3/WM3 with 4.9 mm protrusion at 16 bars driving pressure). This will be formed in a similar manner to a rim shock described earlier. It does not itself attach to the rim of the protrusion because the strength of the compression will cause a strong shock to form which will not attach itself to the nearest discontinuity. The jet has a cellular structure which may indicate that the expansion outside the nozzle has accelerated the flow to supersonic velocities but this is difficult to determine.

Figure 5.10 illustrates an interesting case of IN3/WM3 running at 26 bars driving pressure with no protrusion. The thin horizontal line above the exit region of the nozzle shows the presence of a mach disc which is little more than a normal shock wave. i.e. the flow becomes subsonic after passing the Mach disc. The gas pattern in the area above the mach disc is very similar to that seen for a subsonic jet flowing from a nozzle. This pattern may be caused by gas being drawn up the flow tube (which

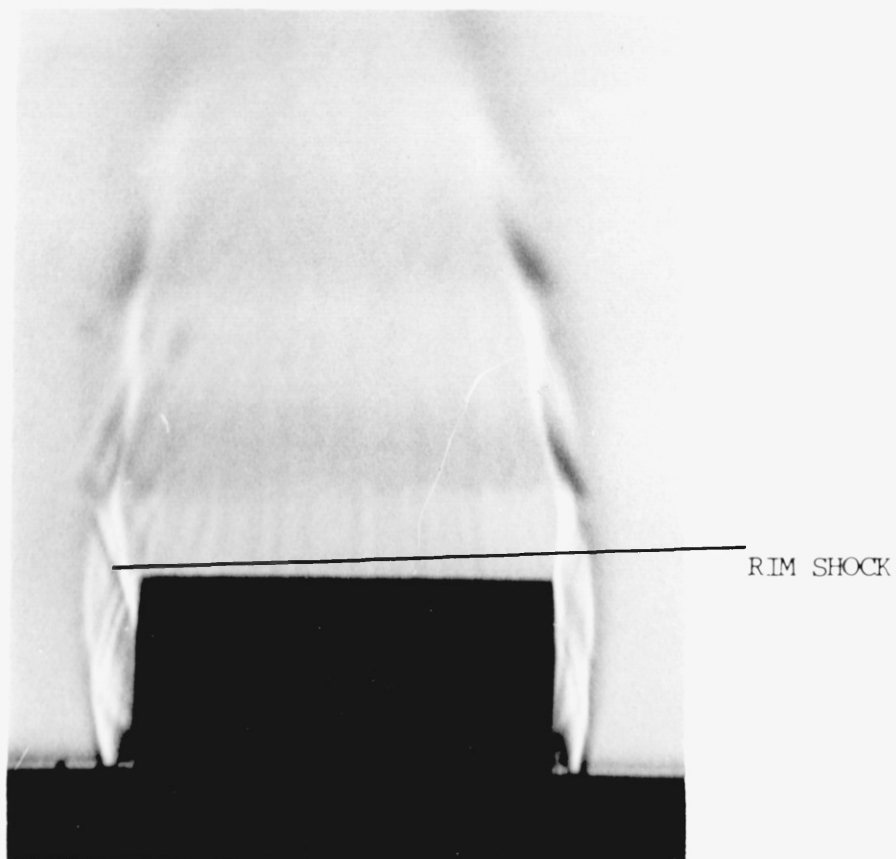


FIGURE 5.7

NOZZLE - IN3/WM4 16.00 BARS DRIVING PRESSURE (UNDER EXPANDED)

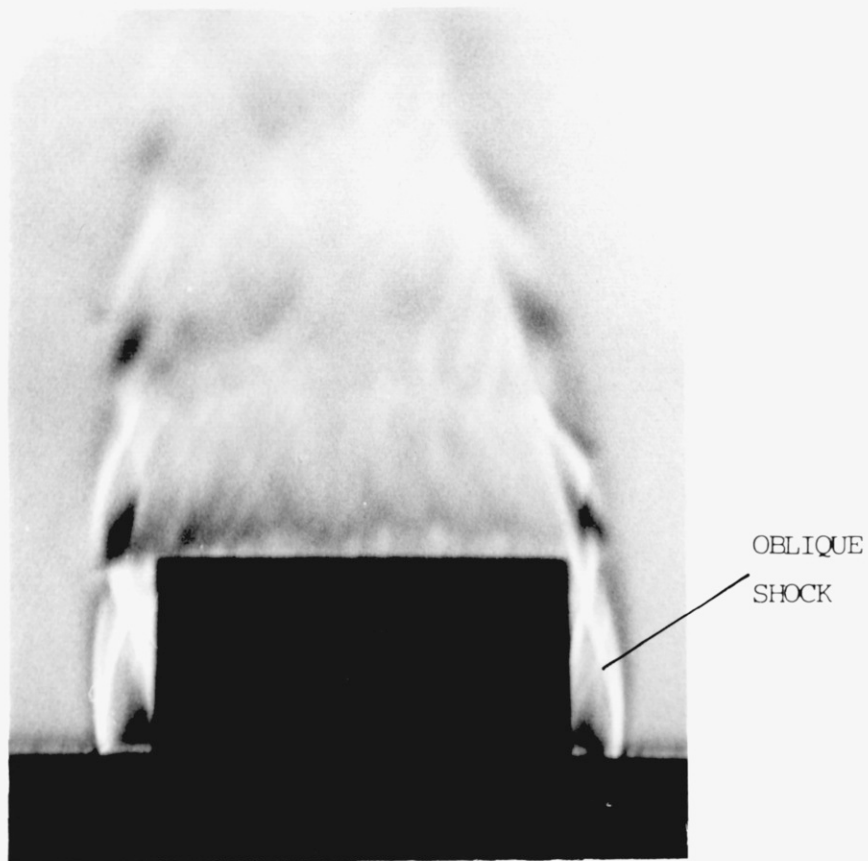


FIGURE 5.8

NOZZLE - IN3/WM5 16.00 BARS DRIVING PRESSURE (OVER EXPANDED)

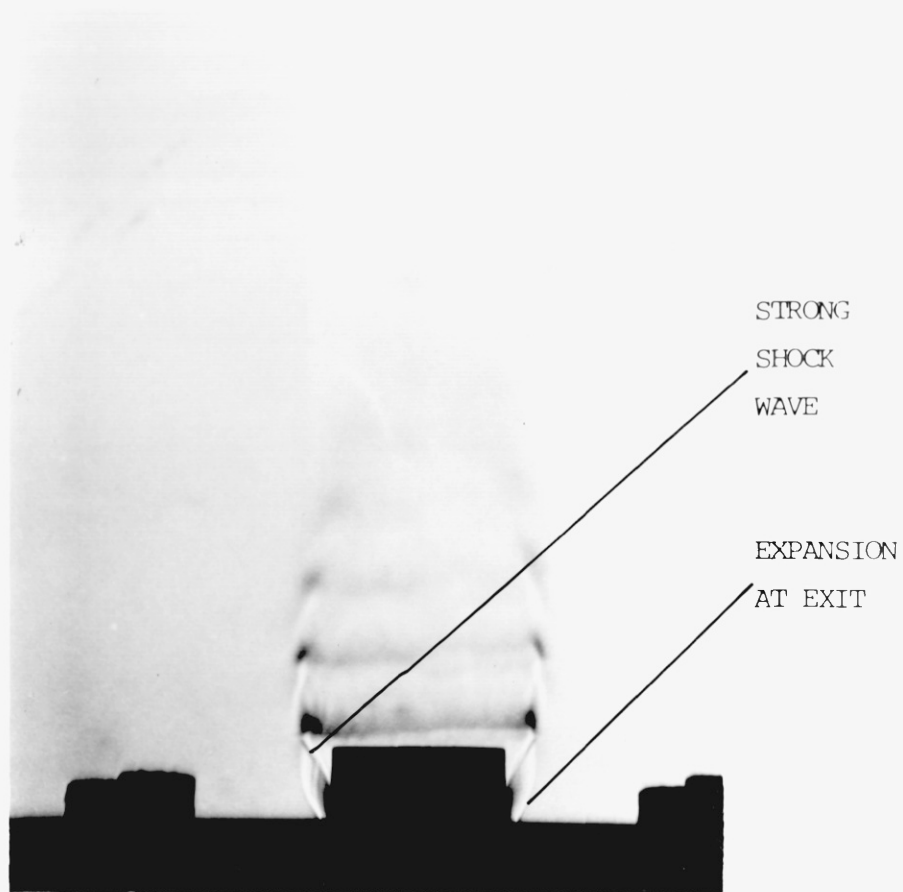


FIGURE 5.9

NOZZLE - IN3/WM3 16.00 BARS DRIVING PRESSURE  
4.9 mm PROTRUSION

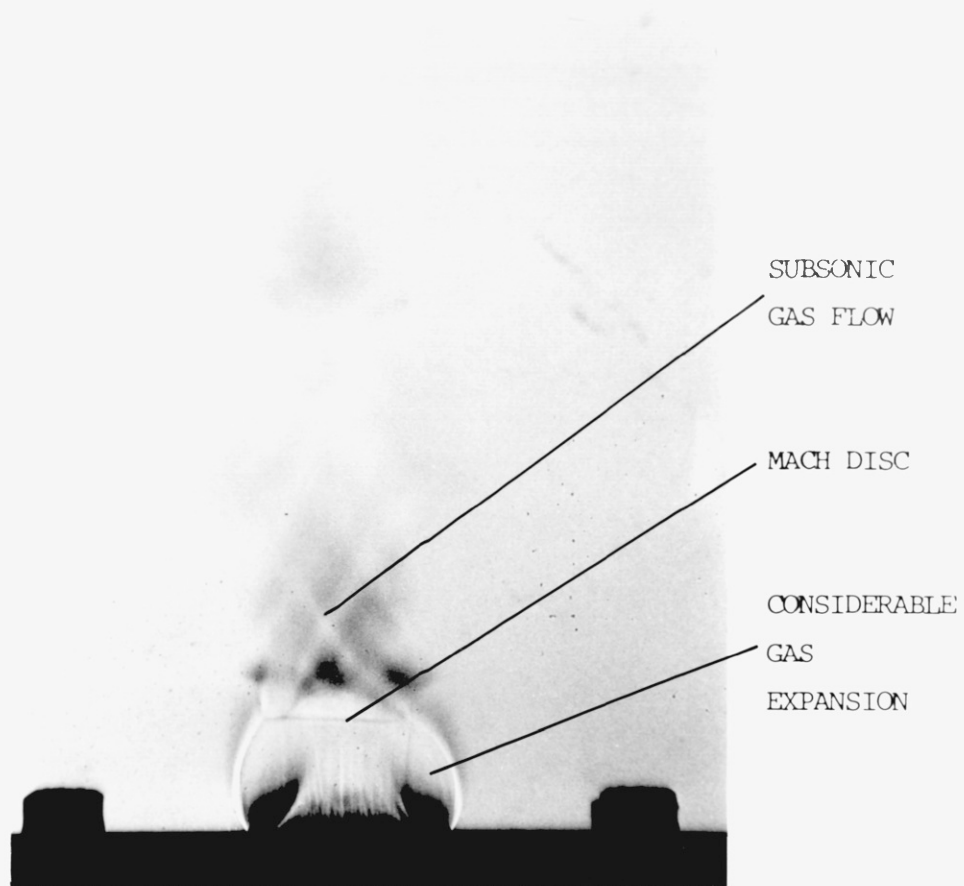


FIGURE 5.10

NOZZLE - IN3/WM3 26.00 BARS DRIVING PRESSURE

0.0 mm PROTRUSION

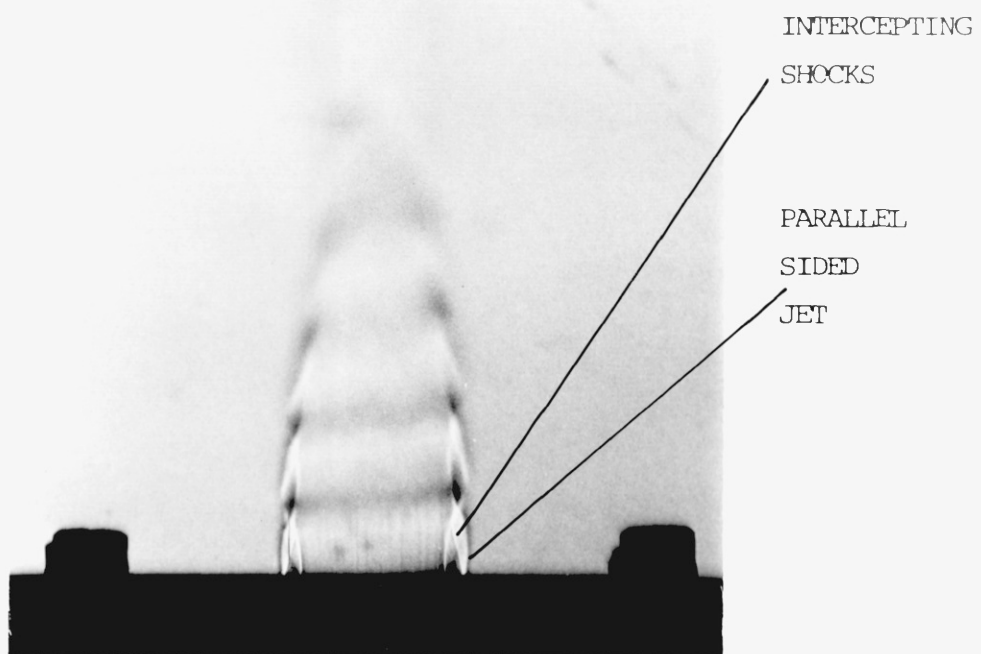


FIGURE 5.11

NOZZLE - IN4/WM7 16.00 BARS DRIVING PRESSURE

0.0 mm PROTRUSION



UNCONCENTRIC  
NOZZLE  
OPERATION

FIGURE 5.12

NOZZLE - IN5/WM8 21.00 BARS DRIVING PRESSURE

0.0 mm PROTRUSION

was open while the photographs were taken) and accelerated to above supersonic velocities by the gas jetting from the annulus. Downstream from the mach disc the gas is subsonic and so the gas drawn up the flow tube could be said to be acting in the same manner as a subsonic round nozzle with an exit diameter equal to that of the Mach disc.

#### 5.2.4 EFFECT OF FLOW TUBE DIAMETER

The characteristics of nozzles used are as follows:

IN4/WM7 -  $A/A_* = 2.50$ ,  $P_{ideal} = 15.81$ ,  $M = 2.45$ ,  $D = 10.0$  mm

IN5/WM8 -  $A/A_* = 2.69$ ,  $P_{ideal} = 17.62$ ,  $M = 2.52$ ,  $D = 12.2$  mm

Figure 5.11 illustrates very nicely the parallel sided jet with intercepting shocks within the jet as schematically shown in Figure 3.5.

Figure 5.12 of IN5/WM8 illustrates very nicely the fact that the nozzle is operating unconcentrically. The unconcentricity was caused by a very small throat gap, 0.325 mm, making the concentric assembly of the nozzle almost impossible. The nozzle was used in its unconcentric form for the atomization experiments described in the next chapter.

### 5.3 PITOT TUBE ANALYSIS OF MACH NUMBER AND OBLIQUE SHOCK WAVES

#### INTRODUCTION

A pitot tube can be used to measure the stagnation pressure of a gas stream. However the readings obtained can only be used to calculate Mach numbers if the static pressure in the pitot tube region is known. The assumption that the static pressure is 1 bar can be used as an approximation but as shown earlier (in Chapter 3 - the section on shock wave behaviour in nozzles) the static pressure varies considerably from this value.

The Mach number can be calculated from equation 5.2<sub>(40)</sub> given that the static pressure and the stagnation pressure are known.

$$P_{\text{stag}}/P_o = [ \{ (k+1) [(k+1)M^2/2]^k \} / \{ 2(kM^2+1) - (k+1) \} ]^{1/(k-1)} \quad (5.2)$$

where  $k$  = ratio of specific heats (1.4 for air)

$P_{\text{stag}}$  = stagnation pressure

$P_o$  = static pressure

Before an understanding of static pressure was gained the pitot tube was used for measuring exit Mach numbers on IN2/NN2. Subsequent understanding of the difficulties of measuring the static pressure, meant that the pitot tube was only used for determining the concentricity of the nozzle except for one interesting experiment carried out to see if the position of a shock wave could be measured using the pitot tube.

#### 5.3.1 MACH NUMBER WORK ON IN2/NN2

( $A/A_* = 1.725$ ,  $P_{\text{ideal}} = 8.07$ ,  $M = 2.02$ )

In order to look at the effect of Mach number the pitot tube was traversed across the top of the nozzle, at different driving pressures and the stagnation pressure recorded. The results obtained and the results of the following calculation are shown in Table 5.3.1.

Using equation 5.2 to calculate the Mach number,  $M_1$ , assuming that the static pressure is 1.0 bar, and using the values of the stagnation pressure that were measured, the Mach number,  $M_1$ , increases as the driving pressure increases. However the Mach number values calculated (see Table 5.3.1) do not equal 2.02 as would be expected if IN2/NN2 was running ideally and the static pressure was 1.00 bar.

This illustrates that without accurate knowledge of the static pressure it is difficult to calculate the Mach number. However we know that ideally IN2/NN2 should run at a pressure of 8.07 bars ( $P_e/P_d = 0.1239$ ). With this information we can estimate the static pressure at the exit of the nozzle,  $P_o$  (see Table 5.3.1).

TABLE 5.3.1

MACH NUMBER CALCULATIONS ON IN2/NN2

| STAGNANTION<br>PRESSURE<br>$P_{stag}$ | DRIVING<br>PRESSURE | MACH<br>NUMBER<br>$M_1$ | $P_o$ | $P_{stag}/P_o$ | MACH<br>NUMBER<br>$M_2$ |
|---------------------------------------|---------------------|-------------------------|-------|----------------|-------------------------|
| 2.78                                  | 6.0                 | 1.32                    | 0.743 | 3.735          | 1.582                   |
| 4.59                                  | 11.0                | 1.78                    | 1.363 | 3.368          | 1.488                   |
| 6.40                                  | 14.5                | 2.14                    | 1.797 | 3.561          | 1.538                   |
| 8.01                                  | 21.0                | 2.42                    | 2.602 | 3.078          | 1.408                   |

Pressure in Bars(a)

Thus we can now calculate values of  $P_{\text{stag}}/P_o$  based on the calculated values of static pressure and so estimate the Mach number,  $M_2$ , from this data.

From these calculations it is clear that the calculated Mach number is smaller than the 2.02 theoretically expected. The Mach number,  $M_2$ , however is reasonably constant indicating that the exit Mach number being measured is probably constant. The differences between calculated and predicted values are probably caused by the complex gas flow above the nozzle. Also<sup>if</sup> the pitot tube is not exactly parallel to the gas flow the pressure measured by the pitot tube may not be purely stagnation pressure but will probably include some static pressure component as well. This would cause the value of stagnation pressure measured to be smaller and so the calculated Mach number to be smaller as found in the measurements made.

Further work using a pitot static tube, which would have helped to have eliminated some of the problems of accurately assessing the static pressure were not carried out because by the time the nature of the gas flow was better understood other work was in progress and pitot tube work was no longer part of the experimental program. This was because by the time the nature of the gas flow was better understood Schlieren photography was being used as the method for assessing the nature of the gas flow and found to be a more useful tool.

### **5.3.2 DETERMINATION OF SHOCK WAVE POSITION ALONG THE PROTRUSION** **IN IN3/WM2**

The nozzle protrusion was 2.89 mm in this experiment. The same pitot tube used for concentricity measurements was again used and placed parallel to the protrusion at a height of 2.29 mm above the exit plane of the nozzle as shown in Figure 5.13. The driving pressure was slowly increased and the stagnation pressure measured. The results obtained are shown in Table 5.3.2.

From these it can be seen that there is a minimum pitot stagnation pressure at a driving pressure of 8.6 bars and this is likely to correspond to the passing of a shock wave.

FIGURE 5.13

PITOT TUBE POSITION

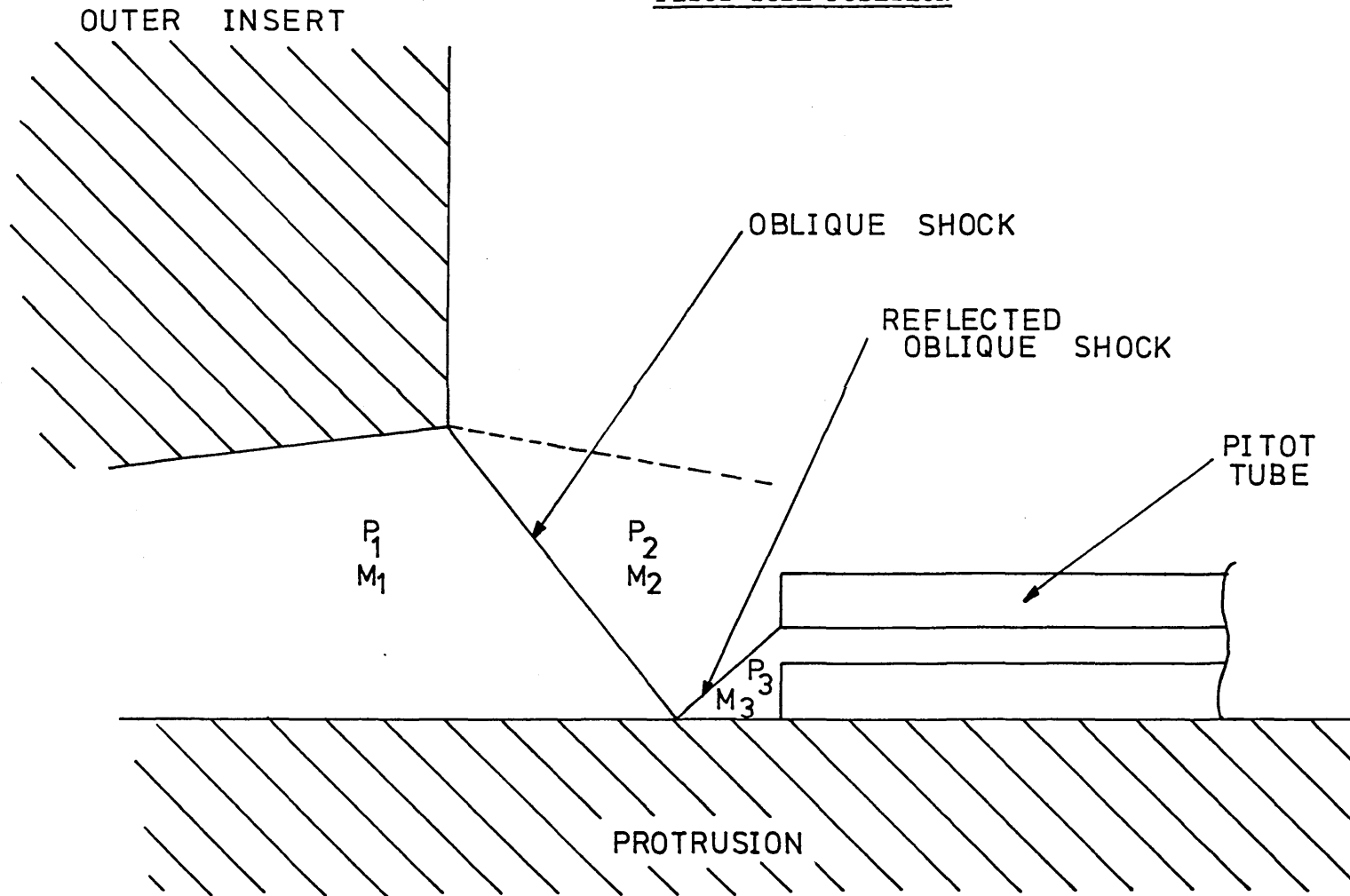


TABLE 5.3.2

PITOT TUBE STAGNATION PRESSURE VARIATION WITH  
DRIVING PRESSURE

| PITOT STAGNATION<br>PRESSURE | DRIVING PRESSURE |
|------------------------------|------------------|
| bars (a)                     | bars (a)         |
| 2.082                        | 2.862            |
| 2.854                        | 4.325            |
| 3.603                        | 5.655            |
| 4.011                        | 6.852            |
| 4.528                        | 7.384            |
| 4.238                        | 7.916            |
| 3.971                        | 8.608            |
| 3.999                        | 8.947            |
| 4.352                        | 9.672            |
| 4.646                        | 10.625           |
| 5.038                        | 11.587           |

Pitot height above exit plane = 2.29 mm

### ANALYSIS OF SHOCK PASSING ALONG THE PROTRUSION

By following the same reasoning as used earlier, in Chapter 3 on gas flow, the position of the oblique shock can be calculated. (the nomenclature followed is the same). The calculations are shown in Appendix 7.

Given that the pitot tube is constructed with an outer diameter of 0.63 mm and an inner diameter of 0.35 mm the shock will be first detected when it enters the pitot tube a distance of 0.49 mm from the side of the flow tube protrusion. As the pitot tube is 2.29 mm from the exit, and the point at which the oblique shock reflection occurred is 1.53 mm from the exit, the pitot tube is a distance of 0.76 mm from the point of reflection. It is known that the angle between the shock reflection and the protrusion,  $\theta_2$ , is  $31.87^\circ$ . Then the position of the shock reflection at a distance of 2.29 mm from the exit of the nozzle can be shown to be a distance of  $\tan 31.87^\circ \times 0.76 = 0.47$  mm from the side of the flow tube protrusion. The predicted figure of 0.47 mm and measured figures of 0.49 mm are very close.

This adequately shows that the pitot tube is detecting the reflected shock wave. The fact that the pitot did not measure the shock at a slightly lower pressure, as might have been theoretically expected, may be due to the boundary layer along the protrusion causing the shock reflection to occur a small distance from the protrusion wall.

Further analysis of the position of the shock wave using the measured stagnation pressure becomes increasingly difficult as the shock wave now is interacting with the pitot tube. The fact that a drop occurs in the stagnation pressure measured shows that there is a decrease in the stagnation pressure across the reflected shock. Analysis already carried out has shown that theoretically the static pressure drops from,  $P_3$ , 2.06 bars to,  $P_2$ , 1 bar across the reflected oblique shock. However the value of  $P_{\text{stag}}/P_0$  (using equation 5.2) only drops slightly from 5.26 ( $M_2 = 1.92$ ) to 3.10 ( $M_3 = 1.41$ ). Thus the theoretical value of  $P_{\text{stag}}$  expected before the oblique shock reflection is  $3.10 \times 2.06 = 6.39$  bars and after the shock  $5.26 \times 1.00 = 5.26$  bars. Thus the stagnation pressure can be shown to decrease across an oblique

shock reflection. The ratio of the calculated stagnation pressure drop is  $6.39/5.26 = 1.21$ . The ratio of the measured stagnation pressure drop is  $4.528/3.971 = 1.14$ . Thus differences in the calculated stagnation pressure and the measured pressure are likely to be caused by turbulence occurring downstream from the shock reflection, the non-theoretical gas flow and possibly interference from the boundary layer.

The above calculations again illustrate the difficulties of predicting Mach numbers, using the pitot tube, in regions where the static pressure varies and the flow is complex. It can however be used as a qualitative tool to measure how gas flows change.

#### 5.4 THE SUCTION DEVELOPED AT THE PROTRUSION TIP

The suction developed at the tip of the protrusion was measured for nozzles IN3/WM2, IN3/WM3, IN3/WM4, IN3/WM5, IN4/WM7, IN5/WM8 (see Figures 5.14 to 5.23). All pressures are given in bars absolute. The gas used was air unless otherwise mentioned. By considering each nozzle in turn the suction variations can be summarized.

##### 5.4.1 INFLUENCE OF PROTRUSION ON SUCTION IN IN3/WM2 ( $A/A_* = 2.665$ , $P_{ideal} = 17.35$ , $M = 2.51$ )

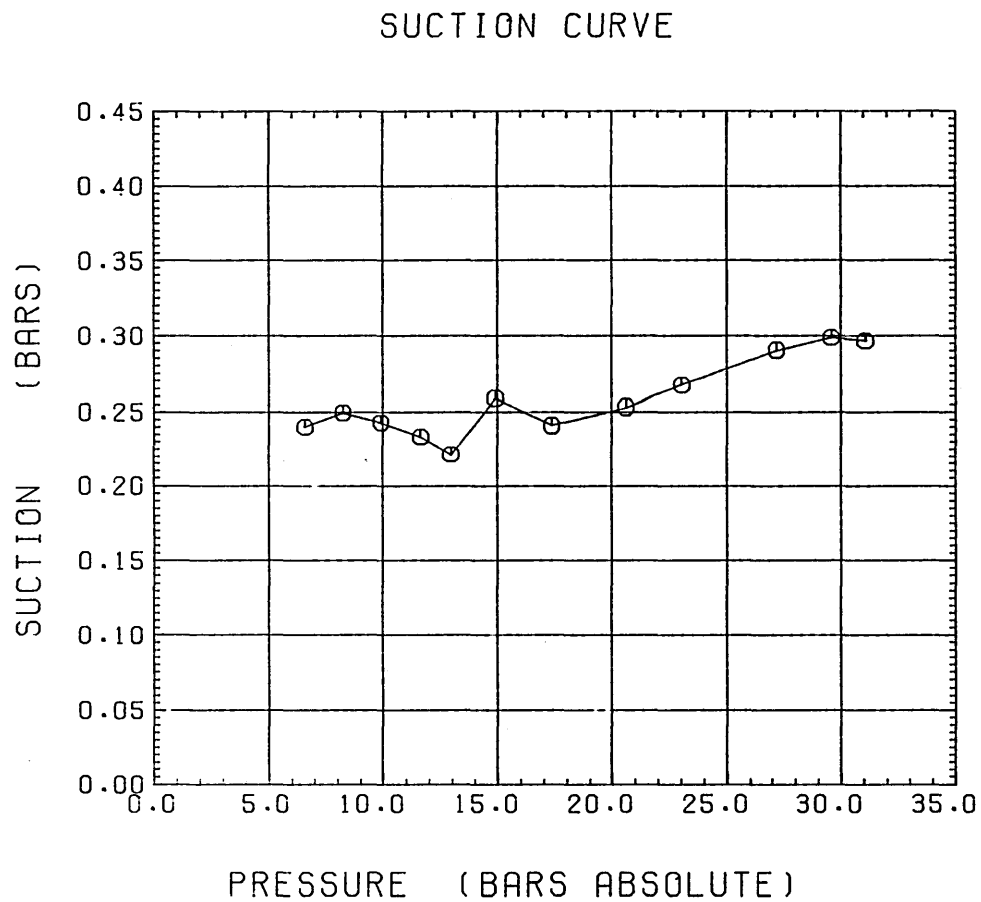
Figures 5.14 to 5.18 show suction variations in IN3/WM2 with increasing protrusion. The suction behaviour can be divided into four different regimes based on the protrusion.

(i) very low protrusion. (0.15 mm) - Figure 5.14

The suction rapidly rises to 0.25 bar and remains constant until the driving pressure reaches 20.0 bars. The suction then slowly increases to 0.30 bars.

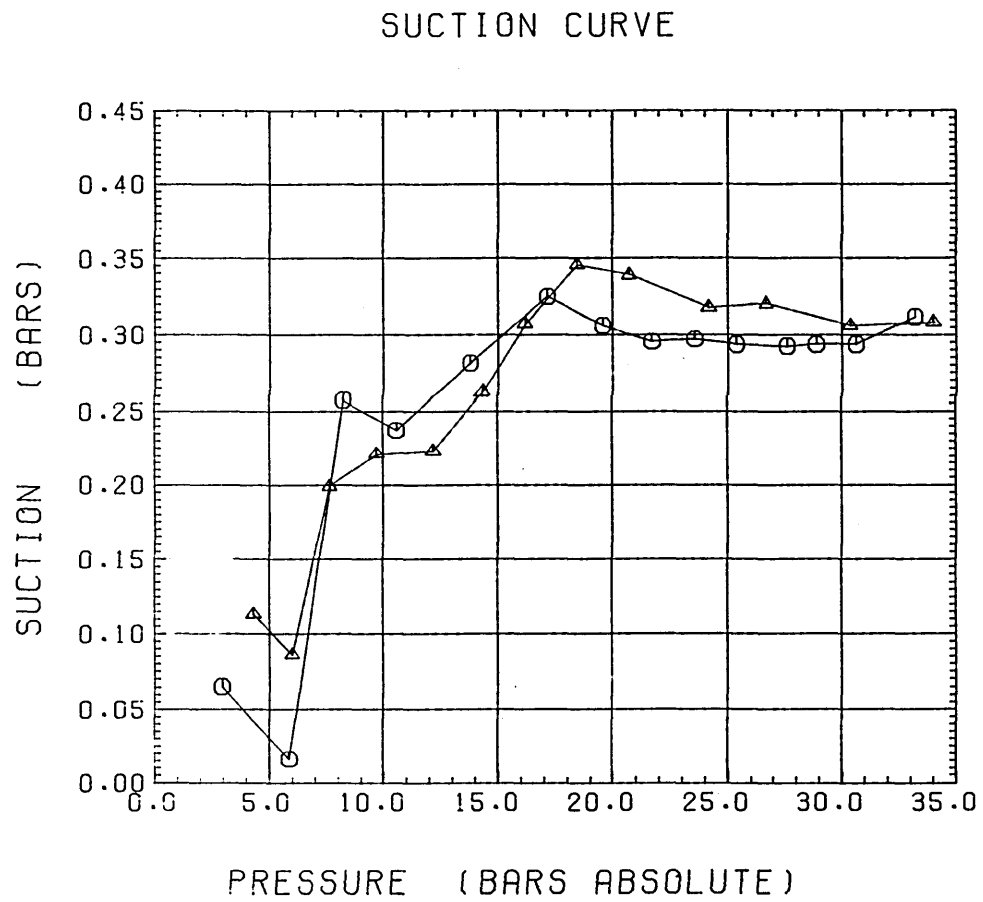
(ii) low protrusions (0.89 mm-1.42 mm) - Figure 5.15

A trough in suction occurs at a driving pressure of 6 bars. The suction then rises rapidly to 0.25 bars. There is then a rise in the suction to 0.32 bars before it falls to 0.3 bars and



| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN3/WM2        | ⊙      | 0.15             |

**FIGURE 5.14**



| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN3/WM2        | ⊙      | 0.89             |
| IN3/WM2        | △      | 1.42             |

**FIGURE 5.15**

remains constant. The profile was similar for 1.42 mm protrusion.

(iii) intermediate protrusions (2.16 mm-2.90 mm)-Figure 5.16

The suction in this regime were very similar to each other. Troughs in suction appear at approximately 0.16 bars suction. The pressure at which the trough occurs increases as the protrusion increases, the troughs occur at 7.0, 8.5, 10.0 bars for protrusions of 2.16, 2.54, 2.90 mm respectively. The suction then increased in two stages; an initial rapid increase followed by a more gradual increase to between 0.36 and 0.43 bars. The transition from rapid to gradual increase occurred at 11.5, 14.0, 14.0 bars for protrusions of 2.16, 2.54, 2.90 mm respectively.

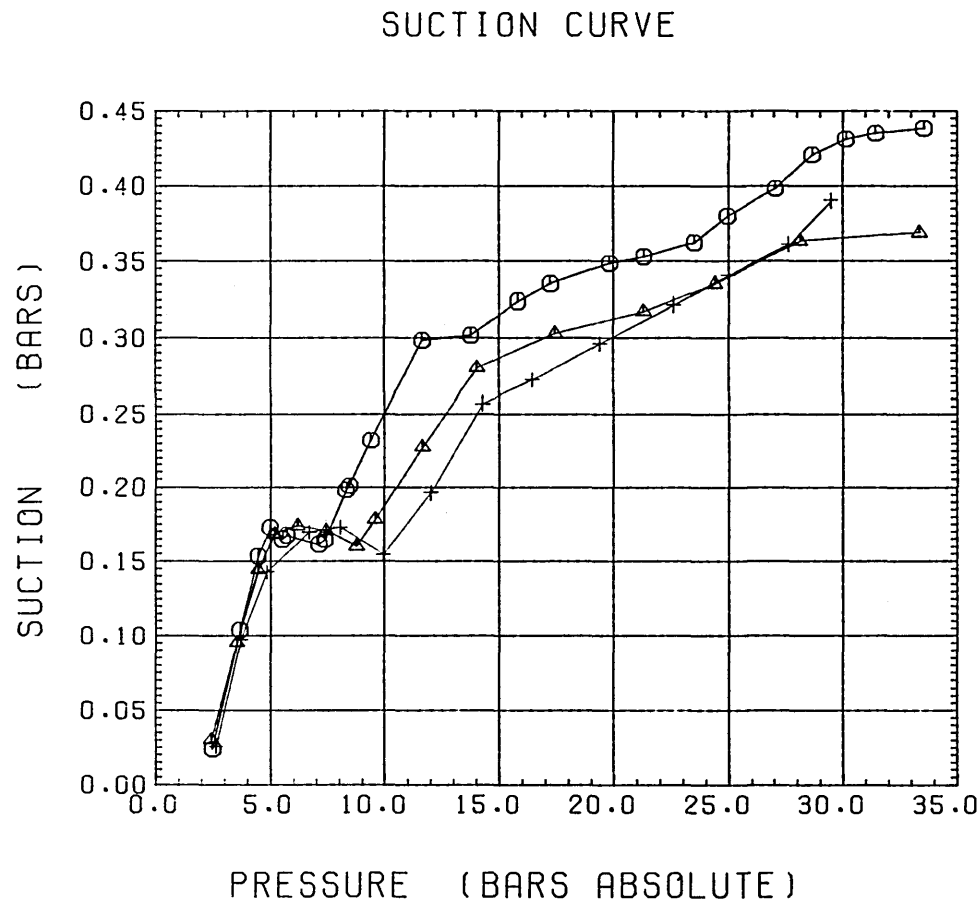
(iv) higher protrusions (4.9 mm) - Figure 5.17

The suction curve profile changes here and shows two peaks which occur at approximately 8.0 and 14.0 bars driving pressure at suction of 0.26 and 0.22 bars respectively. The suction then gradually increases to 0.37 bars.

The suction in the flow tube was measured for argon (Figure 5.18) using a 4.9 mm flow tube protrusion. The same suction characteristics were found as those when using air, but they occurred at higher pressures. The reasons for this are explained later. (5.4.5)

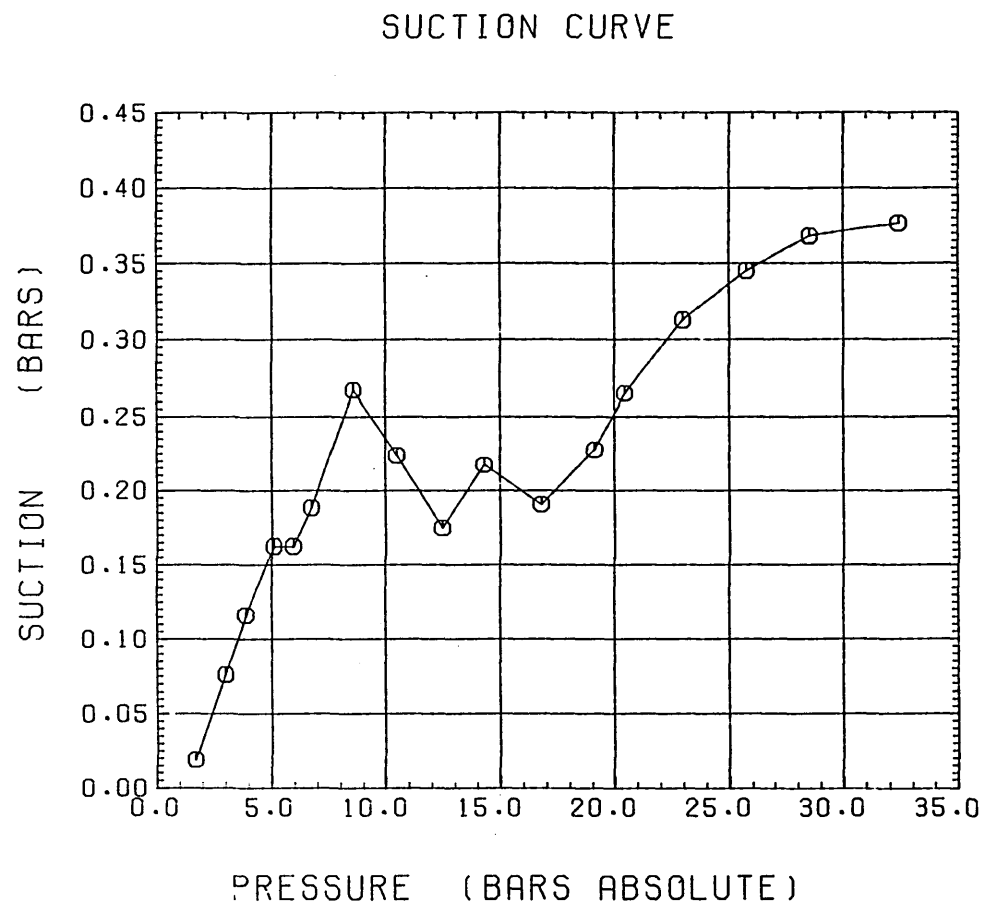
#### 5.4.2 SUCTION DEVELOPED IN CONVERGENT ONLY NOZZLE - IN3/WM3 (M = 1.0)

Figure 5.19 shows the suction variation in IN3/WM3 with a 4.9 mm protrusion as driving pressure is increased. The suction profile shows a sudden trough in suction about 6.5 bars driving pressure. The suction then increases, in a smooth curve, reaching 0.325 bars suction. The profile bears no resemblance to that of IN3/WM2.



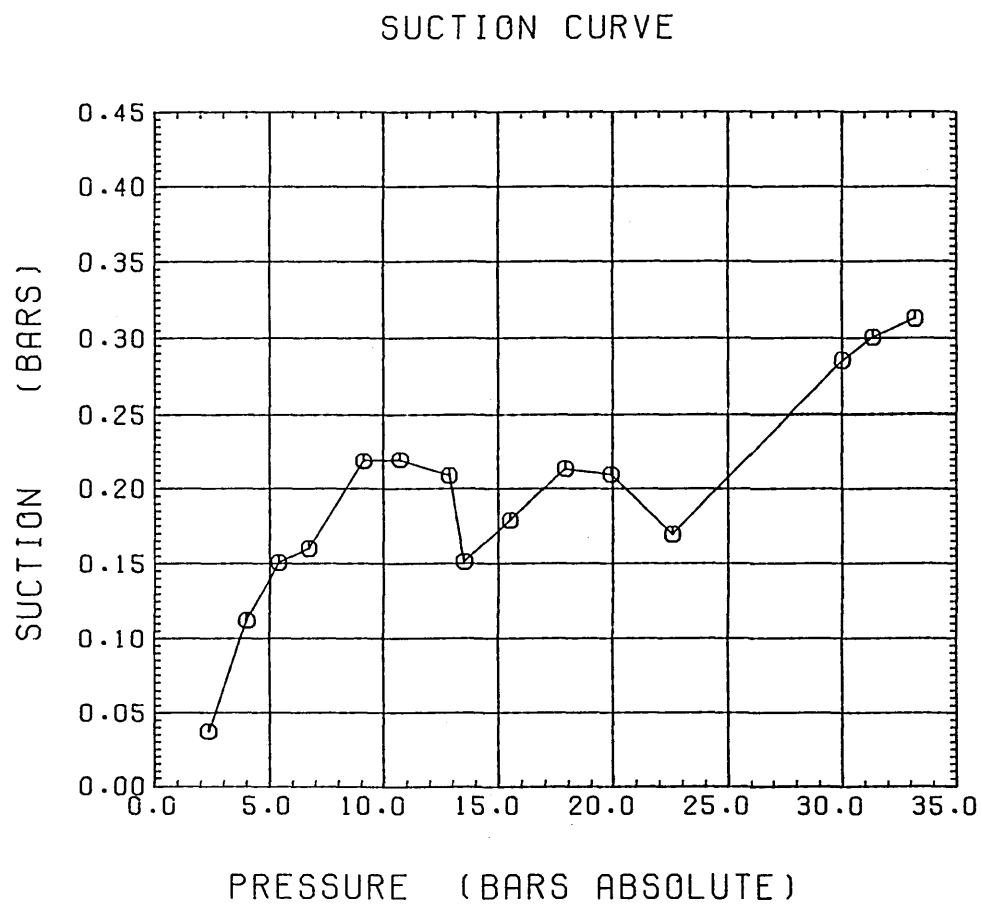
| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN3/WM2        | ⊙      | 2.16             |
| IN3/WM2        | △      | 2.54             |
| IN3/WM2        | +      | 2.90             |

**FIGURE 5.16**



| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN3/WM2        | ⊖      | 4.90             |

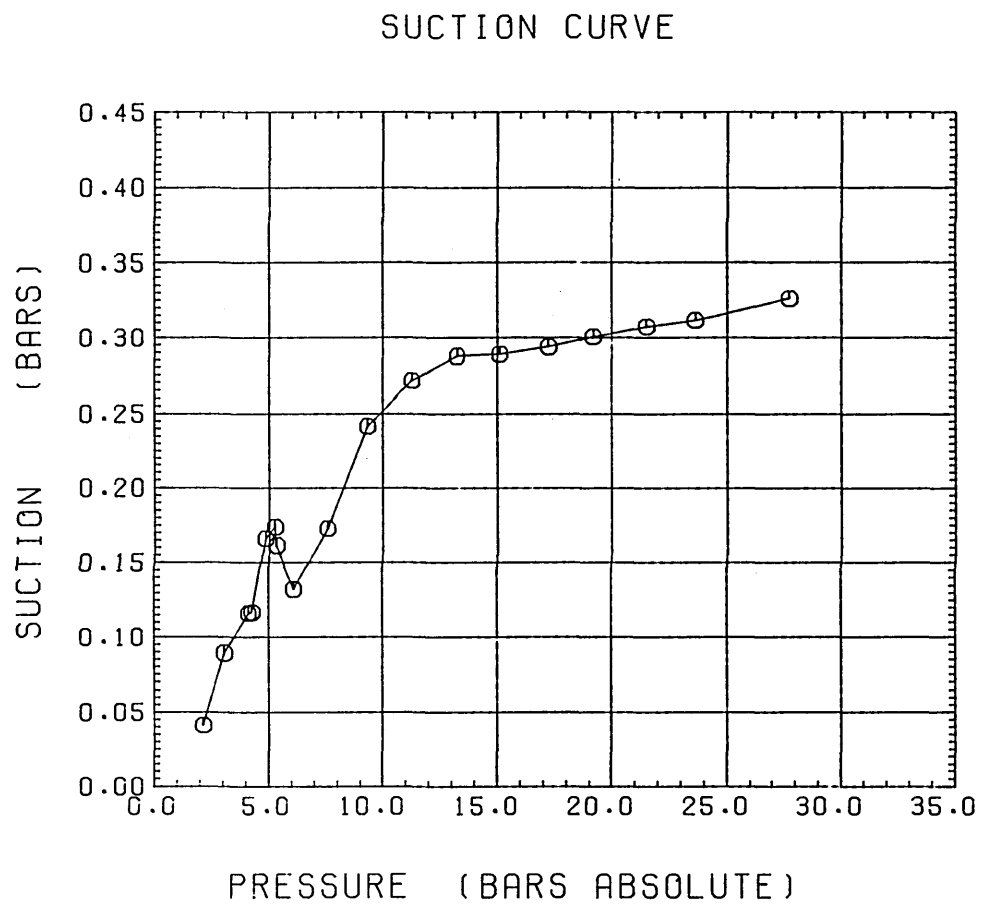
FIGURE 5.17



| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN2/WM2        | ⊙      | 4.90             |

⊙ - ARGON

FIGURE 5.18



| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN3/WM3        | ⊖      | 4.90             |

FIGURE 5.19

### 5.4.3 VARIATION OF SUCTION WITH MACH NUMBER

#### SUCTION IN

IN3/WM4 -  $A/A_* = 1.80$ ,  $P_{ideal} = 8.84$  bars,  $M = 2.08$

IN3/WM2 -  $A/A_* = 2.27$ ,  $P_{ideal} = 17.35$  bars,  $M = 2.51$

IN3/WM5 -  $A/A_* = 3.53$ ,  $P_{ideal} = 27.56$  bars,  $M = 2.81$

The suction profiles were similar in all three nozzles. Figures 5.20 and 5.21 illustrate IN3/WM4 and IN3/WM5.

#### (i) IN3/WM4

The suction increases to a maximum value of 0.245 bars before it falls to a minimum of 0.15 bars at about 16.0 bars driving pressure. The suction then gradually increases to a value of 0.32 bars.

#### (ii) IN3/WM2

(as illustrated earlier in figure 5.17)

#### (iii) IN3/WM5

The suction increases to a maximum value of 0.185 bars before it falls to a minimum of 0.15 bars at about 14.5 bars driving pressure. The suction then increases to a maximum of 0.395 bars at about 28 bars driving pressure before another minimum occurs at a driving pressure of 30.0 bars. The suction then begins to increase again.

### 5.4.4 VARIATION OF SUCTION WITH FLOW TUBE DIAMETER

IN4/WM7 -  $A/A_* = 2.50$ ,  $P_{ideal} = 15.81$  bars,  $M = 2.45$ ,  $D = 8.0$  mm

IN3/WM2 -  $A/A_* = 2.27$ ,  $P_{ideal} = 17.35$  bars,  $M = 2.51$ ,  $D = 10.0$  mm

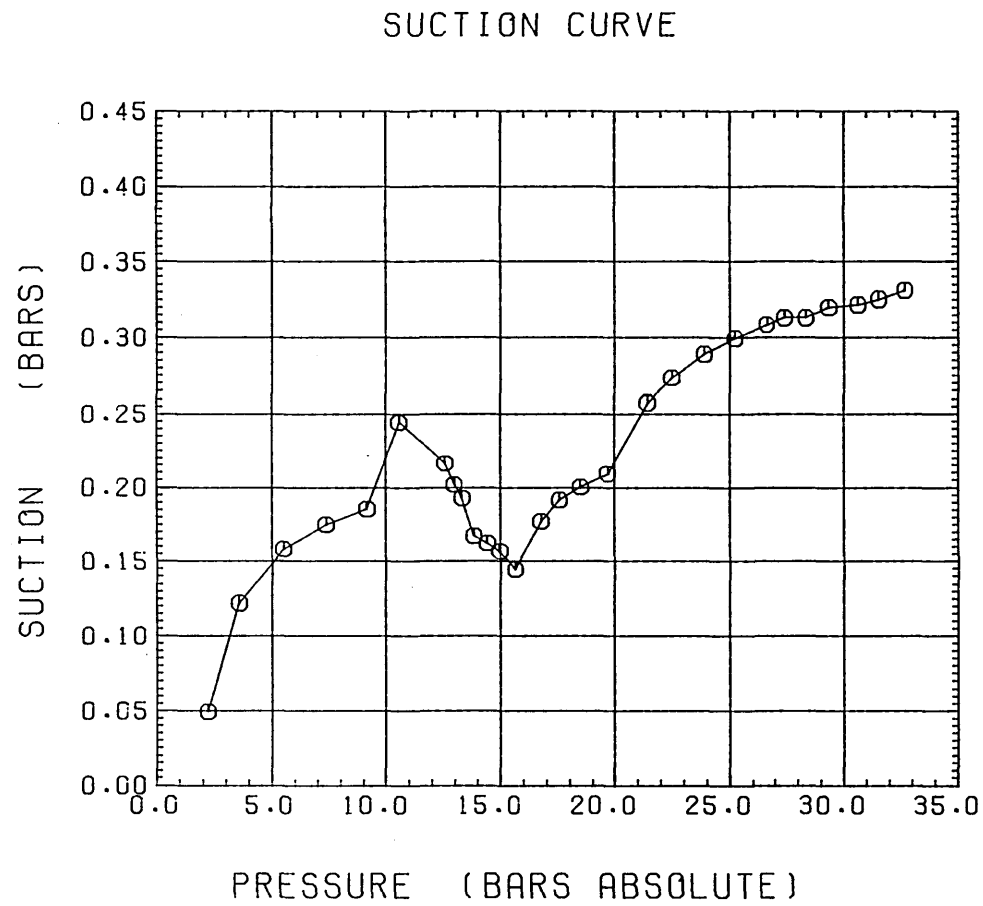
IN5/WM8 -  $A/A_* = 2.69$ ,  $P_{ideal} = 17.62$  bars,  $M = 2.52$ ,  $D = 12.2$  mm

The suction profiles are similar in all three nozzles. Figures 5.22 and 5.23 illustrate IN4/WM7 and IN5/WM8.

#### (i) IN4/WM7

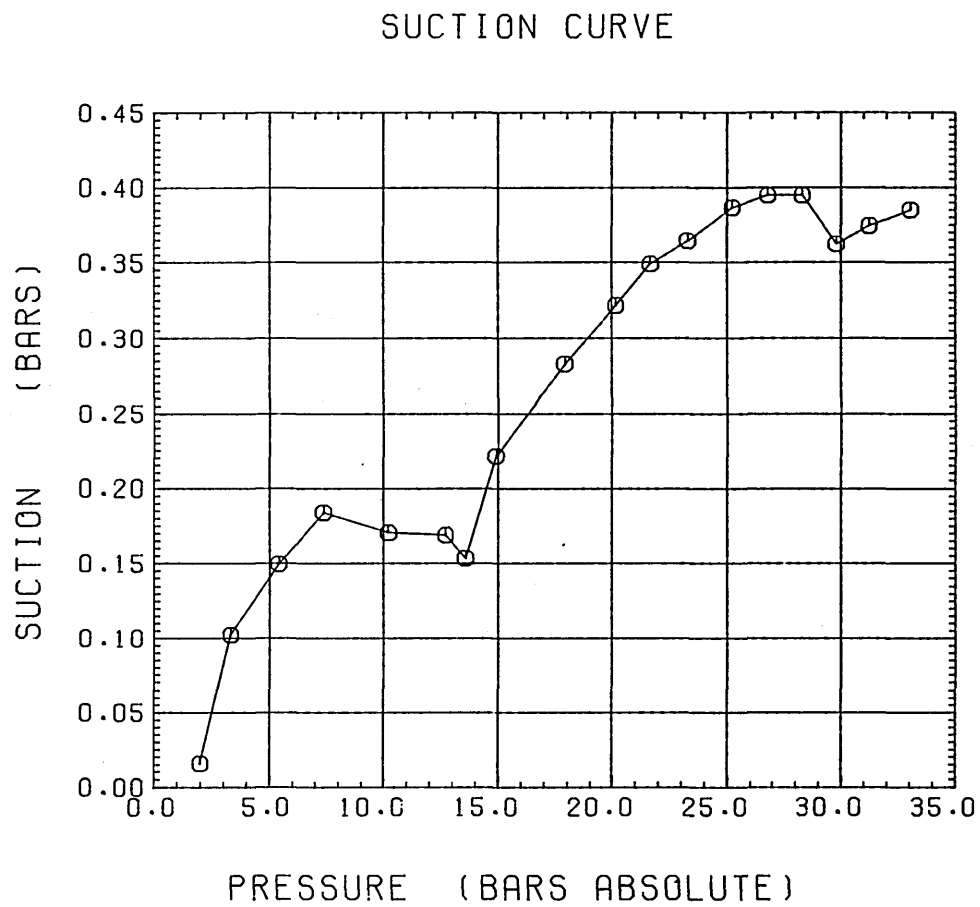
The suction increases to a maximum pressure of 0.23 bars before it then falls to a minimum of 0.13 bars. The suction then gradually increases to a value of 0.325 bars.

#### (ii) IN3/WM2



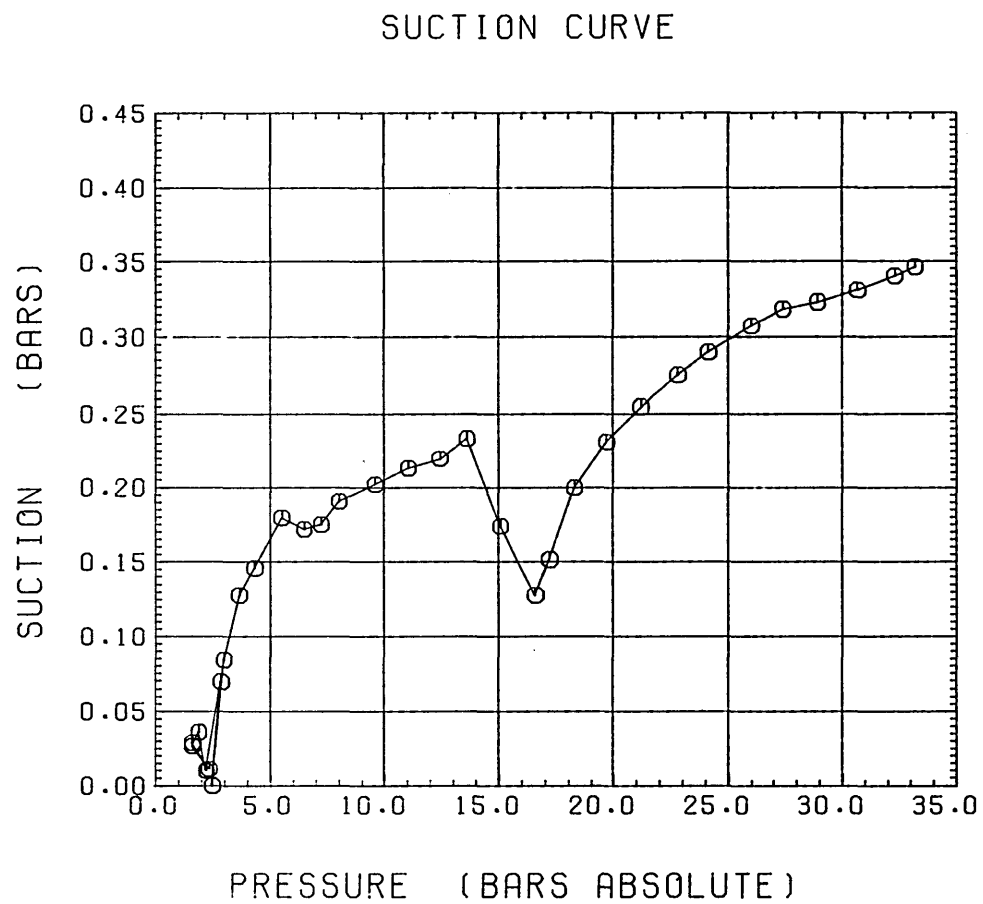
| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN3/WM4        | ⊙      | 4.90             |

FIGURE 5.20



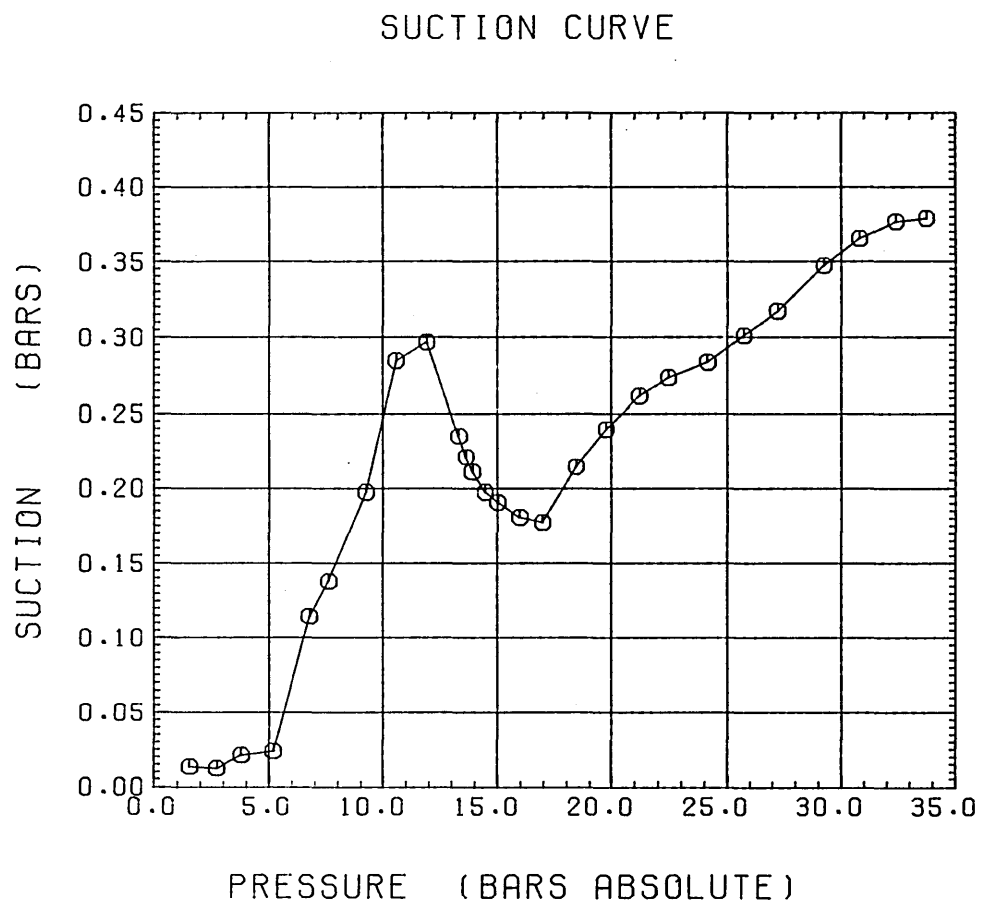
| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN3/WM5        | ⊖      | 4.90             |

FIGURE 5.21



| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN4/WM7        | ⊙      | 4.90             |

**FIGURE 5.22**



| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN5/WM8        | ⊙      | 4.90             |

**FIGURE 5.23**

(as illustrated earlier in figure 5.17)

(iii) IN5/WM8

The suction increases to a maximum pressure of 0.295 bars before it then falls to a minimum of 0.175 bars. The suction then gradually increases to a value of 0.36 bars.

#### 5.4.5 ANALYSIS OF SUCTION DEVELOPED AT THE TIP OF THE PROTRUSION

##### INTRODUCTION

The suction developed in the flow tube is a very complex subject and theoretical determination is beyond the scope of this project. [Note: suction seems to have no effect on particle sizes produced by atomization.] However suction variations can be explained qualitatively by looking at the behaviour of shock waves, along the protrusion.

As described in Chapter 3 the shock wave flow along the protrusion can take one of two forms depending upon whether the nozzle is running in the over expanded or under expanded condition. The over expanded case is shown diagrammatically in Figure 5.24 and the under expanded case in Figure 5.25. If we consider the two types of flow separately it is possible, with reference to Figures 5.24 and 5.25, to explain suction increases and decreases.

##### Overexpanded case

As the driving pressure in the nozzle is increased the angle at which the oblique shock, between regions 1 and 2, meets the flow tube protrusion decreases. This has the effect of elongating the pattern of shock waves. The static pressure in the regions 1-6 can be calculated and the effect on suction can be examined. However the benefits of these calculations are minimal. It is more useful to look at the trends in static pressure, in regions 1-6, as the driving pressure is increased towards ideal, without making detailed calculations.

In regions 2, 4 and 6 the static pressure is always ambient (1 bar).

FIGURE 5.24  
OVEREXPANDED

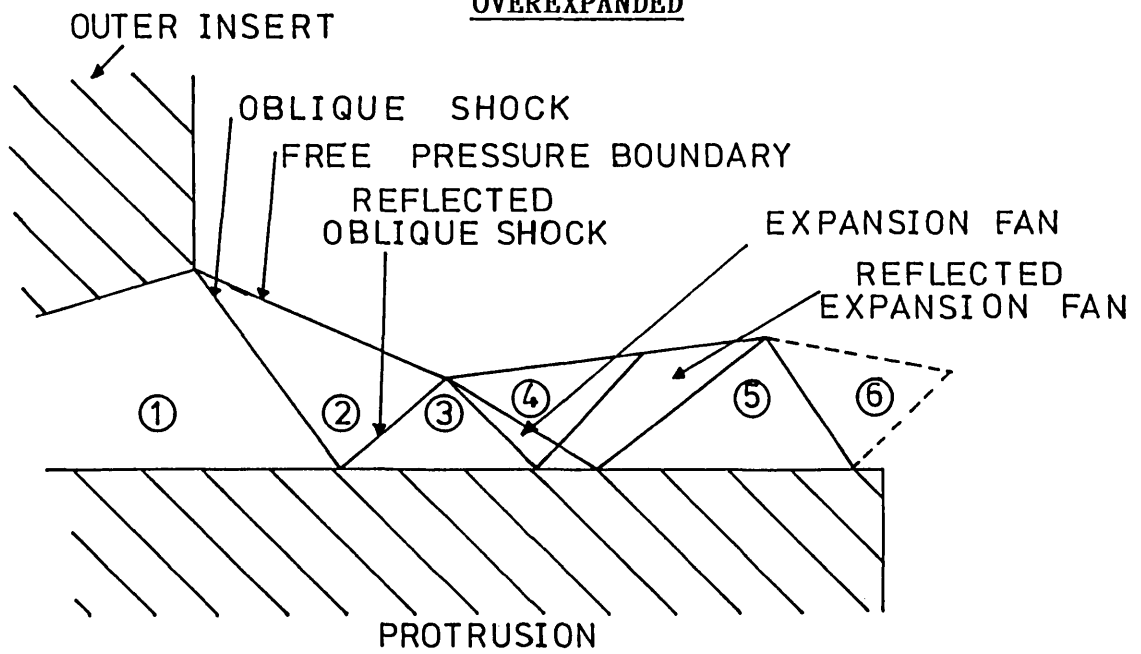
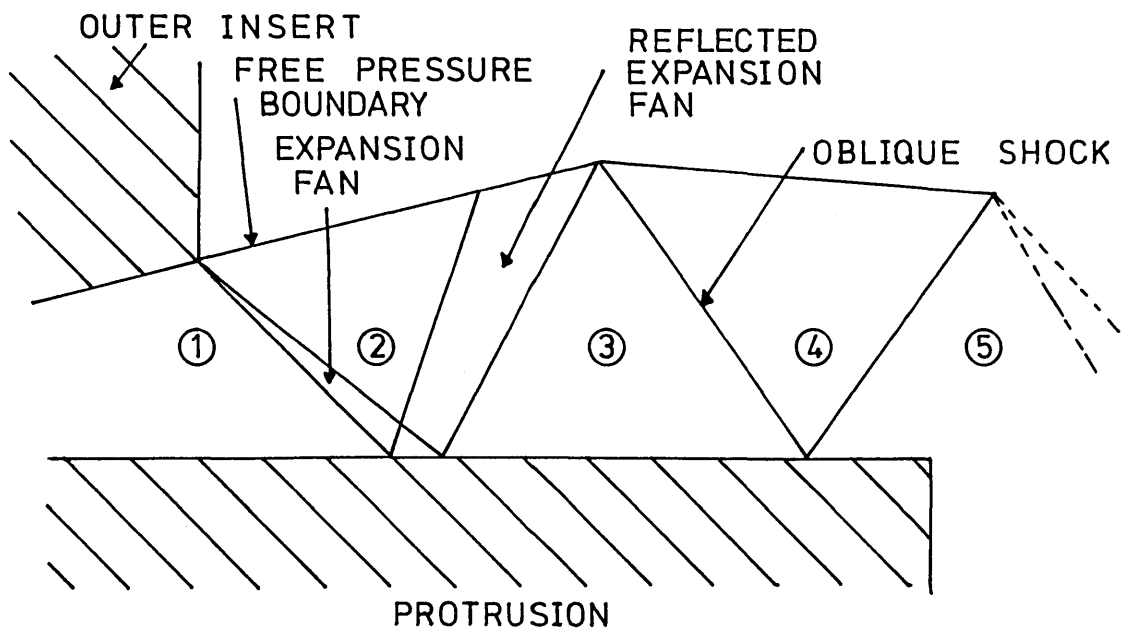


FIGURE 5.25  
UNDEREXPANDED



In regions 1 and 5 the static pressure increases until, at the ideal driving pressure, it is equal to ambient.

The static pressure in region 3 is greater than ambient and decreases until, at the ideal driving pressure, it is equal to ambient.

The pressure in the area, of the expansion wave reflection between regions 3 and 5, changes from below ambient to above ambient, on moving from region 5 to 3. Thus there is a pressure gradient across this region. The angle of the expansion wave decreases as the driving pressure is increased.

#### Underexpanded case

The pressure in region 1 increases as the driving pressure increases in the underexpanded nozzle. Increasing driving pressure also causes the angle of the expansion fan to increase.

The pressure in regions 2 and 4 is ambient.

The pressure in region 3 decreases as the pressure in region 1 increases.

#### EXAMPLE OF SUCTION ANALYSIS ON IN3/WM2 WITH 4.9 MM PROTRUSION

The information given above facilitates an analysis of Figure 5.17 showing the suction developed in IN3/WM2, with a 4.9 mm protrusion. By looking at the development of shock waves in the nozzle we can match the changes from one shock wave region to another with the suction changes at the tip of the protrusion.

At low driving pressures the tip is in region 5 of Figure 5.24 the over-expanded case. However, at low driving pressures, the dominant factor in developing suction is the increasing ability of exiting gas to entrain surrounding air and so increase suction developed at the tip of the protrusion.

When the driving pressure reaches 8-9 bars the sudden fall in suction is probably due to the leading section of the reflected expansion wave, the area between regions 3 and 5, reaching the tip.

The suction gradually falls as the driving pressure is increased to 12.5 bars. This occurs because the static pressure from region 3 to 5 is changing from above ambient to below

ambient, as this reflection area crosses the tip .

The tip, after the expansion wave has passed, is in region 3 where the suction slowly increases as the pressure in this region falls.

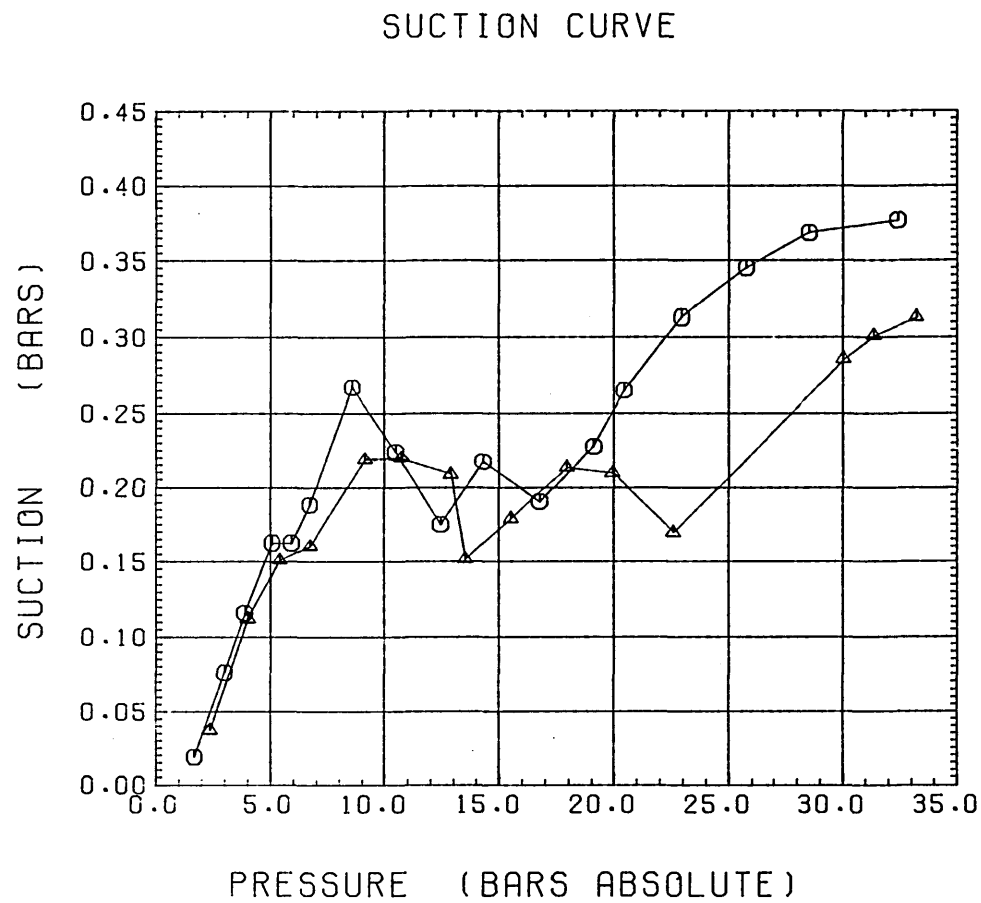
However the suction starts to fall again at 14 bars driving pressure. This indicates that there is another disturbance at the tip. This is probably the disturbance caused by the re-attachment of the separated laminar boundary layer region which separates just upstream of the point where the reflected oblique shock wave meets the protrusion. This disturbance must affect the tip region before the separation region has reached the tip because rundown is not observed until 15.5 bars (see Chapter 6, section 6.8 on the causes of rundown).

At just over 17 bars the nozzle changes from the over to the under expanded operating mode. Then the tip is in region 3, of Figure 5.17, and suction gradually increases without any further disturbances.

#### FURTHER EXAMPLE USING THE SAME PRINCIPLES.

If we now apply the same arguments towards the 2.9 mm protrusion case we can see from Figure 5.16 that a suction peak occurs between 5 and 10 bars driving pressure. At 9 bars the reflected section of the expansion fan has passed the tip. Thus the peak between 5 and 10 bars is probably due to the expansion fan moving past the tip. There is a less abrupt change in suction, associated with the expansion fan, than in the 4.9 mm case. This is probably because expansion fan angles are larger at lower pressures and so the change in static pressure across the expansion fan is more gradual.

The pressure difference between the minimum and maximum suction is smaller, and the minimum is at a lower pressure, than with the 4.9 mm case because the protrusion is smaller. The width of the peak is smaller at lower protrusions because the change in region moving past the flow tube tip occurs more quickly, as the driving pressure is increased, at lower driving pressures. The peak occurs at lower pressures because, as the protrusion is decreased, the expansion fan reaches the tip at lower pressures.



| NOZZLE<br>NAME | SYMBOL | PROTRUSION<br>MM |
|----------------|--------|------------------|
| IN3/WM2        | ⊙      | 4.90             |
| IN2/WM2        | △      | 4.90             |

**FIGURE 5.26**

The change in suction, associated with the separated flow, observed in the 4.9 mm case, is not seen here. This may be due to the fact that a simple shock reflection is impossible and a Mach reflection is occurring. When this occurs the oblique shock turns so that it meets the wall at right angles.

#### COMPARISON OF SUCTION DEVELOPED WITH AIR AND ARGON

Figure 5.26 shows the difference in the suction profile obtained in IN3/WM2 using argon and air. The pattern achieved with argon shows the same characteristics as that for air but at higher pressures. This would be expected as the specific heat ratio is different for argon being 1.67 as compared to 1.4 for air. For example: the position at which the first shock wave reflects, will occur at a given pressure when the gas constant is 1.67 (monatomic gas), and occur at a lower pressure when the gas constant is 1.4 (diatomic gas).

## CHAPTER SIX

### WAX ATOMIZATIONS

## 6.0 INTRODUCTION

In order to investigate the behaviour of the atomization nozzles wax atomizations were carried out.

The experimental program consisted of two parts, the investigation of the effect of processing parameters and the investigation of the effect of nozzle design, and this structure is reflected in the chapter.

The processing parameters were investigated by looking at the effect of the mass flow rate of wax, the mass flow rate ratio, the driving pressure and wax viscosity and temperature.

The nozzle design was investigated by examining the effect of the flow tube protrusion, the Mach number i.e. the angle of divergence of the diverging portion of the nozzle, rundown i.e. the mode of contact between liquid and gas and the liquid flow tube diameter.

The effect of processing parameters is discussed first.

## 6.1 THE EFFECT OF THE FLOW RATE OF WAX ON PARTICLE SIZE

In order to investigate the effect of the wax flow rate a series of atomizations were carried out on IN3/WM2. All runs were carried out at 11.0 bars driving pressure and 4.9 mm protrusion. The wax flow rate was varied between 333.3 and 1000.0 cm<sup>3</sup>/min. The results (Table 6.1.1) are shown in Figure 6.1.1, a plot of particle size (SMD and VMD) versus wax flow rate. From this it is possible to see that there was a considerable decrease in particle size produced as the wax flow rate was decreased from 1000cm<sup>3</sup>/min to 333cm<sup>3</sup>/min. At wax flowrates below 500 cm<sup>3</sup>/min the rate at which the particle size decreases falls and there is a slight tendency for the particle size to increase.

The wax flow rate can be examined in terms of the effect it has on the wax film thickness, velocity decay in the jet and heat transfer between the wax droplet and atomizing gas.

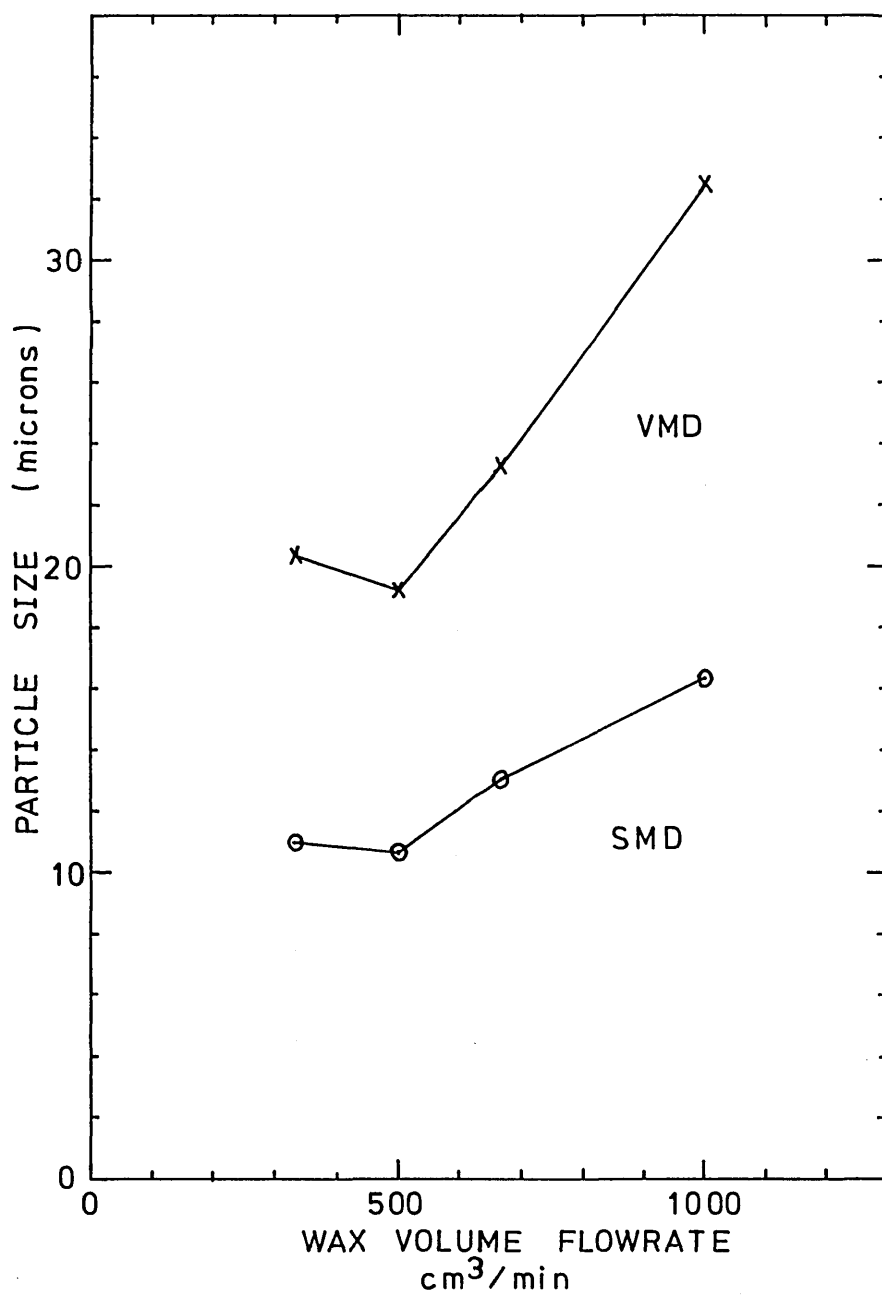


FIGURE 6.1.1  
PARTICLE SIZE VERSUS WAX FLOWRATE

TABLE 6.1.1

VARIATION OF PARTICLE SIZE WITH WAX FLOW RATE

| RUN<br>NUMBER | WAX<br>FLOWRATE<br>cm <sup>3</sup> /min | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER |
|---------------|-----------------------------------------|----------------|----------------|----------------|------------------|
| 46A           | 1000.0                                  | 16.22          | 30.69          | 33.82          | 1.72             |
| 46B           | 1000.0                                  | 16.20          | 33.27          | 35.90          | 1.63             |
| 46C           | 1000.0                                  | 16.61          | 33.63          | 35.24          | 1.69             |
| 47A           | 666.6                                   | 13.59          | 23.93          | 27.71          | 1.77             |
| 47B           | 666.6                                   | 12.95          | 22.76          | 26.21          | 1.76             |
| 47C           | 666.6                                   | 12.53          | 23.18          | 26.71          | 1.68             |
| 48A           | 500.0                                   | 11.89          | 22.41          | 25.54          | 1.66             |
| 48B           | 500.0                                   | 11.07          | 20.42          | 20.68          | 1.84             |
| 48C           | 500.0                                   | 10.53          | 20.37          | 23.41          | 1.61             |
| 53            | 333.3                                   | 10.72          | 20.06          | 23.11          | 1.65             |
| 53.1          | 333.3                                   | 10.92          | 17.99          | 21.33          | 1.82             |
| 53.2          | 333.3                                   | 8.92           | 14.22          | 17.20          | 1.70             |
| 49A           | 333.3                                   | 10.71          | 21.86          | 24.52          | 1.58             |
| 49B           | 333.3                                   | 12.26          | 20.95          | 24.85          | 1.81             |
| 49C           | 333.3                                   | 10.00          | 18.32          | 21.47          | 1.67             |

(Letters after a run number show repeat size tests on the same run)  
(numbers after a run number show repeat atomization runs)

### Wax Film Thickness

As the wax flow rate increases, the wax film on the top of the flow tube gets thicker. Gretzinger and Marshall<sup>(23)</sup> estimated the film thickness,  $t$ , at the perimeter of the protrusion where the gas meets the wax, by using the following equation:

$$t = [ (3\mu_1 \dot{m}_1) / (\rho_1^2 g \pi D) ]^{1/3} \quad (6.1)$$

Where:

$\mu_1$  = dynamic viscosity Pa.s

$\rho_1$  = liquid density kg/m<sup>3</sup>

$D$  = diameter of flow tube, m

$\dot{m}$  = mass flow rate wax kg/s

$g$  = gravitational acceleration m/s<sup>2</sup>

In IN3/WM2  $D = 10$  mm,  $\rho_1 = 770$  kg/m<sup>3</sup>,  $\mu_1 = 0.01176$  Pa.s. These figures give a film thickness of 1.07 mm for a wax flow rate of 500 cm<sup>3</sup>/min and a film thickness of 1.55 mm for a wax flow rate of 1500 cm<sup>3</sup>/min. The average radial velocity,  $V_r$ , of the wax at the perimeter of the flow tube can easily be calculated when the film thickness is known using:

$$V_r = [\dot{m}_1 / (\rho_1 \pi D t)]$$

which gives a radial velocity of 0.25 m/sec with a wax flow rate of 500 cm<sup>3</sup>/min.

These figures can be used to give useful order of magnitude estimates for film thickness and radial velocity. Thus an increase in the wax flow rate will cause an increase in the film thickness and an increase in the average particle size. This is likely to be a result of the thicker film of wax causing the average particle size at the end of primary break up to be larger. In extreme cases, the film may break up only incompletely, in the primary break up stage, and small sheets of wax may be produced instead of droplets. These are likely to break up into ligaments and then drops in flight as described by Dombrowski<sup>(25)</sup>.

Using Bernoulli's Equation,  $dP/\rho_1 + dV^2/2 + hg = 0$ , the height,  $h$ , above the centre of the liquid flow tube which the wax would travel without recirculating gas flow, can be determined. The term  $dP/\rho_1$  is zero. The velocity of the exiting liquid, given the

flow tube bore,  $D_1$ , is 4.0 mm can be calculated for a wax volume flow of  $500\text{cm}^3/\text{min}$  to be 0.66 m/s thus:

$$h = V^2/2g = 22.4 \text{ mm}$$

This shows the importance of the recirculating gas flow on filming and may explain why Thompson<sup>(9)</sup> who atomized up to a rate of 3.5 kg/min of aluminium ( $h = 150 \text{ mm}$ ), in a similar nozzle, observed "fountaining".

#### Velocity Decay of Jet

The wax flow rate will also affect the rate at which the jet velocity decays. It has been found that in subsonic round jets the velocity of the jet decays more quickly when it has to entrain a fluid denser than itself<sup>(49)</sup>. Thus increasing wax flow rate is likely to cause an increase in the rate of velocity decay resulting in a shorter secondary break up period. Also as the rate of velocity decay increases the relative velocity between the gas and particle decreases more quickly which means that stable droplet sizes, a given height above the nozzle, will be larger.

#### Heat Transfer between Atomizing Gas and Wax Droplet

Heat transfer between the atomizing gas and the wax is likely to be important especially when the wax flow rate is low or when the superheating of the wax is low, as this will allow the wax to solidify prematurely causing incomplete secondary break up and therefore coarser particles. As mentioned earlier, at low wax flowrates (below  $500 \text{ cm}^3/\text{min}$ ) the particle size produced is beginning to coarsen. Some of the coarsening is caused by the particles changing from a spherical shape to a more elongated shape as a result of premature solidification. This is shown in Figure 6.1.2, a photograph of wax powder from run 49 (see table 6.1.1), where it is possible to see elongated particles. Other powder samples, taken from runs with higher wax flowrates, showed that the powder produced was spherical.

In atomizations where the wax flow rate is very low, and the pressure is low, wax solidifies at the tip of the protrusion and builds up around the rim as schematically shown in Figure 6.1.3. This would cause extreme cooling of wax. This is because hot wax,

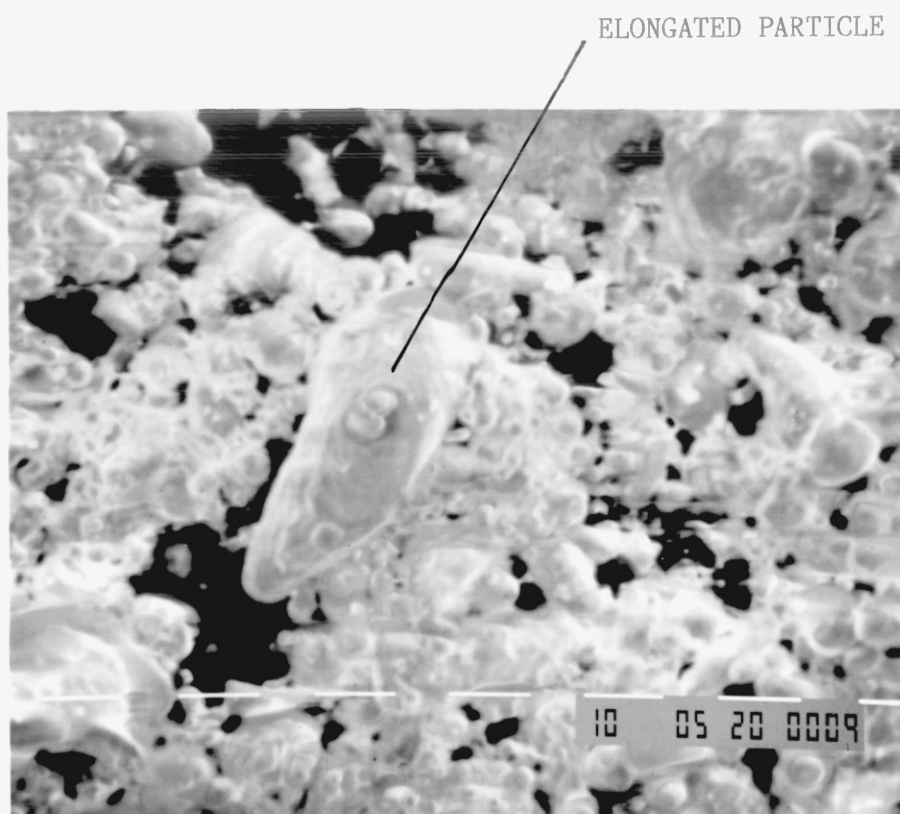


FIGURE 6.1.2

SEM PHOTOGRAPH OF RUN 49  
SHOWING ELONGATED PARTICLE

exiting from the top of the flow tube contacts cold wax and so cools before it meets the atomizing gas. This build up was not observed at higher wax flowrates. The build up therefore causes solidification of the wax to take place even sooner than in the case where there is no build up on the rim of the tip.

Thus the coarsening of particle size with increasing wax flow rate is caused by:

(1) the increased particle size in primary break up requiring longer to complete secondary break up

(2) faster velocity decay resulting in secondary break<sup>up</sup> occurring over a shorter period of time

(3) and stable droplet size being larger, a given height above the nozzle, as a result of decreasing relative velocity.

Therefore it is the coarser fraction of powder produced which is affected more by an increase in the wax flow rate and not the finer fraction. This is confirmed by the results. By comparing the SMD and VMD plots in figure 6.1.1, above 500 cm<sup>3</sup>/min, it can be seen that the VMD particle size is coarsening more quickly than the SMD particle size with increasing wax flow rate. As VMD is more sensitive to an increase in large particles this indicates that the proportion of coarse particles is increasing and that the explanation for coarser particles is consistent with the results.

Figure 6.1.1 shows that coarsening of wax powder can occur both above and below, a given mass flow rate of wax. Thus there is a region where there is little change in the size of powder produced despite an increase in the wax flow rate. If the experiments had only been carried out in the area of this minimum, in Figure 6.1.1 500 cm<sup>3</sup>/min +/- 100 cm<sup>3</sup>/min, the conclusions drawn from the experiments may well have been misleading. For example if the minimum, for a particular nozzle, extended over a wider range of wax flow rates, for example +/- 300 cm<sup>3</sup>/min, and the experiments were carried out in the region of the minimum then examination of the results would probably conclude that there was no effect of wax flow rate on size; an incorrect conclusion.

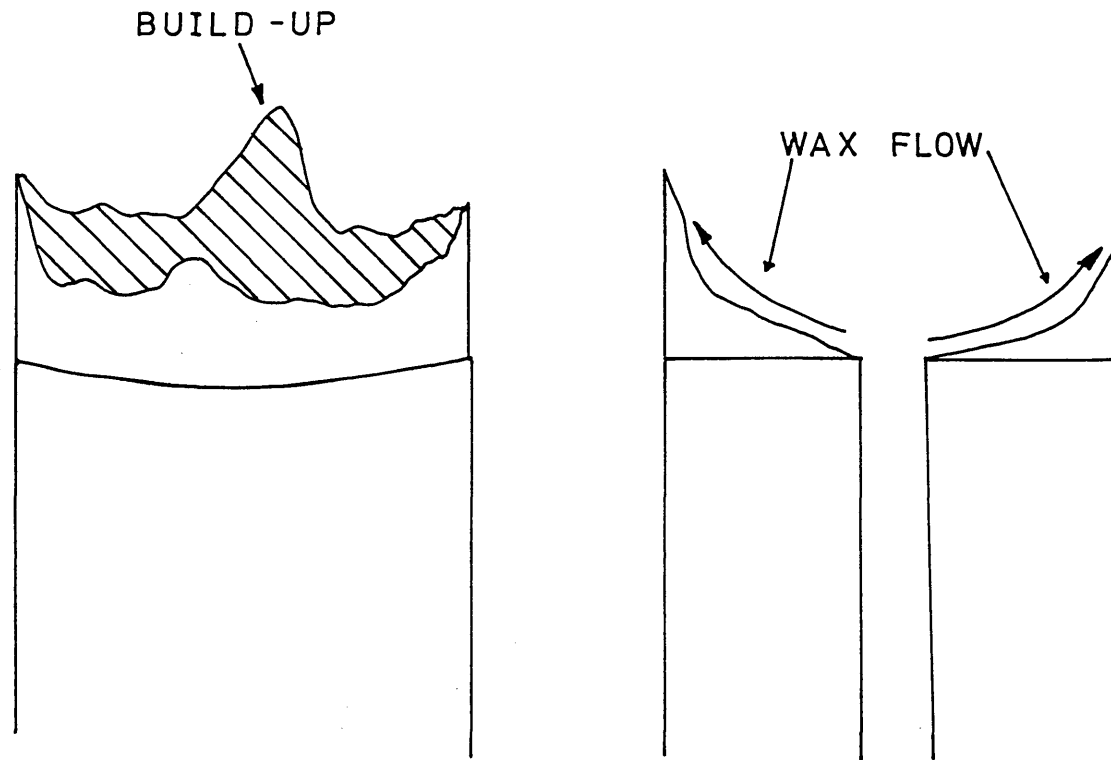


FIGURE 6.1.3  
WAX BUILD-UP ON FLOW TUBE TOP

There appears to be no correlation between the Rosin Rammler distribution parameter and the wax flow rate. A correlation would be expected as we have earlier shown that the VMD increases more quickly than SMD as the wax flowrate is increased. Thus it would be expected that a change in the distribution parameter would occur.

## 6.2 THE EFFECT OF THE MASS FLOW RATE RATIO ON PARTICLE SIZE.

The mass flow rate ratio,  $\dot{m}_g/\dot{m}_l$  is the ratio of gas mass flow rate,  $\dot{m}_g$ , to liquid mass flow rate,  $\dot{m}_l$ . This dimensionless variable defines the feed conditions for the nozzle.

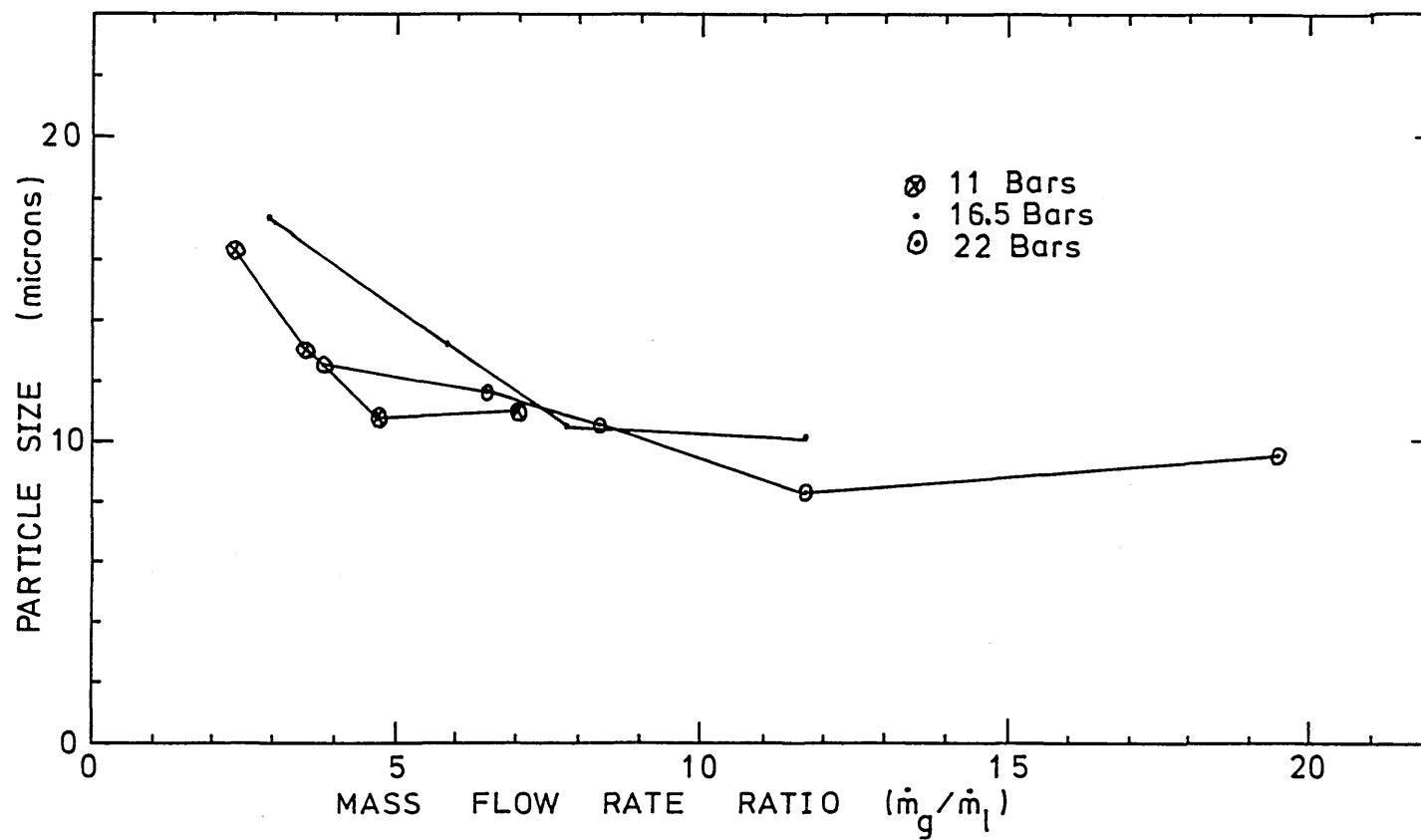
By calculating the mass flow rate ratio for atomizations carried out under similar conditions, using IN3/WM2 (see Table 6.2.1), the relationship between the mass flow rate ratio and the particle size (SMD) can be plotted as shown in Figure 6.2.1. The plot shows the effect of the mass flow rate ratio at driving pressures of 11.0, 16.5, 22.0 bars(a) [Note: this plot shows that the driving pressure seems to have no effect on the particle size].

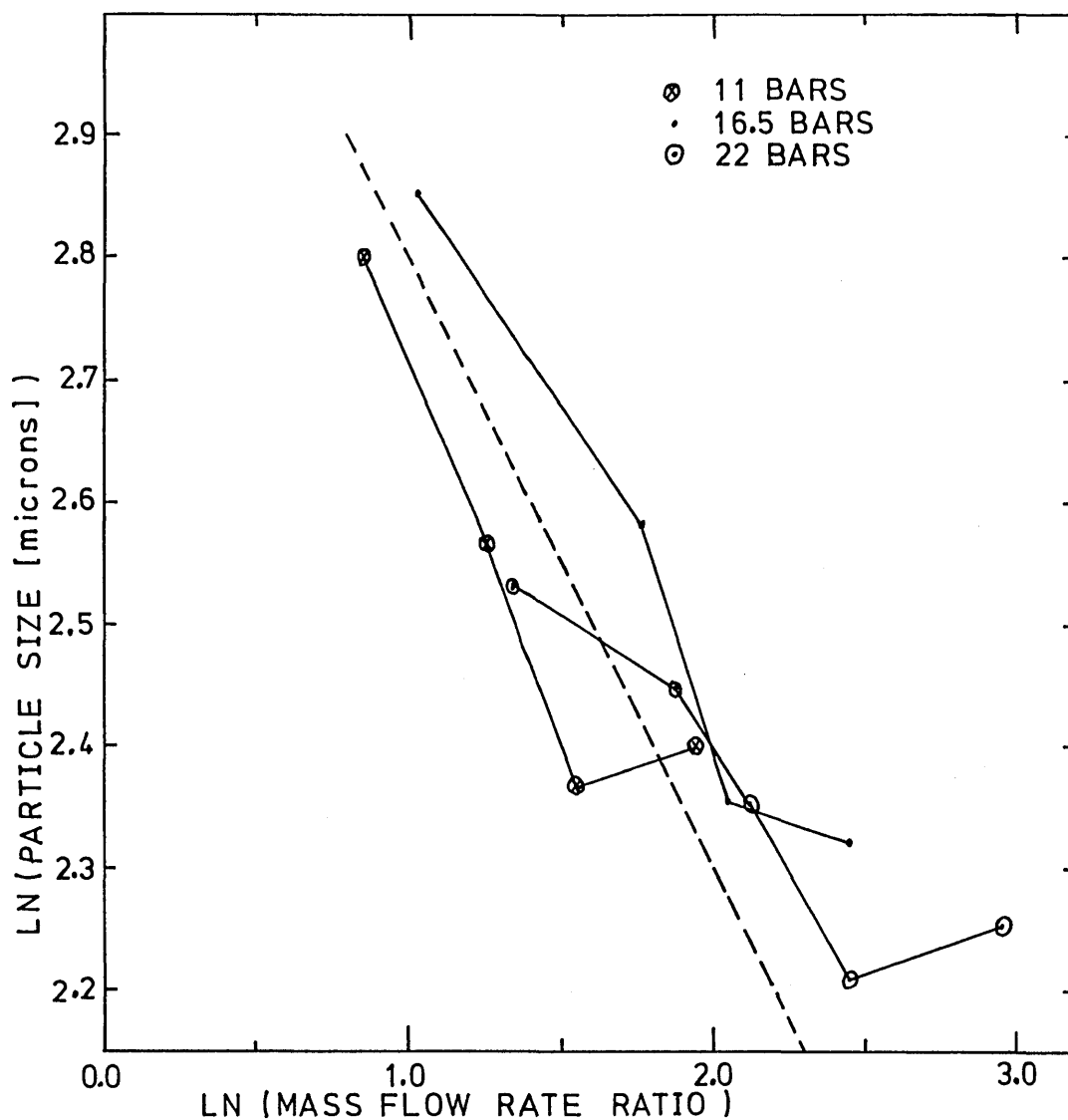
The effect of mass flow rate ratio is one of the dimensionless groups investigated by Lubanska<sup>(34)</sup> and Kim and Marshall<sup>(19)</sup>. They both found that the particle size was proportional to the [mass flow rate ratio]<sup>-0.5</sup>.

The correlation between the mass flow rate ratio and particle size can be estimated from figure 6.2.2 which shows a plot of  $\ln[\text{mass flow rate ratio}]$  versus  $\ln[\text{particle size (SMD)}]$ . There is some scatter in the data which makes it difficult to estimate the slope of the plot. The line drawn in the plot as an estimate of the correlation, has a slope of -0.5 corresponding to Lubanska's correlation:  $[\text{mass flow rate ratio}]^{-0.5}$  is proportional to the particle size. However although this value is only an estimate it seems likely that the relationships found by Lubanska and Kim and Marshall between mass flow rate ratio and particle size are correct.

FIGURE 6.2.1

EFFECT OF MASS FLOW RATE RATIO ON SIZE





EFFECT OF MASS FLOW RATE RATIO ON SIZE

FIGURE 6.2.2

**TABLE 6.2.1**

**MASS FLOW RATE RATIO AND PARTICLE SIZE DATA**

| RUN<br>NUMBER | $\dot{m}_g/\dot{m}_l$ | SMD<br>microns | VMD<br>microns | PRESSURE<br>bars(a) | $\dot{m}_l \times 10^2$<br>kg/sec | $\ln$<br>$\dot{m}_g/\dot{m}_l$ | $\ln$<br>SMD | $\ln$<br>VMD |
|---------------|-----------------------|----------------|----------------|---------------------|-----------------------------------|--------------------------------|--------------|--------------|
| 46            | 2.34                  | 16.34*         | 32.53*         | 11.0                | 1.280                             | 0.8502                         | 2.794        | 3.482        |
| 64            | 2.92                  | 17.32          | 36.80          | 16.5                | 1.710                             | 1.0716                         | 2.852        | 3.605        |
| 47            | 3.51                  | 13.02*         | 23.29*         | 11.0                | 0.856                             | 1.2556                         | 2.566        | 3.148        |
| 86            | 4.52                  | 12.57          | 20.17          | 22.0                | 1.660                             | 1.5085                         | 2.531        | 3.004        |
| 48,53         | 4.68                  | 10.68*         | 19.25*         | 11.0                | 0.642*                            | 1.5433                         | 2.368        | 2.958        |
| 62            | 5.84                  | 13.24          | 22.62          | 16.5                | 0.856                             | 1.7647                         | 2.583        | 3.119        |
| 110           | 6.49                  | 11.57          | 19.61          | 22.0                | 0.773*                            | 1.8703                         | 2.448        | 2.976        |
| 49            | 7.01                  | 10.99*         | 20.38*         | 11.0                | 0.428                             | 1.9473                         | 2.397        | 3.015        |
| 54            | 7.79                  | 10.54*         | 19.93*         | 16.5                | 0.642                             | 2.0528                         | 2.355        | 2.992        |
| 109           | 8.35                  | 10.52          | 19.46          | 22.0                | 0.642                             | 2.1223                         | 2.353        | 2.968        |
| 108           | 11.69                 | 9.14           | 14.98          | 22.0                | 0.535                             | 2.4587                         | 2.213        | 2.707        |
| 61            | 11.69                 | 10.17          | 17.86          | 16.5                | 0.535                             | 2.4587                         | 2.319        | 2.883        |
| 107           | 19.48                 | 9.52           | 16.18          | 22.0                | 0.385                             | 2.9694                         | 2.253        | 2.784        |

\* ---- AVERAGE VALUE

### 6.3 EFFECT OF DRIVING PRESSURE ON PARTICLE SIZE.

The effect of driving pressure was investigated in IN3/WM2, with 4.9 mm protrusion. The driving pressure was varied between 7.0 and 21.0 bars. The mass flow rate ratio  $\dot{m}_g/\dot{m}_l$  was kept constant. Figure 6.3.1 shows a plot of the results (table 6.3.1) and from this it can be seen that particle size (SMD) is independent of driving pressure. Indirectly the work on mass flowrate ratio and the work on the differences between IN3/WM2 and IN3/WM3 support this. Figure 6.2.1 illustrates the atomizations carried out at driving pressures between 11.0 and 22.0 bars where there is no appreciable difference between the particle size that can be distinguished. Figure 6.7.3 illustrates the atomizations for IN3/WM3 and IN3/WM2. From this it can be seen that pressure has very little effect on the particle size of wax produced. Both these sets of atomizations also show that particle size is independent of driving pressure.

This contradicts the work carried out by Small and Bruce<sup>(12)</sup>, Lawley<sup>(24)</sup> as well as the findings of Dixon's<sup>(20)</sup> review of atomization. They all report that an increase in the driving pressure results in a decrease in the particle size. It is likely however, that in all cases, the effect of driving pressure noted is a result of the inability of the experimenter to keep the mass flow rate ratio constant, therefore eliminating the influence of the mass flow rate of gas and liquid. Thompson<sup>(9)</sup> inadvertently came to the same conclusions as in this project, i.e. pressure has no effect on particle size, because in his experiments the mass flow rate of liquid increases as the pressure increases. This probably resulted in a constant mass flow rate ratio and so eliminated the effect of gas and liquid mass flow rates.

From Figure 6.3.1 finer powder is produced at 9.0 and 11.5 bars. Section 6.6 will show that if an expansion fan exists at the tip of the flow tube protrusion finer powders are produced.

FIGURE 6.3.1

EFFECT OF DRIVING PRESSURE  
IN3 / WM2

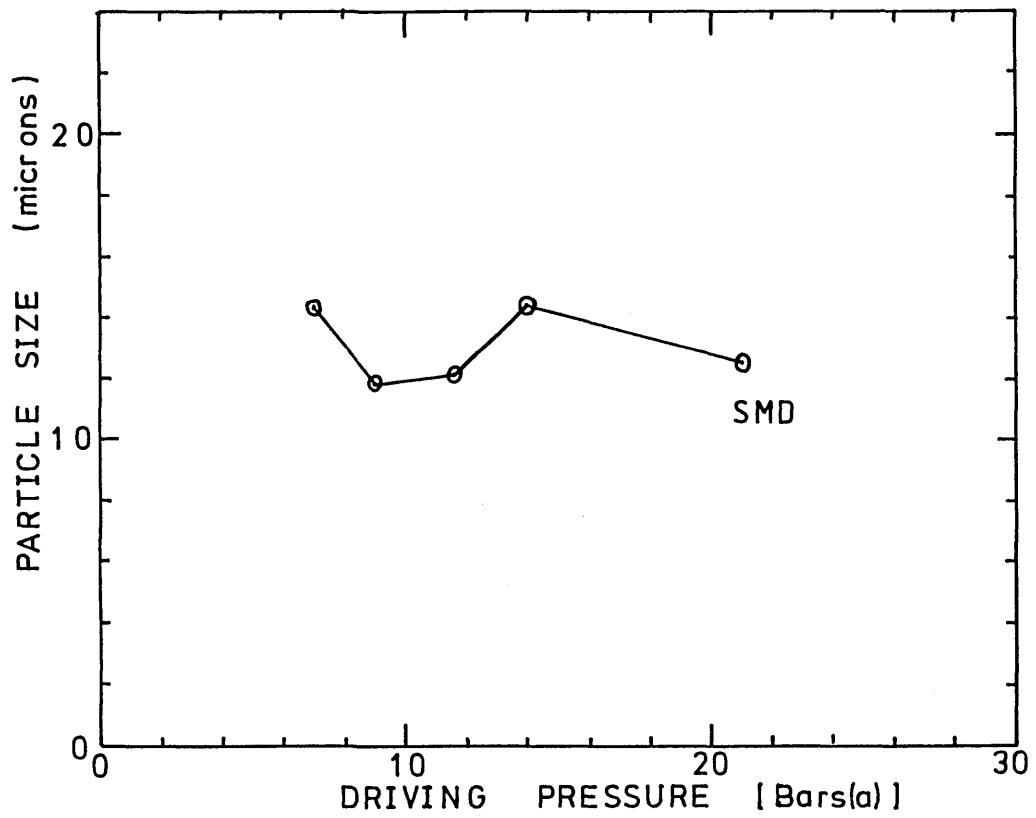


TABLE 6.3.1

VARIATION OF PARTICLE SIZE WITH DRIVING PRESSURE

| RUN<br>NUMBER | WAX<br>FLOWRATE<br>cm <sup>3</sup> /min | DRIVING<br>PRESSURE<br>bars(a) | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER | RR<br>VARIANCE |
|---------------|-----------------------------------------|--------------------------------|----------------|----------------|----------------|------------------|----------------|
| 82            | 333.3                                   | 7.0                            | 14.32          | 24.06          | 27.86          | 1.85             | 4.03           |
| 83            | 458.3                                   | 9.0                            | 11.90          | 18.99          | 22.48          | 1.89             | 2.77           |
| 84            | 625.0                                   | 11.5                           | 12.18          | 21.77          | 25.41          | 1.74             | 7.79           |
| 85            | 833.3                                   | 14.0                           | 14.46          | 24.06          | 28.16          | 1.85             | 5.90           |
| 86            | 1291.7                                  | 21.0                           | 12.57          | 20.17          | 23.73          | 1.88             | 3.08           |

Between 9.0 and 11.5 bars driving pressure, in IN3/WM2, the expansion fan is at the tip of the flow tube and so it would be expected that the particles produced at this pressure would be finer.

#### 6.4 THE EFFECT OF VISCOSITY ON PARTICLE SIZE

In order to investigate the effect of viscosity on the particle size the composition of the wax was altered to change its viscosity. This was carried out by adding 10% and 20% by weight polyethelene. This caused the viscosity to increase without significantly changing the density and surface tension of the wax. Since the surface tension and density of the wax compositions were practically constant, the change in particle size which occurred was considered to be caused by the change in liquid wax viscosity alone.

The atomizations were carried out using IN3/WM2 at 11.0 bars(a) driving pressure and a flow tube protrusion of 4.9 mm. It can be seen from Figure 6.4.1 that an increase in viscosity causes a small increase in the atomized particle size. This is in agreement with literature<sup>(7,8,19)</sup>. Table 6.4.1 shows the results which were plotted. The method used for viscosity measurement is described in Appendix 8.

By plotting  $\ln$  [particle size] versus  $\ln$  [dynamic viscosity] it is simple to determine the correlation between size and dynamic viscosity.

Figure 6.4.2 shows a plot of  $\ln$  [MMD] versus  $\ln$  [dynamic viscosity]. The point plotted for Kerawax 508 uses the average particle size of runs 48 and 53. The slope of the plot is 0.36 and the 'y' intercept is 4.488. The straight line fit between the three points is good with a correlation coefficient of 0.9995. Thus particle size [MMD] is proportional to [dynamic viscosity ( $\text{mm}^2/\text{sec}$ )]<sup>0.36</sup>.

This agrees with the findings of Master's<sup>(8)</sup> review of atomization who found that  $n$  varied between 0.3 and 0.37 where  $[\mu_1]^n$  is proportional to particle size.

FIGURE 6.4.1

EFFECT OF VISCOSITY

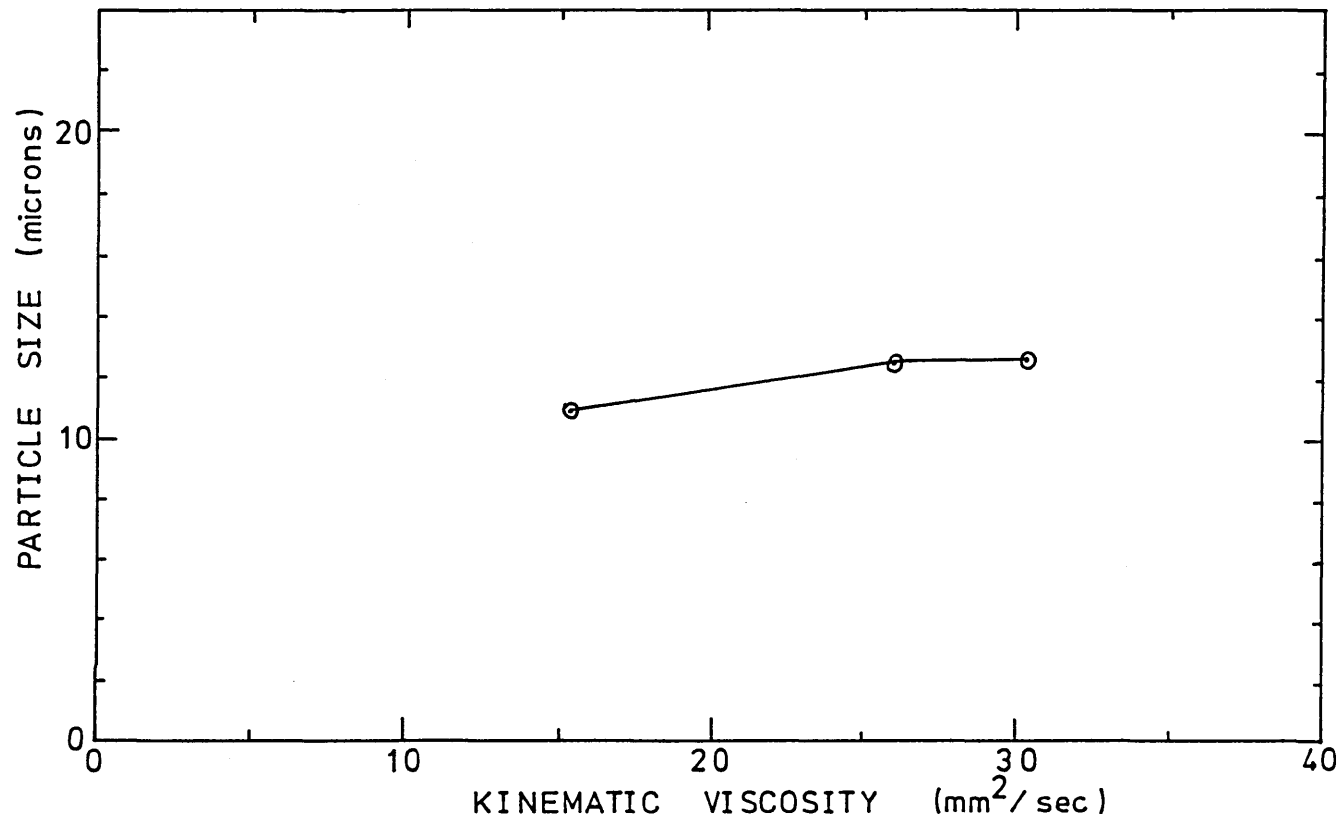


FIGURE 6.4.2  
EFFECT OF DYNAMIC VISCOSITY

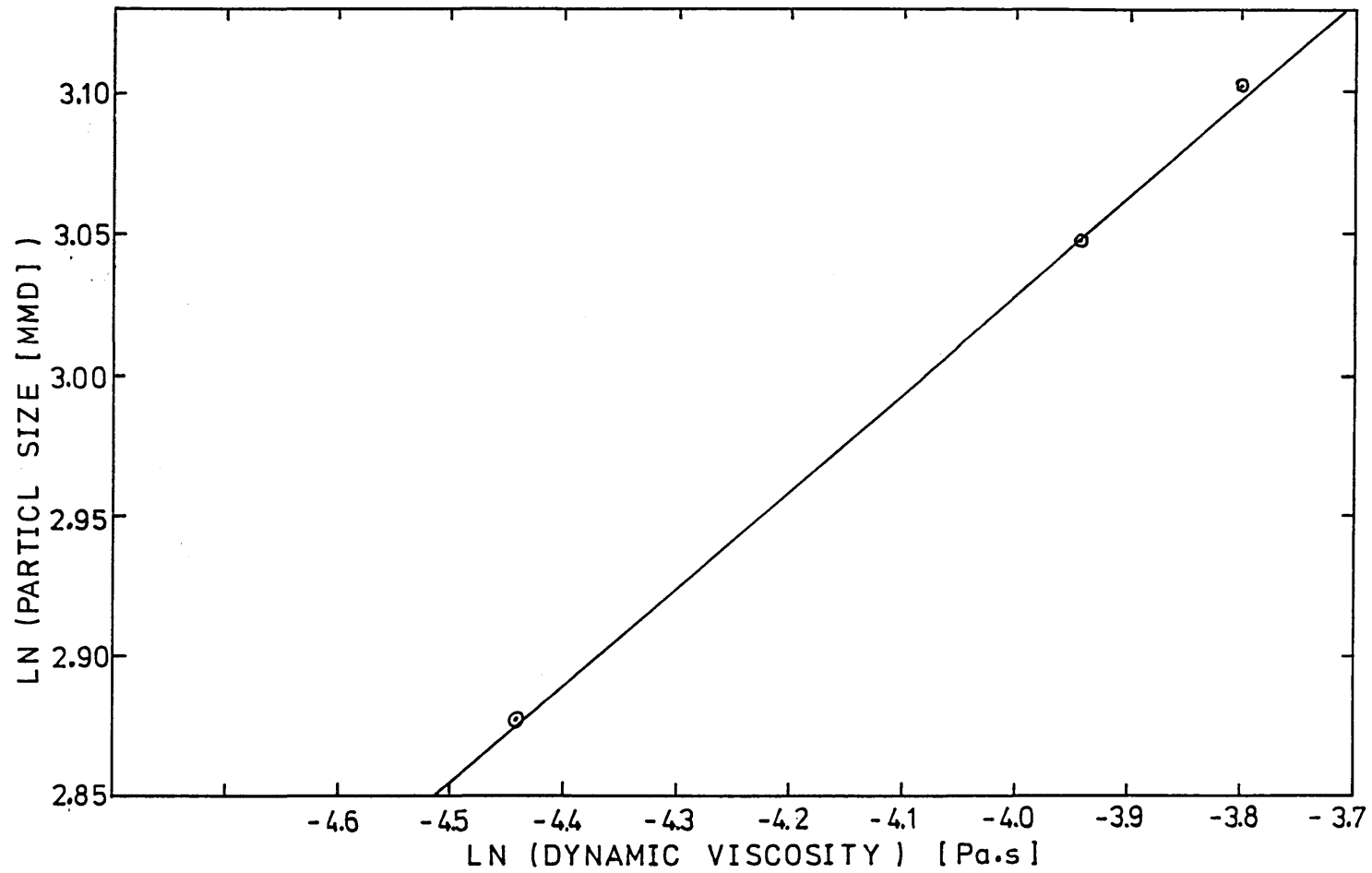


TABLE 6.4.1

VARIATION OF PARTICLE SIZE WITH WAX COMPOSITION

| RUN<br>NUMBER | WAX<br>COMPOSITION | SMD     | VMD     | MMD     | LN<br>SMD | LN<br>VMD | LN<br>MMD |
|---------------|--------------------|---------|---------|---------|-----------|-----------|-----------|
|               |                    | microns | microns | microns | microns   | microns   | microns   |
| 48*           | + 0%               | 11.16   | 21.07   | 18.70   | 2.412     | 3.048     | 2.929     |
| 53*           | + 0%               | 10.82   | 19.03   | 16.60   | 2.381     | 2.946     | 2.809     |
| 66A           | +10%               | 13.10   | 24.72   | 22.47   | 2.573     | 3.208     | 3.112     |
| 66B           | +10%               | 12.29   | 22.42   | 20.71   | 2.509     | 3.110     | 3.004     |
| 67A           | +10%               | 12.76   | 23.54   | 21.69   | 2.546     | 3.159     | 3.077     |
| 67B           | +10%               | 11.79   | 22.12   | 20.21   | 2.467     | 3.096     | 3.006     |
| 68A           | +20%               | 13.28   | 26.32   | 23.17   | 2.586     | 3.270     | 3.143     |
| 68B           | +20%               | 12.88   | 25.86   | 22.74   | 2.556     | 3.253     | 3.124     |
| 69A           | +20%               | 12.00   | 23.37   | 21.02   | 2.485     | 3.151     | 3.045     |
| 69B           | +20%               | 12.32   | 24.98   | 22.08   | 2.511     | 3.218     | 3.095     |

Notes

\* - data is average values of runs A, B and C

Wax compositions given as weight % Epolene N11 added to Kerawax 508

|                                           | <u>KERAWAX 508</u>      | <u>+10%</u>             | <u>+20%</u>             |
|-------------------------------------------|-------------------------|-------------------------|-------------------------|
| KINEMATIC VISCOSITY (m <sup>2</sup> /sec) | 15.28 x 10 <sup>6</sup> | 25.94 x 10 <sup>6</sup> | 30.20 x 10 <sup>6</sup> |
| DENSITY (kg/m <sup>3</sup> )              | 770                     | 747                     | 741                     |

## 6.5 THE EFFECT OF TEMPERATURE ON PARTICLE SIZE.

To investigate the effect of temperature on particle size a series of atomizations were carried out using IN3/WM2, with a wax flow rate of  $500 \text{ cm}^3/\text{min}$ , 11.0 bars(a) driving pressure and 4.9 mm protrusion. The temperature was varied between  $140^\circ\text{C}$  and  $180^\circ\text{C}$  and was found to have a noticeable effect on particle size.

Figure 6.5.1 shows a plot of the results (Table 6.5.1) obtained. It can be seen that the particles formed are much coarser at lower temperatures.

The variation in particle size with temperature may be the result of two separate factors. One the variation of liquid properties with temperature and the other premature solidification.

Cooling of the wax will cause an increase in the viscosity of the wax. This in turn will increase the film thickness (see equation 6.1) and so result in coarser particles in primary break up. This agrees with the work of Johnson and See<sup>(10)</sup> who found an increase in the proportion of ligaments increased at low temperatures indicating incomplete primary break-up. The secondary break up is likely to be affected as well with premature solidification of the wax occurring in flight, so resulting in incomplete break-up of the wax, and a sharp increase in the powder particle size.

It was also found that the atomizations carried out at low temperatures were subject to blockages in the wax flow tube. This was never the case when atomizing at  $180^\circ\text{C}$  and due to premature solidification of the wax in the flowtube. The effect of temperature variation on powder particle size seems to be very small at  $180^\circ\text{C}$  and so this temperature was chosen for all the atomization runs carried out in this project.

FIGURE 6.5.1

EFFECT OF TEMPERATURE

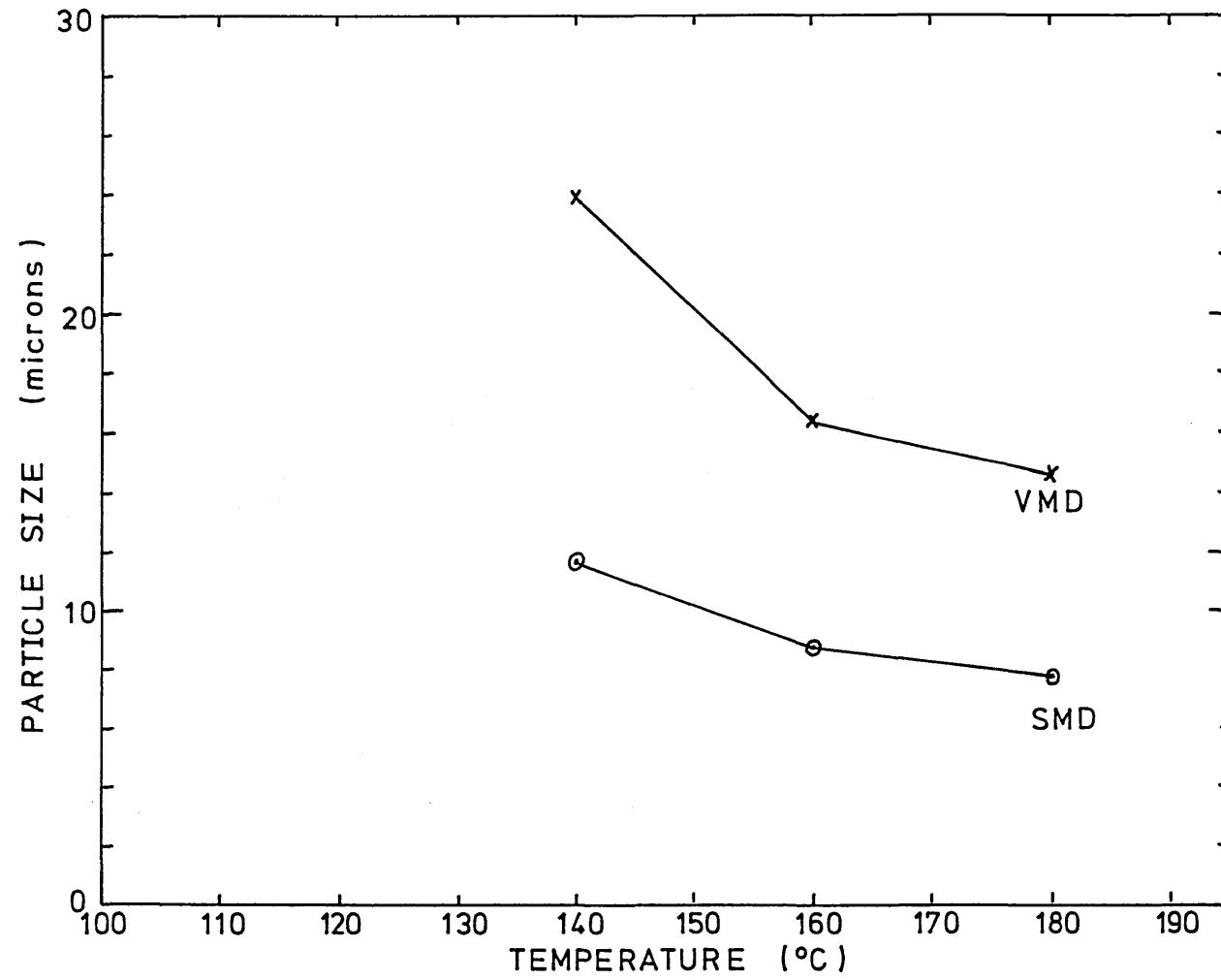


TABLE 6.5.1

VARIATION OF PARTICLE SIZE WITH TEMPERATURE

| RUN<br>NUMBER | TEMPERATURE<br><br>°C | SMD<br><br>microns | VMD<br><br>microns | RRM<br><br>microns | RRD<br>PARAMETER | RR<br>VARIANCE |
|---------------|-----------------------|--------------------|--------------------|--------------------|------------------|----------------|
| 75A           | 180.0                 | 9.10               | 16.42              | 17.58              | 1.80             | 3.49           |
| 75B           | 180.0                 | 7.99               | 15.32              | 17.66              | 1.58             | 1.29           |
| 76B           | 180.0                 | 6.89               | 13.39              | 14.43              | 1.66             | 1.72           |
| 76C           | 180.0                 | 6.81               | 13.03              | 13.12              | 1.80             | 3.89           |
| 77A           | 160.0                 | 8.57               | 15.03              | 18.10              | 1.67             | 2.88           |
| 77B           | 160.0                 | 7.74               | 14.53              | 15.73              | 1.72             | 2.55           |
| 77C           | 160.0                 | 7.68               | 14.50              | 17.08              | 1.58             | 2.00           |
| 78A           | 160.0                 | 9.90               | 18.67              | 21.63              | 1.63             | 2.43           |
| 78B           | 160.0                 | 9.55               | 18.44              | 20.76              | 1.63             | 0.53           |
| 78C           | 160.0                 | 8.83               | 17.00              | 19.33              | 1.61             | 0.78           |
| 79A           | 140.0                 | 13.35              | 26.24              | 29.11              | 1.65             | 5.46           |
| 79B           | 140.0                 | 12.66              | 26.30              | 28.78              | 1.59             | 5.19           |
| 79C           | 140.0                 | 11.21              | 22.70              | 25.35              | 1.59             | 1.92           |
| 80A           | 140.0                 | 11.70              | 26.08              | 27.89              | 1.52             | 6.35           |
| 80B           | 140.0                 | 10.45              | 21.50              | 23.93              | 1.56             | 1.21           |
| 80C           | 140.0                 | 10.32              | 21.62              | 23.95              | 1.54             | 1.03           |
| 81A           | 140.0                 | 11.85              | 22.67              | 25.51              | 1.65             | 1.49           |
| 81B           | 140.0                 | 12.20              | 26.67              | 28.80              | 1.54             | 4.59           |
| 81C           | 140.0                 | 10.93              | 21.23              | 23.81              | 1.63             | 1.01           |

## 6.6 EFFECT OF NOZZLE PROTRUSION ON PARTICLE SIZE

The protrusion of a liquid flow tube above the exit of an atomizing nozzle has been investigated by Thompson<sup>(9)</sup> and mentioned by Klar and Shafer<sup>(14)</sup>. Thompson concluded that altering the protrusion has no great effect on atomization and Klar and Shafer make no mention of the effect of protrusion on particle size.

In this project, in order to investigate the effect of flow tube protrusion, the wax flow rate was kept constant at  $500\text{cm}^3/\text{min}$  and the pressure at 11.0 bars. The results (Table 6.6.1) plotted in Figure 6.6.1, conclusively show that the flow tube protrusion has a very definite effect; a minimum in the particle size occurring for a protrusion between 5.0 mm and 6.5 mm.

The study carried out in Chapter 3 looked at the shock wave pattern along the flow tube protrusion for IN3/WM2 running, at 11.0 bars(a) driving pressure, in the overexpanded mode. The positions of the shock wave and expansion fan were illustrated in Figure 3.7. From this work it is possible to determine in which region of the shock wave pattern the minimum particle size occurred. The oblique shock wave formed at the nozzle exit reflects from the flow tube protrusion at 1.98 mm from the nozzle exit. The reflected oblique shock reflects from the free pressure boundary at a distance of 3.38 mm from the nozzle exit. Thus the tip of the flowtube is in the region of the expansion fan when the protrusion is 4.9mm. The expansion fan reflects from the flow tube protrusion at a distance of between 4.51 mm and 5.28 mm, from the nozzle exit. The Schlieren photography of IN3/WM2 running at 11.0 bars with a 4.9 mm protrusion, figure 5.2, shows a shock wave reflecting from the protrusion at approximately 2.00 mm and this agrees well with the calculations.

From the results and from the analysis of shock waves it can be concluded that the minimum powder size is associated with the expansion fan reflecting at the tip of the nozzle flow tube protrusion. The region is one of change, in pressure and gas flow direction, which combined with the turbulent flow which occurs downstream from the oblique shock will aid the primary break up

FIGURE 6.6.1

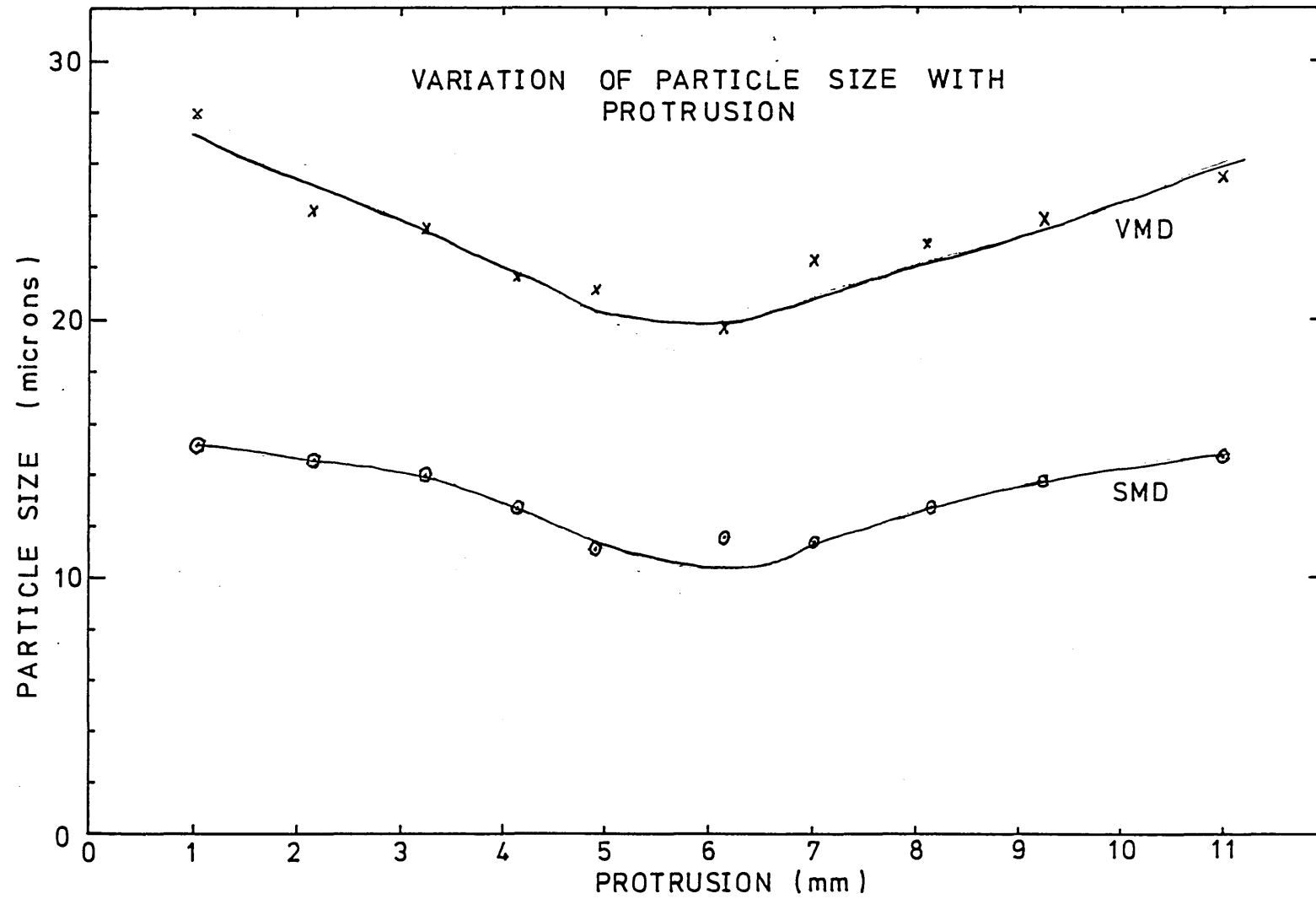


TABLE 6.6.1

VARIATION OF PARTICLE SIZE WITH PROTRUSION

| RUN<br>NUMBER | PROTRUSION<br>mm | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER | RR<br>VARIANCE |
|---------------|------------------|----------------|----------------|----------------|------------------|----------------|
| 92            | 1.04             | 15.07          | 27.96          | 30.97          | 1.76             | 6.18           |
| 91            | 2.16             | 14.58          | 24.12          | 28.15          | 1.86             | 4.69           |
| 90            | 3.25             | 14.00          | 23.43          | 27.30          | 1.83             | 3.84           |
| 89            | 4.14             | 12.66          | 21.52          | 25.39          | 1.78             | 5.42           |
| 48*           | 4.90             | 11.16          | 21.07          | 23.21          | 1.70             | 4.94           |
| 87            | 6.17             | 11.56          | 19.65          | 23.41          | 1.78             | 4.58           |
| 122.1         | 7.04             | 10.94          | 22.25          | 24.92          | 1.60             | 9.15           |
| 121.1         | 8.16             | 13.07          | 23.26          | 26.55          | 1.75             | 2.49           |
| 121.2         | 8.16             | 12.32          | 22.35          | 25.78          | 1.73             | 6.00           |
| 120.1         | 9.25             | 14.54          | 25.14          | 28.88          | 1.81             | 5.01           |
| 120.2         | 9.25             | 12.91          | 22.44          | 26.32          | 1.78             | 6.52           |
| 119.1         | 11.00            | 15.80          | 27.58          | 27.16          | 1.80             | 5.07           |
| 119.2         | 11.00            | 13.60          | 23.36          | 31.46          | 1.18             | 5.60           |

\* - data is average of runs A, B and C

of liquid resulting in a decreased particle size at the end of primary break up. Thus the average particle size will be lower as the stable particle size at the end of secondary break up will be smaller.

Given that the expansion fan reflection region has an effect on the particle size produced then when running in the overexpanded mode the flow tube protrusion should be decreased when running at lower pressures and increased when running at higher pressures so that the expansion fan reflects from the tip.

The same argument can be applied to the nozzle running in the underexpanded mode. In the underexpanded case the nozzle starts with an expansion fan and so for the reflection to be at the tip of the flow tube protrusion the protrusion should be considerably less than in the overexpanded case.

## 6.7 EFFECT OF MACH NUMBER ON PARTICLE SIZE

To enable the Mach number to be investigated three other nozzle inserts were used, as well as IN3/WM2. Their exit Mach numbers were 2.02 for IN3/WM4, 2.73 for IN3/WM5, and 1.00 for IN3/WM3 compared with an exit mach number of 2.51 for IN3/WM2.

The Mach number was the only variable changed as the throat areas of the nozzles were nearly identical (see Table 2.1 for the nozzle insert dimensions). The atomization tests were carried out at 11.0 bars(a) pressure and the wax flow rate was varied between 250 and 1000 cm<sup>3</sup>/min, for IN3/WM4 and IN3/WM5. IN3/WM3 was investigated separately.

The results (Table 6.7.1) plotted in Figure 6.7.1 show particle size (for all three supersonic nozzles) versus wax flow rate. From this it could be concluded that the Mach number seems to have little effect on particle size.

The convergent only nozzle (exit Mach number = 1), IN3/WM3, was compared to IN3/WM2. The atomization tests were carried out at 10.0 and 22.0 bars (a) with wax flow rates between 300.0 and 900 cm<sup>3</sup>/min. The results (Table 6.7.2) plotted in Figure 6.7.2 show that there is little difference in the particle size produced between the two nozzles.

FIGURE 6.7.1

EFFECT OF MACH NUMBER ON  
PARTICLE SIZE

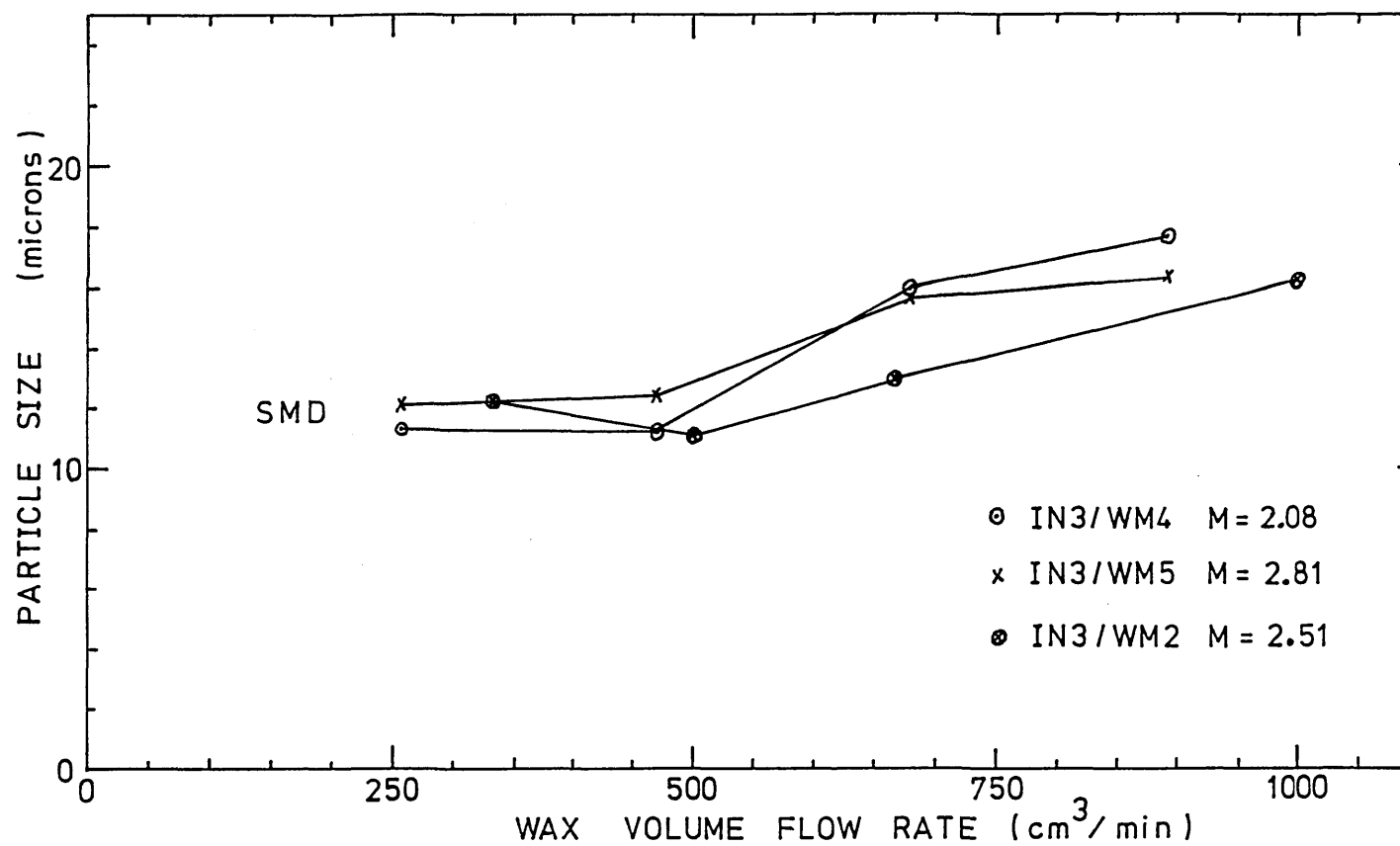


**TABLE 6.7.1**

**VARIATION OF PARTICLE SIZE WITH CONVERGENT ONLY NOZZLE**

| RUN<br>NUMBER                       | WAX<br>FLOWRATE<br>cm <sup>3</sup> /min | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER | RR<br>VARIANCE | $\dot{m}_g/\dot{m}_1$ |
|-------------------------------------|-----------------------------------------|----------------|----------------|----------------|------------------|----------------|-----------------------|
| <b><u>PRESSURE 10.0 BARS(A)</u></b> |                                         |                |                |                |                  |                |                       |
| <u>IN3/WM2 - MACH NO 2.51</u>       |                                         |                |                |                |                  |                |                       |
| 94                                  | 300.0                                   | 11.32          | 19.32          | 22.65          | 1.80             | 3.32           | 6.49                  |
| 95                                  | 500.0                                   | 14.13          | 24.31          | 28.17          | 1.80             | 4.41           | 3.90                  |
| 96                                  | 700.0                                   | 16.04          | 30.61          | 33.73          | 1.73             | 7.84           | 2.78                  |
| 97                                  | 700.0                                   | 14.78          | 26.54          | 30.12          | 1.77             | 5.19           | 2.78                  |
| 98                                  | 900.0                                   | 13.80          | 27.50          | 29.93          | 1.67             | 6.43           | 2.16                  |
| <u>IN3/WM3 - MACH NO 1.00</u>       |                                         |                |                |                |                  |                |                       |
| 99                                  | 900.0                                   | 13.77          | 23.39          | 27.36          | 1.80             | 5.50           | 2.81                  |
| 100                                 | 700.0                                   | 11.76          | 19.70          | 23.37          | 1.81             | 4.13           | 3.62                  |
| 101                                 | 500.0                                   | 12.50          | 22.60          | 26.37          | 1.72             | 6.97           | 5.06                  |
| 102                                 | 300.0                                   | 13.31          | 22.96          | 26.85          | 1.79             | 5.86           | 8.44                  |

**TABLE 6.7.1 (cont)**

| RUN<br>NUMBER                       | WAX<br>FLOWRATE<br>cm <sup>3</sup> /min | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER | RR<br>VARIANCE | $\dot{m}_g/\dot{m}_l$ |
|-------------------------------------|-----------------------------------------|----------------|----------------|----------------|------------------|----------------|-----------------------|
| <b><u>PRESSURE 22.0 BARS(A)</u></b> |                                         |                |                |                |                  |                |                       |
| <u>IN3/WM2 - MACH NO 2.51</u>       |                                         |                |                |                |                  |                |                       |
| 107                                 | 300.0                                   | 9.52           | 16.18          | 19.42          | 1.75             | 3.54           | 19.48                 |
| 108                                 | 500.0                                   | 9.14           | 14.98          | 16.83          | 1.91             | 1.74           | 11.69                 |
| 109                                 | 700.0                                   | 10.52          | 19.46          | 22.85          | 1.66             | 6.28           | 8.35                  |
| 110                                 | 900.0                                   | 11.57          | 19.61          | 23.39          | 1.77             | 4.57           | 6.49                  |
| <u>IN3/WM3 - MACH NO 1.00</u>       |                                         |                |                |                |                  |                |                       |
| 103                                 | 300.0                                   | 10.19          | 16.35          | 18.21          | 1.97             | 2.66           | 20.78                 |
| 104                                 | 500.0                                   | 10.32          | 17.06          | 18.74          | 1.93             | 3.68           | 12.47                 |
| 105                                 | 700.0                                   | 10.18          | 18.12          | 21.51          | 1.70             | 4.19           | 8.91                  |
| 106                                 | 900.0                                   | 10.84          | 17.33          | 20.96          | 1.85             | 4.20           | 6.93                  |

FIGURE 6.7.2

PARTICLE SIZE IN CONVERGENT AND CONVERGENT DIVERGENT  
NOZZLES

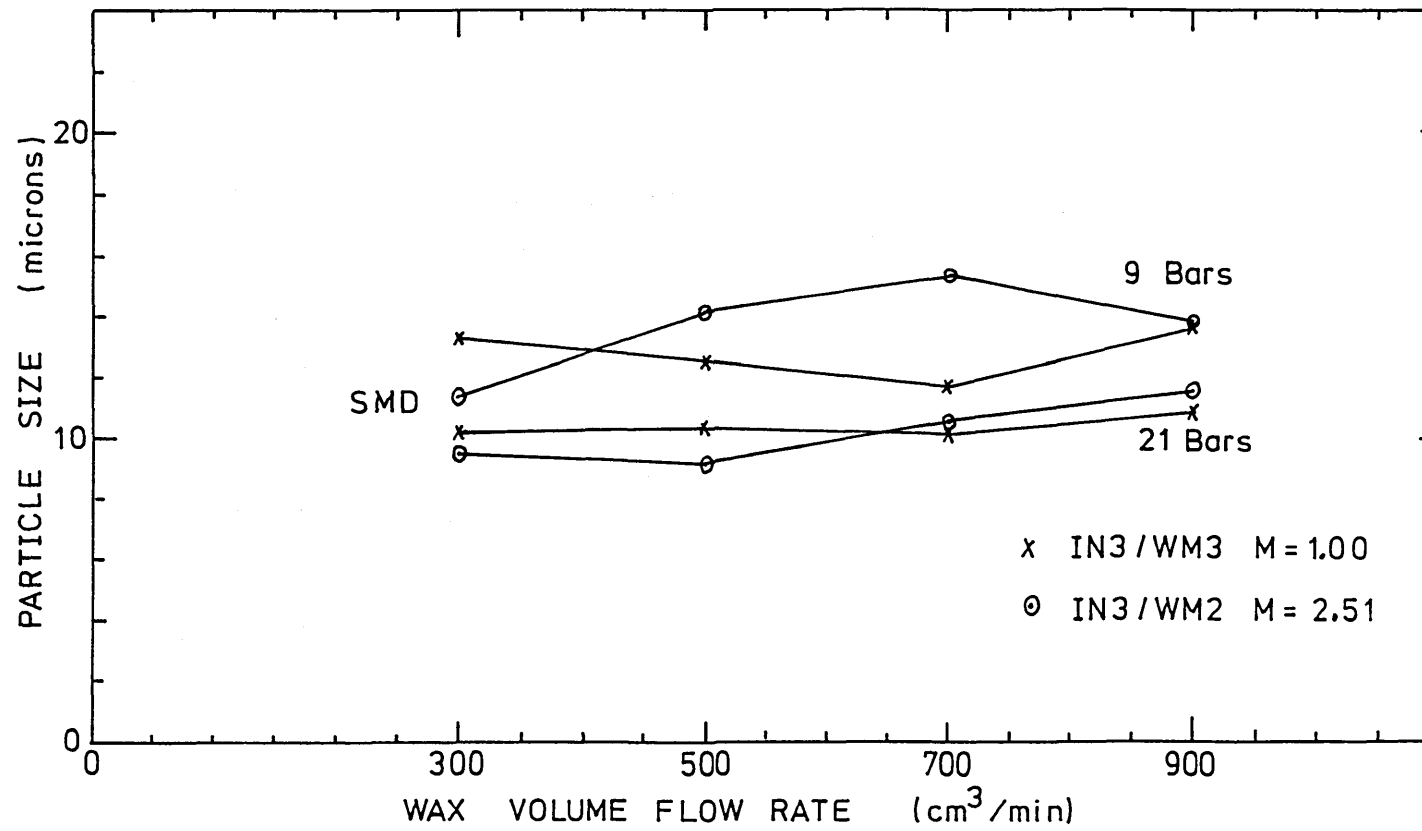


FIGURE 6.7.3

EFFECT OF MACH NUMBER ON PARTICLE SIZE

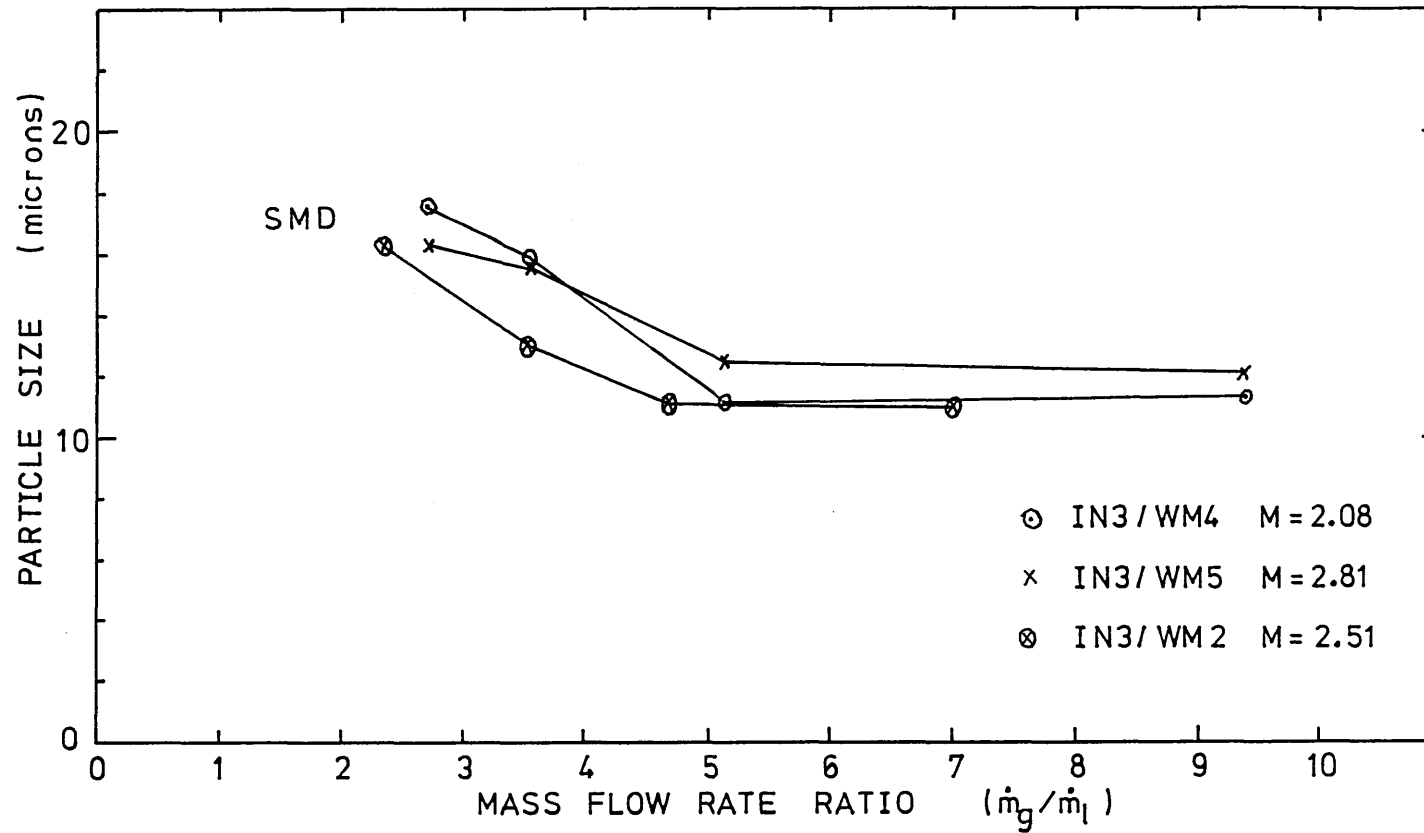


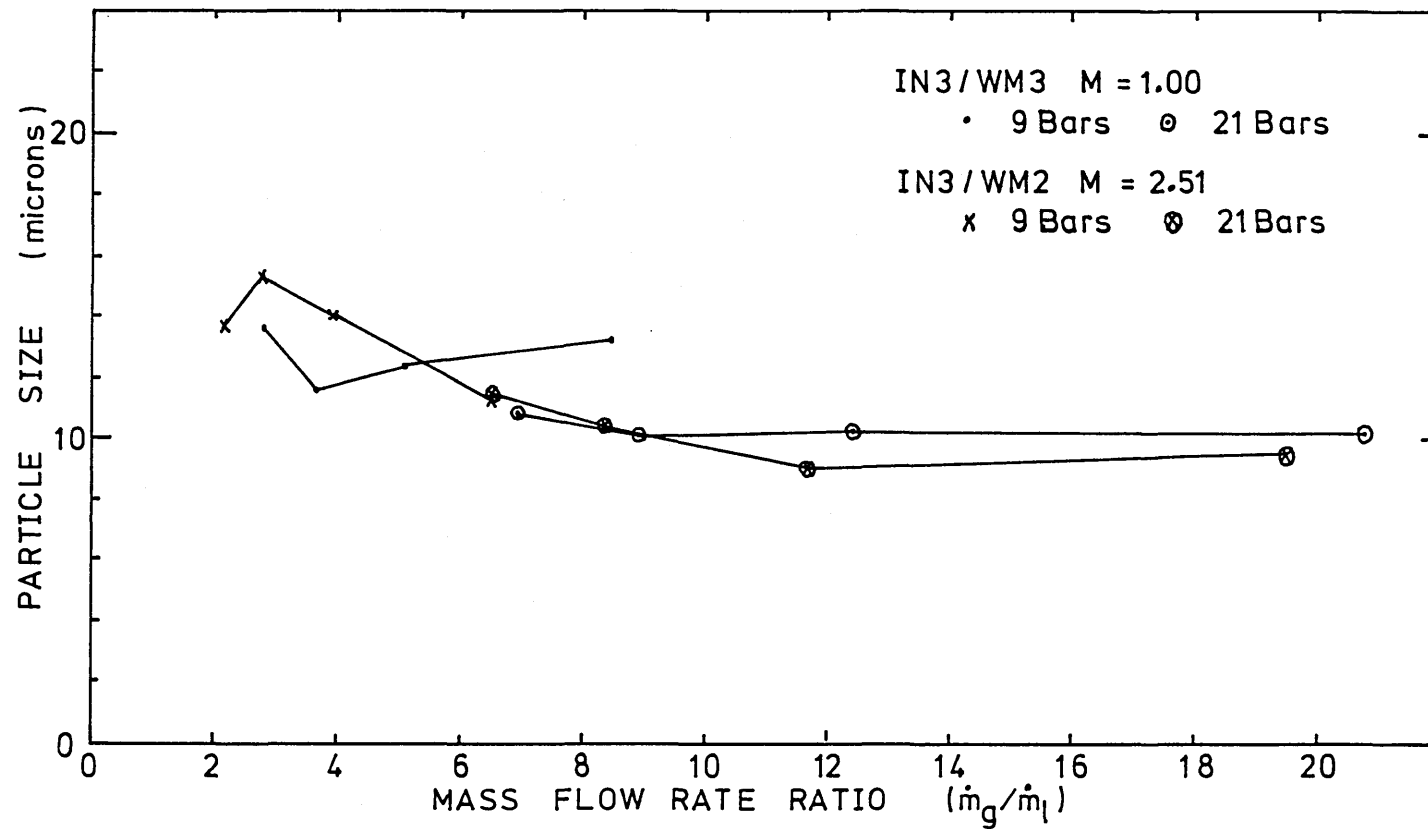
TABLE 6.7.2

VARIATION OF PARTICLE SIZE WITH MACH NUMBER

| RUN<br>NUMBER                 | WAX<br>FLOWRATE<br>cm <sup>3</sup> /min | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER | RR<br>VARIANCE | $\dot{m}_g/\dot{m}_l$ |
|-------------------------------|-----------------------------------------|----------------|----------------|----------------|------------------|----------------|-----------------------|
| <u>IN3/WM4 - MACH NO 2.08</u> |                                         |                |                |                |                  |                |                       |
| 123.1                         | 257.5                                   | 11.32          | 19.21          | 22.53          | 1.82             | 3.45           | 9.38                  |
| 124.1                         | 469.2                                   | 11.18          | 18.20          | 21.78          | 1.85             | 3.51           | 5.15                  |
| 125.1                         | 681.0                                   | 15.95          | 27.30          | 31.09          | 1.85             | 5.82           | 3.55                  |
| 126.1                         | 892.7                                   | 17.62          | 29.61          | 33.58          | 1.89             | 14.35          | 2.71                  |
| <u>IN3/WM5 - MACH NO 2.81</u> |                                         |                |                |                |                  |                |                       |
| 127.1                         | 257.1                                   | 12.10          | 25.60          | 27.16          | 1.66             | 23.48          | 9.38                  |
| 128.1                         | 469.2                                   | 12.42          | 20.16          | 23.67          | 1.87             | 2.97           | 5.15                  |
| 129.1                         | 681.0                                   | 15.61          | 27.04          | 30.58          | 1.84             | 5.58           | 3.55                  |
| 130.1                         | 892.7                                   | 16.34          | 26.48          | 30.52          | 1.93             | 4.76           | 2.71                  |

FIGURE 6.7.4

PARTICLE SIZE IN CONVERGENT AND CONVERGENT DIVERGENT NOZZLES



The plot of particle size versus the mass flow rate ratio for both the above sets of results, Figures 6.7.3 and 6.7.4, show even more conclusively that there is little change in the particle size as the Mach number is varied. These figures also show that at a constant mass flow rate ratio the nozzles act in a very similar fashion.

These are surprising results and contradict the findings of previous investigators. The earlier discussion of the work of Lubanska<sup>(34)</sup>, Kim and Marshall<sup>(19)</sup> and Fraser et al<sup>(7)</sup> had shown that an increase in atomizing gas velocity caused a decrease in particle size. An increase in exit velocity would be expected to increase the time for secondary break up as well as increasing the relative velocity between the gas and wax droplets. Both factors favouring finer powders as the droplets formed in primary break up have longer in secondary break up and the critical particle size which can be produced is smaller (as the relative velocity between the gas and liquid is greater). As the results contradict previous work the gas flow, in the nozzles used, was investigated more carefully.

#### 6.7.1 DETAILED ANALYSIS OF MACH NUMBER

If we firstly investigate IN3/WM4 and IN3/WM5 at 11.0 bars(a) driving pressure, IN3/WM4 is running in the underexpanded mode and IN3/WM5 is running in the overexpanded mode. Therefore the behaviour of the gas along the flow tube protrusion and the Mach number at the flow tube tip will differ from that obtained when running at the ideal driving pressure.

Looking at IN3/WM4 first, and using the same method described earlier in Chapter 3 for the under expanded behaviour of IN3/WM2, it can be shown that with a 4.9 mm flow tube protrusion the Mach number at the tip of the flow tube,  $M_3 = 2.44$ , and the gas flow direction is parallel to the flow tube.

Now looking at the behaviour of IN3/WM5, and once again using the same method it can be shown that the tip of the flow tube is in the region of an expansion fan reflection. The Mach number in this region is between 1.80 and 2.89.

Earlier, in Chapter 3, it was shown that with a 4.9 mm flow tube protrusion, at 11.0 bars(a) driving pressure, IN3/WM2 has an expansion fan reflection at the tip of the flow tube. The Mach number across that region was between 1.94 and 2.51.

If an expansion reflection region at the tip of the flow tube causes finer powders, as described in section 6.6 above, it would be expected that IN3/WM2 and IN3/WM5 would produce finer powders than IN3/WM4. Figure 6.7.3 shows this is the case at high mass flow rate ratios. This once again shows that an expansion fan reflection region at the tip causes finer powders.

Looking at the Mach numbers at the tip of the flow tube and disregarding the influence of the expansion reflection: then in IN3/WM4 the Mach number is 2.44, in IN3/WM2 between 1.94 and 2.51, and in IN3/WM5 between 1.80 and 2.89. If an average of the Mach number is taken in the expansion region then the Mach numbers at the tip of the flow tube are 2.44, 2.23 and 2.35 for IN3/WM4, IN3/WM2 and IN3/WM5 respectively. These are so close together that it is not surprising that each nozzle behaves in a similar manner. Thus although Mach number may aid secondary break up and have an effect on particle size the effect will not be apparent here.

If the convergent only nozzle, IN3/WM3, with an exit mach number of 1.00 is now considered then it can be seen from figure 6.7.4 that there seems to be little difference in the operation of IN3/WM3 and IN3/WM2. From the above discussion it may be possible that the effect of velocity is not apparent because the Mach number is similar at the tip of the flow tube. [note: the increase in driving pressure from 10.0 to 22.0 bars seems to have no effect on particle size. The effect of driving pressure was discussed earlier in section 6.3]

The expansion which occurs outside the exit of IN3/WM3 is much greater than that which occurs in underexpanded converging diverging nozzles. Thus although the Mach number at the exit is 1.00 the exiting gas expands rapidly as it leaves the nozzle exit. The effect of the expansion on the Mach number cannot be calculated using the same method used for IN3/WM2 because, as the Schlieren photography of IN3/WM3 shows (figure 5.9), a large

shock occurs in the exiting gas, decreasing the Mach number. However the structure of the cells in the Schlieren photographs clearly show that the exiting gas, at the tip of the protrusion is still supersonic. The finding that the gas velocity in IN3/WM3 and IN3/WM2 are both supersonic qualitatively explains the finding that both IN3/WM2 and IN3/WM3 produce similar powder sizes. However the gas flow in IN3/WM3 is so complex that the tools available in this project to evaluate the gas flow in the nozzle were inadequate. Further work will be required to fully understand the way in which convergent only nozzles operate.

As the velocity at the tip of the flow tube protrusion, in all the nozzles tested, was similar this investigation into Mach number is inconclusive. It has not shown the affect of velocity although it is likely that this effects secondary break up.

## 6.8 COMPARISON BETWEEN THE MODES OF CONTACT BETWEEN LIQUID AND ATOMIZING GAS

At certain pressures during atomization the liquid wax runs down the outside of the protruding flow tube rather than being atomized at the perimeter of the flow tube protrusion. This effect is known as rundown, and has been reported by Unal<sup>(27)</sup> and is illustrated in figure 1.5 taken from his work. As mentioned earlier, Thompson<sup>(9)</sup> carried out work investigating the effect of flow tube protrusion on atomization. He found (as reported in Chapter 1), that atomization with 0 mm flow tube protrusion was impossible and that a flow tube protrusion of at least 3mm was required before atomization was satisfactory and no blockages occurred. The findings in this project were similar. However, it was possible to carry out atomizations with flow tube protrusions lower than 3mm, although it was found that blockages of the air annulus occurred very easily until the protrusion was increased above 2 mm. The rundown effect is thought to be a main factor contributing to the difficulty of atomizing with low protrusions.

In IN3/WM2 it was found that rundown, as the driving pressure was increased, first occurred at 15.5 bars(a). The effect continued until the driving pressure was about 17.0 bars(a).

In order to see whether the rundown had any effect on the particle size atomization tests were carried out at pressures of 14.5 bars (no rundown) and 16.5 bars (rundown). The wax flow rate was varied from between about 277.8 cm<sup>3</sup>/min to 1333.3 cm<sup>3</sup>/min. The mass flow rate ratio  $\dot{m}_g/\dot{m}_1$  was kept constant by adjusting the wax flow rate, so that comparisons could be made between runs. The results (Table 6.8.1) are plotted in Figure 6.8.1, and conclusively show that rundown has no appreciable effect on particle size.

The particle sizes, SMD and VMD, were plotted against mass flow rate ratio as shown in Figure 6.8.2. As would be expected, the increase in the ratio  $\dot{m}_g/\dot{m}_1$ , caused a decrease in the particle size produced. There was a problem with run 64, at a low value of  $\dot{m}_g/\dot{m}_1$ , in which the atomization was poor. This was caused by the volume of wax being so great that atomization did not take place properly. Thus this result is somewhat suspect but has been plotted.

#### 6.8.1 CAUSES OF RUNDOWN

The rundown phenomenon can be explained by considering the behaviour of shock waves along the protrusion. A strong oblique shock reflecting from the protrusion can cause the laminar boundary layer along the protrusion to separate from the side of the flow tube. If an oblique shock is reflected from the flow tube protrusion, near the tip, the separation of the flow which occurs can allow liquid to flow down the wall to the region where the separation occurs as illustrated in figure 6.8.3.

Rundown is a well defined effect first occurring at a given driving pressure. This indicates that the effect is a result of some pressure dependent phenomena. As described, rundown would normally only occur when the nozzle is running in the overexpanded mode (oblique shock). For rundown to occur two conditions must be met; the shock must be sufficiently strong, to separate the boundary layer from the protrusion, when reflecting

FIGURE 6.8.1

EFFECT OF RUNDOWN ON PARTICLE SIZE

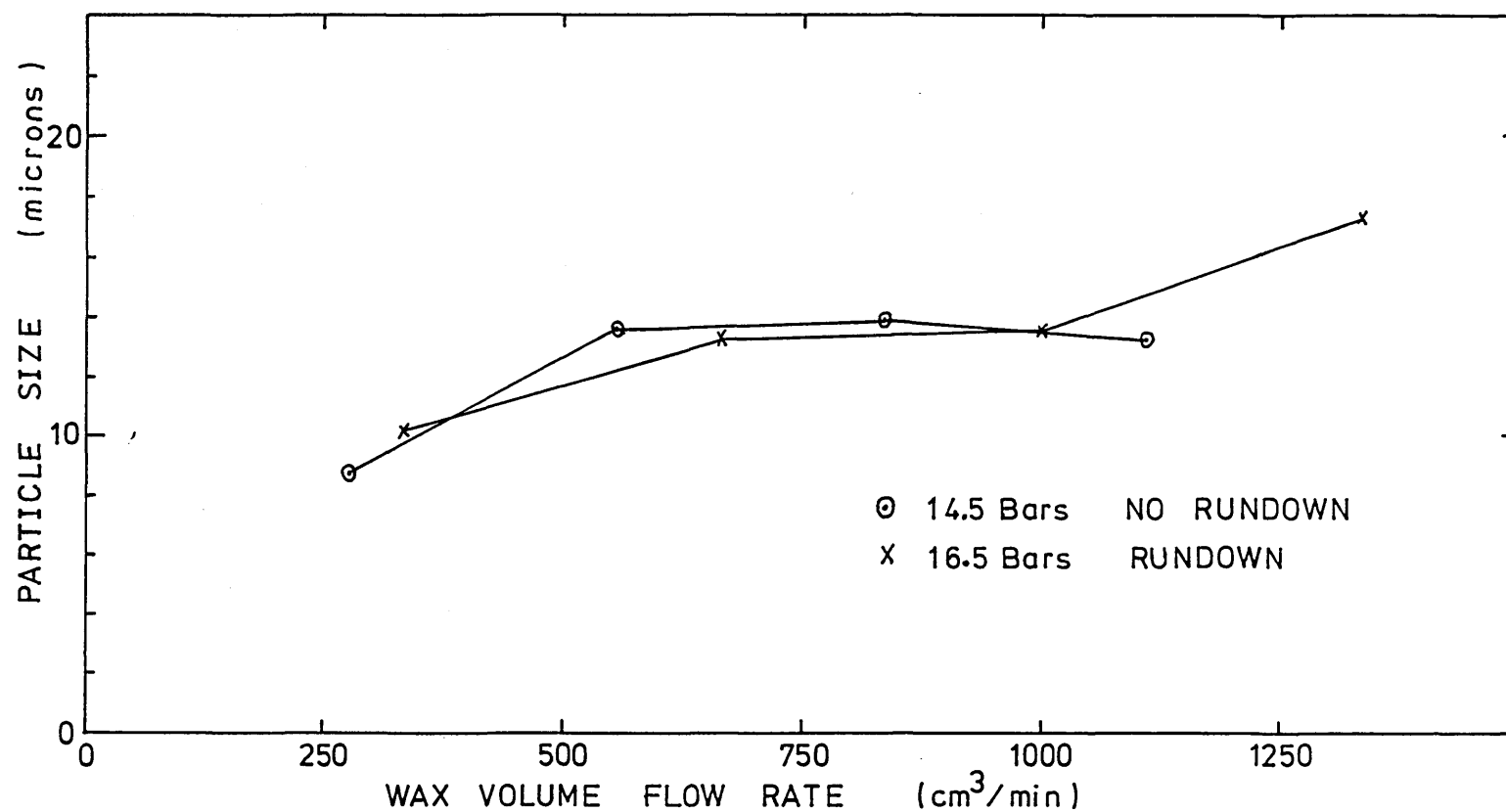


FIGURE 6.8.2

EFFECT OF RUNDOWN ON PARTICLE SIZE

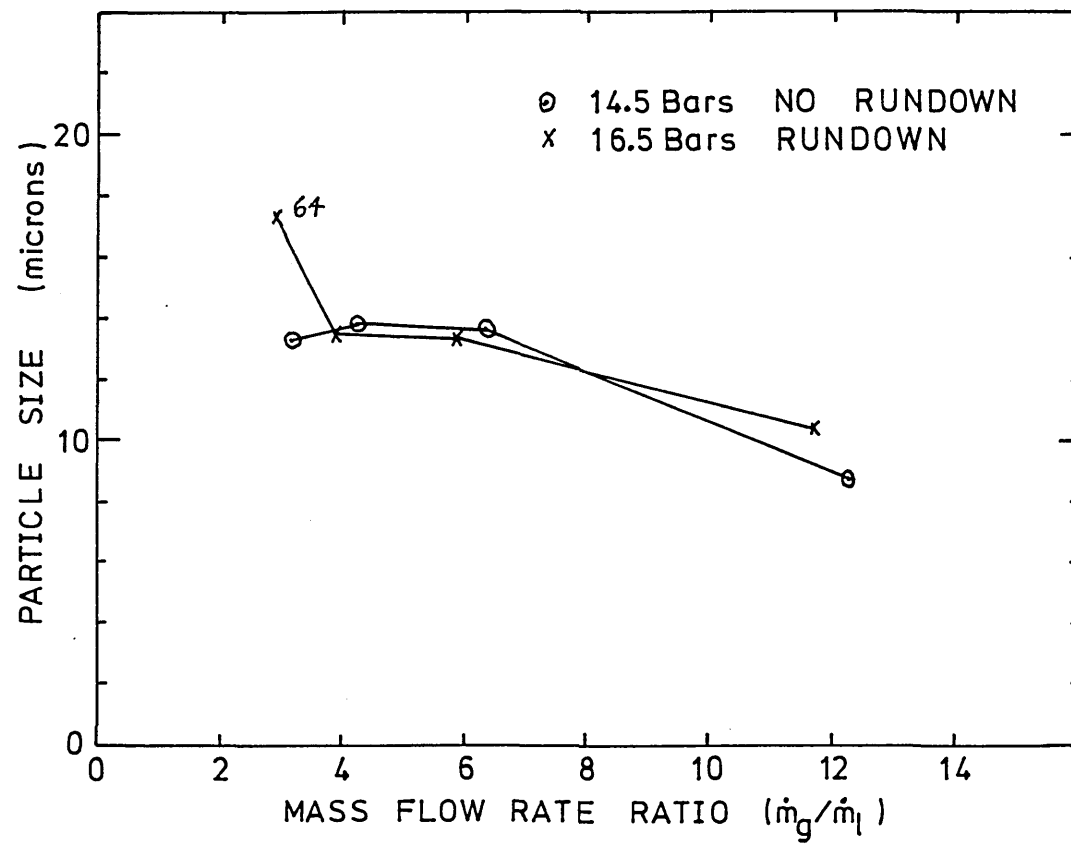


**TABLE 6.8.1**

**VARIATION OF PARTICLE SIZE WITH AND WITHOUT RUNDOWN**

| RUN<br>NUMBER     | WAX<br>FLOWRATE<br>cm <sup>3</sup> /min | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER | RR<br>VARIANCE | $\dot{m}_g/\dot{m}_1$ |
|-------------------|-----------------------------------------|----------------|----------------|----------------|------------------|----------------|-----------------------|
| <u>NO RUNDOWN</u> |                                         |                |                |                |                  |                |                       |
| 56                | 277.8                                   | 8.79           | 15.02          | 18.25          | 1.72             | 3.42           | 12.26                 |
| 57                | 555.5                                   | 14.61          | 24.69          | 28.71          | 1.86             | 10.11          | 6.31                  |
| 57.1              | 555.5                                   | 13.45          | 23.68          | 27.21          | 1.77             | 3.63           | 6.31                  |
| 57.2              | 555.5                                   | 12.70          | 21.86          | 25.68          | 1.78             | 5.71           | 6.31                  |
| 59                | 833.3                                   | 12.56          | 30.58          | 31.16          | 1.49             | 11.59          | 4.21                  |
| 59B               | 833.3                                   | 16.22          | 29.90          | 32.61          | 1.79             | 8.31           | 4.21                  |
| 59.1              | 833.3                                   | 13.42          | 27.16          | 29.26          | 1.65             | 2.88           | 4.21                  |
| 59.2              | 833.3                                   | 13.20          | 32.59          | 32.48          | 1.50             | 12.42          | 4.21                  |
| 60                | 1111.1                                  | 13.24          | 26.61          | 29.38          | 1.63             | 5.36           | 3.16                  |
| <u>RUNDOWN</u>    |                                         |                |                |                |                  |                |                       |
| 61                | 333.3                                   | 11.15          | 18.49          | 22.55          | 1.79             | 6.79           | 11.69                 |
| 61.1              | 333.3                                   | 9.85           | 17.66          | 20.99          | 1.68             | 4.10           | 11.69                 |
| 61.2              | 333.3                                   | 9.52           | 17.43          | 20.59          | 1.65             | 4.47           | 11.69                 |
| 62                | 666.6                                   | 14.31          | 23.81          | 27.88          | 1.87             | 8.46           | 5.84                  |
| 62.1              | 666.6                                   | 12.97          | 21.70          | 22.44          | 1.99             | 8.02           | 5.84                  |
| 62.2              | 666.6                                   | 12.43          | 22.34          | 25.69          | 1.73             | 2.85           | 5.84                  |
| 63                | 1000.0                                  | 13.50          | 22.39          | 26.37          | 1.86             | 5.53           | 3.90                  |
| 64                | 1333.3                                  | 17.32          | 36.80          | 37.15          | 1.70             | 5.18           | 2.92                  |

from the flow tube protrusion, and the reflection must be near enough the tip to allow liquid to flow into the separated region. Tests have shown that the rundown does not exceed about 2.5 mm and is normally of the order of 2.0-2.5 mm. It has also been shown that by adjusting the protrusion the rundown can be controlled. For example an increase in the protrusion, in IN3/WM2 with a 15.5 bars driving pressure, will cause the rundown to disappear as the separation of the boundary layer is no longer near the flow tube tip.

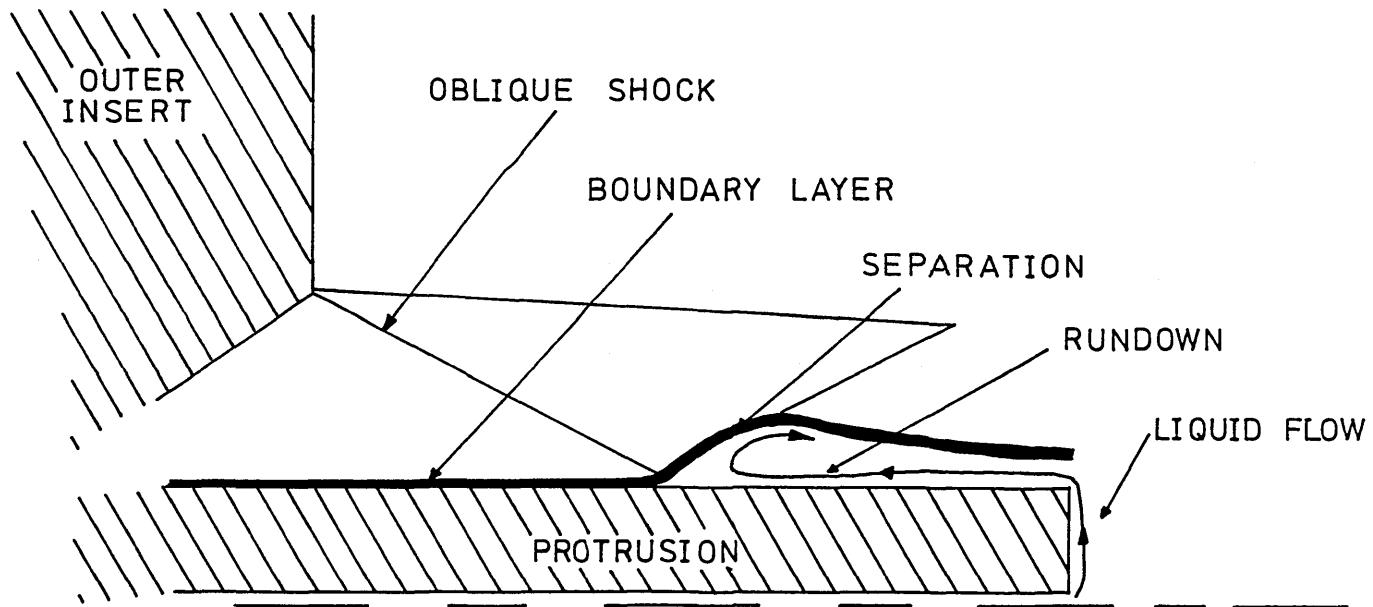
The rundown can be examined in more detail by considering IN3/WM2. If the rundown is of the order of 2.0-2.5 mm, with a 4.9 mm protrusion, then the oblique shock wave which causes the rundown must be reflecting at a point just less than 2.0-2.5 mm, from the tip. The dimensions of IN3/WM2 are such that the nozzle operates ideally at a pressure of 17.36 bars. By calculating the exit Mach number of the nozzle when running at 15.5 bars it is possible to calculate the position of the shock wave. The exit pressure would be  $15.5 \times 0.05762 = 0.8931$  bars. The pressure ratio across the oblique shock is  $1.0/0.8931 = 1.1197$ . The Mach number normal to the shock wave can be looked up in normal shock tables and is found to be 1.05. Thus the sine of the angle the shock makes with the protrusion is  $1.05/2.51 = 0.4183$  and so the angle the oblique shock makes is  $24.73^\circ$ . The oblique shock therefore reflects from the protrusion at a distance of  $1.1025/\tan 24.73^\circ = 2.39$  mm from the exit a distance of  $4.90 - 2.39 = 2.51$  mm from the tip.

These calculations show that the distance down the flow tube protrusion for which the liquid rundown was observed is the right order of magnitude.

It is interesting to note that the oblique shock which occurs at a driving pressure of 15.5 bars is quite weak. It was expected that separation would not occur with weak shocks and yet the fact that rundown occurs shows that there must be some separation. In IN3/WM2 the rundown phenomenon might have gone unnoticed had the protrusion been greater than 4.9mm.

FIGURE 6.8.3

SCHEMATIC OF NOZZLE RUNDOWN



## 6.9 THE EFFECT OF LIQUID FLOW TUBE DIAMETER

In order to investigate the effect of varying the flow tube diameter two sets of nozzle inserts were made up with flow tube diameters of 8.0 mm and 12.2 mm, IN4/WM7 and IN5/WM8 respectively. The nozzles were designed to have the same exit Mach number and throat area as IN3/WM2 (see Table 2.1 for exact nozzle insert dimensions). The atomizations were carried out at 11.0 bars(a) driving pressure and with 4.9 mm flow tube protrusion. The wax flow rate was varied between 275 cm<sup>3</sup>/min and 900 cm<sup>3</sup>/min.

It was found that in both cases the particle size produced was considerably coarser than in IN3/WM2. The results (Table 6.9.1) are plotted in Figure 6.9.1 as particle size (SMD) versus wax flow rate.

By plotting particle size (SMD) versus mass flow rate ratio rather than against wax flow rate as in figure 6.9.2 it is possible to see that the coarsening of powder in IN5/WM8 seems to be similar to IN3/WM2. This would also be the case in IN4/WM7 if the particle size in run 112 was smaller. However there is no evidence in the results to suggest that run 112 was abnormal.

In section 6.1 the effect of wax mass flow rate was investigated in terms of the film thickness at the perimeter of the flow tube protrusion by using Gretzinger and Marshall's<sup>(23)</sup> equation:

$$t = [ (3\mu_1 \dot{m}_1) / (\rho_1^2 g \pi D) ]^{1/3} \quad (6.1)$$

Where:

$\mu_1$  = dynamic viscosity Pa.s

$\rho_1$  = liquid density kg/m<sup>3</sup>

D = diameter of flow tube, m

t = film thickness at the perimeter of the protrusion, m

$\dot{m}_1$  = mass flow rate of liquid kg/s

FIGURE 6.9.1

EFFECT OF FLOW TUBE DIAMETER

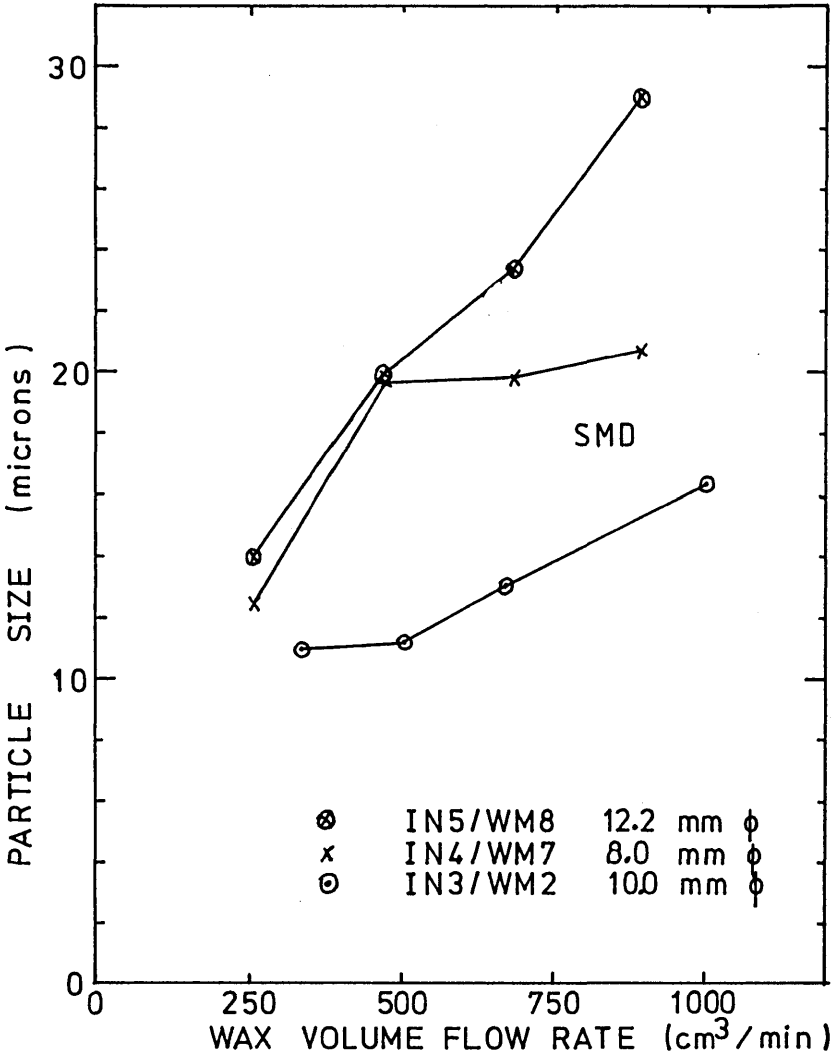


**TABLE 6.9.1**

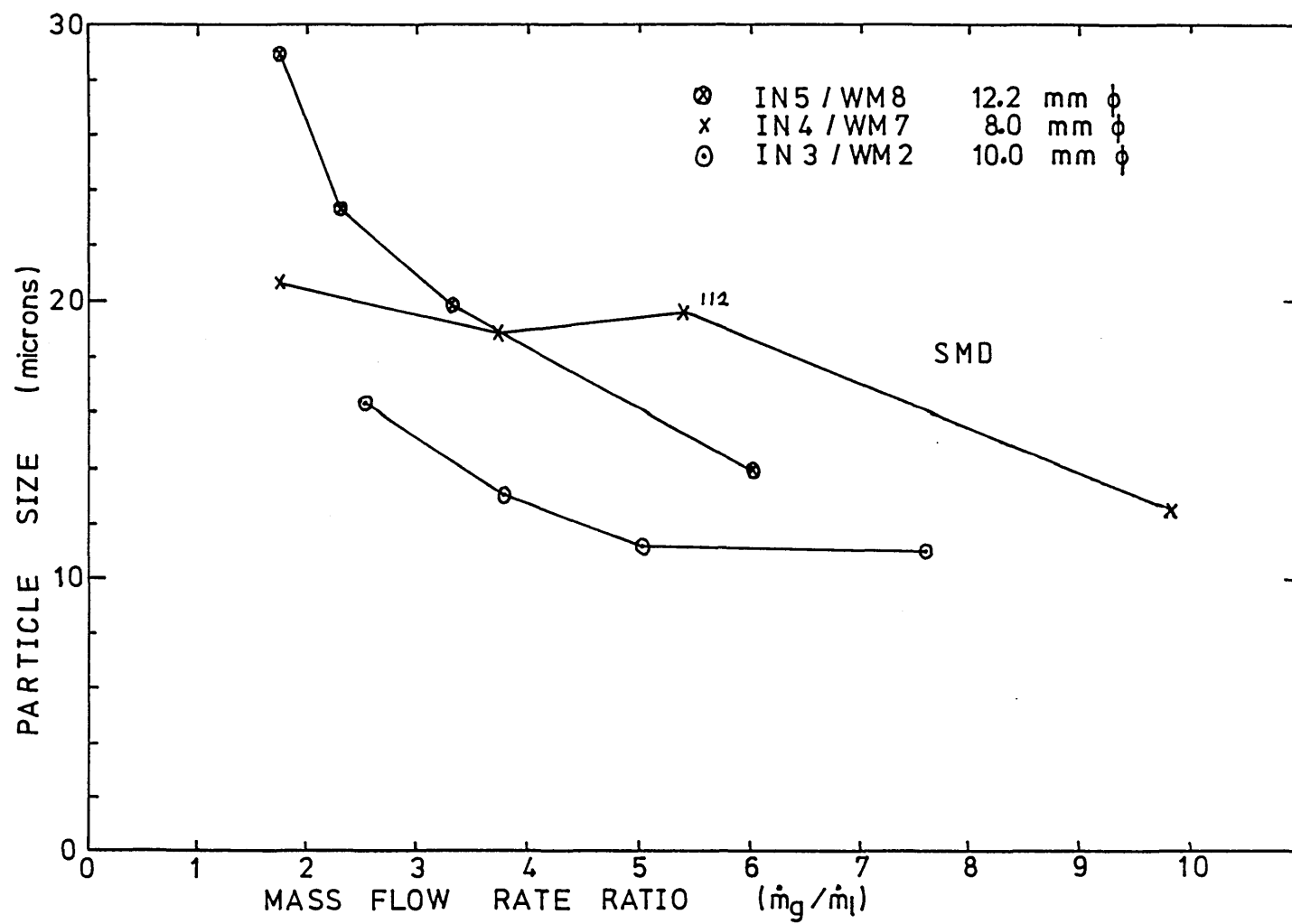
**VARIATION OF PARTICLE SIZE WITH FLOW TUBE DIAMETER**

| RUN<br>NUMBER                             | WAX<br>FLOWRATE<br>cm <sup>3</sup> /min | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER | RR<br>VARIANCE | $\dot{m}_g/\dot{m}_1$ |
|-------------------------------------------|-----------------------------------------|----------------|----------------|----------------|------------------|----------------|-----------------------|
| <u>IN3/WM2 - 10 MM DIAMETER FLOW TUBE</u> |                                         |                |                |                |                  |                |                       |
| 46A                                       | 1000.0                                  | 16.22          | 30.69          | 33.82          | 1.72             | 5.96           | 2.34                  |
| 46B                                       | 1000.0                                  | 16.20          | 33.27          | 35.90          | 1.63             | 4.35           | 2.34                  |
| 46C                                       | 1000.0                                  | 16.61          | 33.63          | 35.24          | 1.69             | 6.64           | 2.34                  |
| 47A                                       | 666.6                                   | 13.59          | 23.93          | 27.71          | 1.77             | 8.20           | 3.51                  |
| 47B                                       | 666.6                                   | 12.95          | 22.76          | 26.21          | 1.76             | 3.14           | 3.51                  |
| 47C                                       | 666.6                                   | 12.53          | 23.18          | 26.71          | 1.68             | 4.52           | 3.51                  |
| 48A                                       | 500.0                                   | 11.89          | 22.41          | 25.54          | 1.66             | 2.57           | 4.68                  |
| 48B                                       | 500.0                                   | 11.07          | 20.42          | 20.68          | 1.84             | 8.49           | 4.68                  |
| 48C                                       | 500.0                                   | 10.53          | 20.37          | 23.41          | 1.61             | 3.77           | 4.68                  |
| 49A                                       | 333.3                                   | 10.71          | 21.86          | 24.52          | 1.58             | 6.01           | 7.01                  |
| 49B                                       | 333.3                                   | 12.26          | 20.95          | 24.85          | 1.81             | 8.61           | 7.01                  |
| 49C                                       | 333.3                                   | 10.00          | 18.32          | 21.47          | 1.67             | 4.32           | 7.01                  |

**TABLE 6.9.1 (cont)**

| RUN<br>NUMBER                             | WAX<br>FLOWRATE<br>cm <sup>3</sup> /min | SMD<br>microns | VMD<br>microns | RRM<br>microns | RRD<br>PARAMETER | RR<br>VARIANCE | $\dot{m}_g/\dot{m}_l$ |
|-------------------------------------------|-----------------------------------------|----------------|----------------|----------------|------------------|----------------|-----------------------|
| <u>IN4/WM7 - 12 MM DIAMETER FLOW TUBE</u> |                                         |                |                |                |                  |                |                       |
| 111.1                                     | 257.5                                   | 13.13          | 26.09          | 28.56          | 1.67             | 9.01           | 9.83                  |
| 111.2                                     | 257.2                                   | 11.74          | 24.97          | 26.83          | 1.62             | 18.49          | 9.83                  |
| 112.1                                     | 469.2                                   | 22.90          | 41.82          | 45.59          | 1.78             | 7.77           | 5.40                  |
| 112.2                                     | 469.2                                   | 16.30          | 27.84          | 30.63          | 1.91             | 4.63           | 5.40                  |
| 113.1                                     | 681.0                                   | 22.43          | 46.87          | 51.66          | 1.59             | 22.08          | 3.72                  |
| 113.2                                     | 681.0                                   | 15.41          | 27.85          | 31.67          | 1.78             | 12.71          | 3.72                  |
| 114.1                                     | 892.7                                   | 21.40          | 41.70          | 42.32          | 1.80             | 11.24          | 1.75                  |
| 114.2                                     | 892.7                                   | 19.87          | 40.52          | 41.66          | 1.72             | 8.62           | 1.75                  |
| <u>IN5/WM8 - 8 MM DIAMETER FLOW TUBE</u>  |                                         |                |                |                |                  |                |                       |
| 115.1                                     | 257.5                                   | 15.59          | 30.32          | 33.25          | 1.69             | 8.85           | 6.05                  |
| 115.2                                     | 257.2                                   | 12.25          | 22.62          | 25.97          | 1.72             | 8.34           | 6.05                  |
| 116.1                                     | 469.2                                   | 23.93          | 47.20          | 45.97          | 1.83             | 18.66          | 3.32                  |
| 116.2                                     | 469.2                                   | 15.66          | 32.21          | 33.65          | 1.71             | 17.81          | 3.32                  |
| 117.1                                     | 681.0                                   | 22.13          | 50.87          | 50.21          | 1.62             | 19.91          | 2.29                  |
| 117.2                                     | 681.0                                   | 24.53          | 52.40          | 49.85          | 1.75             | 17.67          | 2.29                  |
| 118.1                                     | 892.7                                   | 31.21          | 60.42          | 63.13          | 1.73             | 10.96          | 1.75                  |
| 118.2                                     | 892.7                                   | 26.69          | 48.88          | 47.62          | 1.96             | 29.60          | 1.75                  |

FIGURE 6.9.2  
EFFECT OF FLOW TUBE DIAMETER



$g = \text{gravitational acceleration m/s}^2$

This can now be used to compare the effect of 8.0 mm, 10.0 mm and 12.2 mm flow tube diameters on the film thickness when the wax flow rate is 500 cm<sup>3</sup>/min.

$\rho_1 = 770 \text{ kg/m}^3$ ,  $g = 9.81 \text{ m/s}^2$ ,  $\mu_1 = 0.01176 \text{ Pa.s.}$

8.0 mm  $t = 1.157 \text{ mm}$

10.0 mm  $t = 1.074 \text{ mm}$

12.2 mm  $t = 1.005 \text{ mm}$

We have already suggested that an increase in the film thickness results in an increase in the particle size in primary break up and so a coarser final particle size. Thus it would be expected that IN4/WM7 would give coarser particles than IN3/WM2 and IN5/WM8 finer particles. Thus, with all other factors constant, it would be expected that IN4/WM7 would give coarser particles than IN3/WM2 and IN5/WM8 finer particles. However other factors do affect atomization and if IN4/WM7 and IN5/WM8 are looked at individually then the nozzle operation can be investigated in more detail.

#### IN4/WM7

The mass flow rate of gas is nearly identical in IN3/WM2 and IN4/WM7 and so this is not a factor contributing to coarser particles. Closer examination however points to other reasons:

1. The smaller flow tube diameter may cause greater cooling of the wax in the flow tube and so cause incomplete atomization which, for reasons discussed earlier, produces coarser particles. This is likely to be a more important factor at low wax flowrates.

2. The gas flow characteristics at the exit, because of the greater exit gap, are different. The expansion reflection region is not at the tip of the protrusion in IN4/WM7 as it is in IN3/WM2. This, from the evidence produced earlier, will account for a particle size of perhaps 3.0 microns at the outside but not the 6 microns or greater (SMD) difference shown in figure 6.9.2 as explained earlier when discussing the effect of protrusion on

particle size. A comparison of Schlieren photographs of IN4/WM7 and IN5/WM8, figures 5.11 and 5.12, even if they are at different pressures, show that there is a difference between the shape of the expansion of the gas outside the nozzle.

#### IN5/WM8

The Schlieren photographs for IN5/WM8 show clearly that the nozzle is running unconcentrically and so one would expect the particle size of the powder produced to be coarser than that in IN3/WM2. (This unconcentricity was caused by the extremely small throat gap).

The results show that the powder produced by IN5/WM8 has extremely high variances and the scatter in particle size between results is greater than in IN3/WM2. This supports Gretzinger and Marshall's<sup>(23)</sup> work which showed that the concentricity of the nozzle is of primary importance in the production of fine particles and reproduceable results.

## **CHAPTER SEVEN**

### **CONCLUSIONS AND FURTHER WORK**

## INTRODUCTION

The literature on atomization techniques is numerous, as described earlier in Chapter 1. This project has been concerned with the effect of nozzle design and process parameters on atomization nozzle operation in terms of gas flow as well as the size of powder produced. This chapter will summarize the findings and suggest the direction further work should take.

## ATOMIZATION NOZZLES

The choice of a confined annular atomization nozzle design proved successful. This nozzle type allowed pre-filming of the liquid, which aids finer powder, and running vertically aided the pre-filming process.

Chapter 2 described the way in which the design developed in some detail. Considerable trouble was taken to ensure that the nozzles were concentric. The results from IN5/WM8 showed that this aids the production of fine powders. The way in which the nozzle is machined - ensuring both the inner and outer inserts are concentric - and the horizontal adjustment screws proved the most successful ways of ensuring concentricity. A combination of both methods would probably prove to be the best type of nozzle design and should be investigated. Considerable effort, whatever design method is used should be made in ensuring concentricity so that the powder produced is uniform and the operation repeatable.

## GAS FLOW

The gas flow in the atomization nozzles, especially in terms of shock wave behaviour, was investigated in more detail than anywhere in the atomization literature.

The shock waves were pictured using Schlieren photography very successfully. The calculated shock wave position and the Schlieren photographed position were shown to be similar in the supersonic nozzles. This showed that supersonic nozzle behaviour, in terms of shock waves, can be predicted.

The convergent only nozzle flow was considerably more difficult to measure and predict as the expansion outside the nozzle was so great. Considerable further work could still be done on characterizing the gas flow above this type of nozzle as well as the convergent divergent nozzles.

Further work could still be done on Mach number measurements using suitable apparatus and a pitot static tube. It should also be possible, using this apparatus, to determine the exact position of the shock waves and expansion waves and their effects on the atomization process.

It was possible to quantitatively explain the suction measurements made in terms of shock wave behaviour. However as suction does not affect the atomization process any further work on nozzle suction is thought to be unnecessary at this time.

The nozzle mass flow rate was shown to be very nearly theoretical and the deviation from theoretical were explained in terms of boundary layer growth in the nozzles.

## EXPERIMENTAL

The use of wax as the material atomized was good. The way in which the material simulates metal and the ease of handling the material were its main benefits.

The experimental apparatus proved to be very suitable for short atomization runs however it would need to be redesigned to enable it to cope with longer runs. One area which could do with considerable refinement is the final collection of the wax. The removal of the wax from the collection bin proved to be messy and tiresome.

The Malvern Particle Size Analyser was an excellent method of sizing the powder ,especially as this allowed agglomerated wax particles to be separated.

## WAX ATOMIZATION TESTS

The effect of liquid mass flow rate, mass flow rate ratio, viscosity, temperature, flowtube protrusion velocity, rundown and flow tube diameter on the atomization process and the size of powder produced were investigated.

The study of the mass flow rate of liquid proposed that the formation of large droplets in the primary break-up stage and the secondary break-up of the droplets in flight are the two factors which affect the final size and distribution of powder formed.

This area of particle formation and break-up is one which would benefit from much further work. A closer study of nozzle design could improve the efficiency of the primary break-up stage. This could be done using high speed photography. The secondary break-up process could be better understood by using Schlieren as well as high speed photography to study the liquid droplet break-up in flight.

This increased understanding of droplet break-up, especially the transisition from primary to secondary break-up, would enable the whole atomization process to be better understood. It seems at present that the overall coarsening of the powder which can occur is a result of an increase in coarse fraction of particles produced and not a coarsening of the fine powder. An increased understanding of particle break-up would enable the identification of the factors in the break-up which causes the increase in the coarse fraction.

The effect of exiting gas velocity was investigated and the results indicated that velocity had no effect on particle size.

However as explained earlier the Mach number in the nozzles used was inadvertently similar. Consequently the velocity effect was not observed. Further work, especially on convergent only nozzles, into the effect of velocity would help identify its role in the atomization process and particle formation.

The effect of flow tube diameter was investigated but as one of the nozzles (IN5/WM8) was very unconcentric the investigation was inconclusive. Further work could also be usefully spent here.

It was concluded from the experiments that there was no effect of driving pressure on particle size. It is thought that earlier work which has quoted driving pressure as an independent variable had failed to take account of the other factors, such as mass flowrate of gas, which the driving pressure can effect.

The effect of flowtube protrusion was successfully related to the shock wave behaviour in the nozzles. It would be interesting to see what effect changes in the nozzle

characteristics has on the effect of protrusion.

#### SUMMARY

The use of confined annular atomization nozzles (in a vertically upwards direction) is suitable, provided the nozzle is concentric, for atomization of liquid wax. By using suitable materials the nozzles could easily be converted for use with liquid metal.

The effect of nozzle design on the atomization process would also benefit from further experimental work, especially on the differences between convergent only and convergent divergent nozzles and the effect of gas flow on these two types of nozzle.

The gas flow in the nozzle is very important in determining the size of powder produced. It determines the efficiency of the primary and secondary break-up stages as well as the optimum nozzle geometry. This project has shown that the nozzle geometry can be altered to suit the gas flow however the exact effect of gas flow on primary and secondary break-up needs to be investigated further and is the area which requires the most attention at the present time.

## **APPENDIX ONE**

### **CALCULATION OF OVEREXPANDED BEHAVIOUR**

### Calculation of the angle of the oblique shock, $\theta_1$ .

If the pressure ratio across the nozzle is 0.05762 and the driving pressure is 11.0 bars then the exit pressure,  $P_1$ , is 0.6338 bars. The Mach number,  $M_1$ , is 2.51. If the oblique shock wave makes an angle of  $\theta_1$  with the flow tube protrusion then the normal component of the mach number,  $M_{n1} = M_1 \sin \theta_1$ . As the shock raises the pressure to ambient, i.e.  $P_2 = 1.0$  bar, the pressure ratio across the shock is  $1.0/0.6338 = 1.5777$ . From normal shock tables when the pressure ratio across a shock is 1.5777 the mach number before the shock is 1.2228.

Thus:

$$\begin{aligned}M_{n1} &= M_1 \times \sin \theta_1 \\1.2228 &= 2.51 \times \sin \theta_1 \\ \sin \theta_1 &= 0.4872 \\ \theta_1 &= 29.16^\circ\end{aligned}$$

### Calculation of the angle of flow deflection, $\delta_1$ , and $M_2$

The mach number on the other side of the oblique shock is  $M_2$ . Across the oblique shock, from normal shock tables, the normal component of mach number is  $M_{n2} = 0.8283$ . The temperature ratio,  $T_2/T_1$ , across the shock = 1.1427.

The tangential component of  $M_2$  is  $M_{t2}$ .

$$\begin{aligned}M_{t2} &= M_{t1} \times (T_2/T_1)^{-1/2} \\ &= 2.51 \times \cos \theta_1 \times (1.1427)^{-1/2} \\ &= 2.0505\end{aligned}$$

thus:

$$\begin{aligned}M_2 &= ((2.0505)^2 + (0.8283)^2)^{1/2} \\ &= 2.2115\end{aligned}$$

given:

$$\begin{aligned}M_{n2} &= M_2 \times \sin (\theta_1 - \delta_1) \\ M_{t2} &= M_2 \times \cos (\theta_1 - \delta_1)\end{aligned}$$

then:

$$\tan (\theta_1 - \delta_1) = 0.8283/2.0505$$

$$\begin{aligned}\theta_1 - \delta_1 &= 22.00^\circ \\ \delta_1 &= 29.16 - 22.00 = 7.16^\circ\end{aligned}$$

#### Calculation of the angle of the oblique shock reflection, $\theta_2$

When the oblique shock hits the flow tube protrusion it reflects. If the flow through the reflected shock is adiabatic then by looking up in tables of adiabatic flow through oblique shock for a mach number of 2.20 (the nearest value to 2.2115 in the tables) for a deflection of  $7.0^\circ$  the angle the reflected oblique shock makes with the flow direction,  $\phi_2$ , is  $32.90^\circ$ . Thus the angle the reflected shock makes with the flow tube protrusion  $\theta_2 = 32.90 - 7.16 = 25.74^\circ$ .

#### Calculation of $M_3$ and $P_3$

If a similar analysis is carried out to that used to calculate  $M_2$  then:

$$\begin{aligned}M_{2n} &= M_2 \times \sin \phi_2 = 2.2155 \times \sin 32.90 = 1.2034 \\ M_{t2} &= M_2 \times \cos \phi_2 = 2.2155 \times \cos 32.90 = 1.8602\end{aligned}$$

From normal shock tables the normal component of  $M_3$ ,  $M_{n3} = 0.8401$  and the temperature ratio across the oblique shock,  $T_3/T_2 = 1.1300$ .

Thus:

$$\begin{aligned}M_{t3} &= M_{t2} \times (T_3/T_2)^{-1/2} \\ M_{t3} &= 1.7499\end{aligned}$$

and so:

$$\begin{aligned}M_3 &= ((1.7499)^2 + (0.8401)^2)^{1/2} \\ M_3 &= 1.9411\end{aligned}$$

The pressure ratio,  $P_3/P_2$ , which causes a Mach number equal to  $M_{n3}$  after an oblique shock = 1.5225. Thus as  $P_2 = 1.0$  bars,  $P_3 = 1.5225$  bars.

#### Calculation of $M_4$ , the flow deflection $\delta_2$ , and the expansion fan angle $\gamma$ .

The pressure is now above ambient and in order to return to ambient the gas must go through an expansion from 1.5225 bars to 1.0 bars. The expansion takes the form of a series of expansion

waves which make up an expansion fan. The expansion also changes the direction of gas flow away from the flow tube protrusion.

The pressure ratio across the expansion fan,  $P_4/P_3 = 1.0/1.5225 = 0.6568$ .

Also  $(P_4/P_{t4})/(P_3/P_{t3}) = P_4/P_3$  and in isentropic flow  $P_{t4} = P_{t3}$  so from isentropic flow tables:

$$P_3/P_{t3} = 0.1401$$

therefore:

$$\begin{aligned} P_4/P_{t4} &= 0.6568 \times (0.1401) \\ &= 0.09199 \end{aligned}$$

From isentropic flow tables:

$$M_4 = 2.2106$$

From Prandtl-Meyer tables for gas with  $k = 1.4$ .

$$M_3 = 1.9411 \quad \mu_3 = 31.050^\circ \quad \nu_3 = 24.742^\circ$$

$$M_4 = 2.2106 \quad \mu_4 = 26.892^\circ \quad \nu_4 = 32.007^\circ$$

The flow deflection,  $\delta_2 = (\nu_4 - \nu_3) = 7.265^\circ$

The fan angle,  $\gamma = (\nu_4 - \nu_3) + (\mu_4 - \mu_3) = 11.423^\circ$

The angle the beginning of the expansion fan makes with the flow tube protrusion is equal to  $\mu_3 = 31.050^\circ$ .

The angle the end of the expansion fan makes with the flow tube protrusion is equal to  $\mu_3 - \gamma = 19.627^\circ$ .

#### Calculation of $M_5$ and $P_5$

The expansion fan now reflects from the flow tube protrusion and the gas goes through a further expansion. In order for the gas flow to return parallel to the flow tube protrusion side the flow must turn through an angle equal to the flow deflection,  $\delta_2$ .

therefore:

$$\begin{aligned} \nu_5 - \nu_4 &= 7.265^\circ \\ \nu_5 &= 7.265^\circ + 32.007^\circ = 39.272^\circ \end{aligned}$$

so from Prandtl Meyer tables:

$$M_5 = 2.5063$$

$$\mu_5 = 23.517^\circ$$

Thus the angle the reflected expansion fan makes with the flow tube protrusion is equal to  $\mu_5 = 23.517^\circ$ .

similarly to the earlier section:

$(P_5/P_{t5})/(P_4/P_{t4}) = P_5/P_4$  and in isentropic flow  $P_{t5} = P_{t4}$   
so from isentropic flow tables:

$$P_5/P_{t5} = 0.05796$$

$$P_4/P_{t4} = 0.09199$$

therefore as:

$$P_4 = 1.0 \text{ bar}$$

$$P_5 = 0.6300$$

#### Oblique shock formation following expansion fan reflection

The expansion fan reflection now in turn reflects from the free pressure boundary as a series of Prandtl Meyer compression waves which compress together to form an oblique shock. This is calculated in exactly the same way as described earlier.

$$P_5 = 0.6300 \quad \text{and} \quad P_6 = 1.00$$

therefore:

$$P_5/P_6 = 1.5873$$

$$M_{n5} = 1.2262$$

$$\sin \theta_6 = 0.4893$$

$$\theta_6 = 29.29^\circ$$

$$M_{n6} = 0.8263$$

$$T_6/T_5 = 1.1448$$

$$M_{t6} = 2.0429$$

$$M_6 = 2.2037$$

$$\delta_6 = 7.268^\circ$$

## **APPENDIX TWO**

### **CALCULATION OF UNDEREXPANDED BEHAVIOUR**

Calculation of the expansion fan angle,  $\gamma_1$  and the flow deflection,  $\delta_1$ .

If the pressure ratio across the nozzle is 0.05762 and the driving pressure is 21.0 bars absolute then the exit pressure,  $P_1$ , is 1.2100 bars. The Mach number,  $M_1$ , is 2.51.

The pressure ratio across the expansion fan:

$$\begin{aligned} P_2/P_1 &= 1.0/1.2100 \\ &= 0.8264. \end{aligned}$$

Also  $(P_2/P_{t2})/(P_1/P_{t1}) = P_2/P_1$  and in isentropic flow  $P_{t2} = P_{t1}$  and from isentropic flow tables we know  $P_1/P_{t1} = 0.05762$ .

So:

$$P_2/P_{t2} = 0.04762$$

From isentropic flow tables:

$$M_2 = 2.6330$$

From Prandtl Meyer tables for gas with  $k = 1.4$

$$M_1 = 2.510 \quad \mu_1 = 23.48^\circ \quad \nu_1 = 39.357^\circ$$

$$M_2 = 2.633 \quad \mu_2 = 22.32^\circ \quad \nu_2 = 42.152^\circ$$

The flow deflection,  $\delta_1 = (\nu_2 - \nu_1) = 2.795^\circ$

The fan angle,  $\gamma_1 = (\nu_2 - \nu_1) + (\mu_2 - \mu_1) = 3.955^\circ$

The angle the beginning of the expansion fan makes with the flow tube protrusion is equal to  $\mu_1 = 23.48^\circ$ .

The angle the end of the fan makes with the flow tube protrusion is equal to  $\mu_1 - \gamma_1 = 19.525^\circ$ .

Calculation of  $M_3$  and  $P_3$

The expansion fan now reflects from the flow tube protrusion and the gas goes through a further expansion. In order for the gas flow to return parallel to the flow tube protrusion tube the flow must turn through an angle equal to the flow deflection,  $\delta_1$ . therefore:

$$\begin{aligned} \nu_3 - \nu_2 &= 2.795^\circ \\ \nu_3 &= 2.795^\circ + 42.152^\circ = 44.947^\circ \end{aligned}$$

so from Prandtl Meyer tables

$$M_3 = 2.7619$$

$$\mu_3 = 21.22^\circ$$

The angle the reflected expansion fan makes with the flow tube protrusion is equal to  $\mu_3 = 21.22^\circ$ .

as in the earlier section:

$$(P_3/P_{t3})/(P_2/P_{t2}) = P_3/P_2 \text{ and in isentropic flow } P_{t3} = P_{t2}$$

and from isentropic flow tables:

$$P_3/P_{t3} = 0.03906$$

$$P_2/P_{t2} = 0.04762$$

therefore as:

$$P_2 = 1.0 \text{ bar}$$

$$P_3 = 0.8202 \text{ bar}$$

#### Oblique shock formation following expansion fan reflection

The expansion fan reflection now in turn reflects the free pressure boundary as a series of Prandtl Meyer compression waves which compress together to form an oblique shock. This is calculated in exactly the same way as described earlier.

$$P_3 = 0.8202 \text{ and } P_4 = 1.00$$

therefore:

$$P_3/P_4 = 1.2192$$

$$M_{n3} = 1.09$$

$$\sin \theta_4 = 0.3947$$

$$\theta_4 = 23.25^\circ$$

$$M_{n4} = 0.9196$$

$$T_4/T_3 = 1.059$$

$$M_{t4} = 2.4660$$

$$M_4 = 2.6318$$

$$\delta_4 = 2.80^\circ$$

Further downstream behaviour can be calculated as shown earlier.

### **APPENDIX THREE**

#### **CHOKING IN PIPELINES**

It was found that when the gas supply system was first built it was impossible to achieve the flow rates required in the nozzle. This led to numerous delays and breakages. It was found that this was due to choking in the one quarter inch piping which was then being used.

If the flow in the piping is considered to be adiabatic, then the equation below for Fanno flow<sub>(43)</sub> in a constant area duct with friction can be applied.

$$4fL_*/D = 1/k \left( \frac{1-M^2}{M^2} \right) + \left[ \frac{(k+1)}{2k} \right] \ln \left( \frac{(k+1)/M^2}{2+(k-1)M^2} \right)$$

where  $L_*$  = choking distance, m  
 $D$  = pipe diameter, m  
 $M$  = mach number  
 $k$  = ratio of specific heats of gas  
 $f$  = Fanning friction factor

If we use IN3/WM2 as an example, from figure 5.1 the gas mass flow rate is 0.025 kg/sec at 10 bars driving pressure. Then given that the pipe inner diameter is 3.1 mm [early pipe of outer diameter 6.35 mm (one quarter inch)] then the Mach number in the pipe can be calculated and substituted into the above equation to find a value of  $L_*$ . It should be borne in mind that the pipe length in the gas system is about 3 m.

With  $m = 0.025$  then  $V$  the gas velocity in the pipe  $= m/\rho A$  where  $A$  is pipe cross sectional area and  $\rho$  is air density. Thus  $V = 252$  m/sec. Thus  $M = 0.77$  for air ( $T = 265K$ ) using equations 3.5 and 3.7. If we take  $f = 0.004$  and substitute  $M$  into the above equation then  $L_* = 0.019$  m or 19 mm. Thus choking takes place in a very short distance.

However the pipe used in the final design [12.7 mm outer diameter (half inch)] has an inner diameter of 10.21 mm. Thus for the same mass flow rate of gas  $V = 23$  m/sec. Thus  $M = 0.07$  and  $L_* = 87$  m.

From this it can be seen that the final pipe diameter of 10.21 mm prevented choking in the pipeline.

## APPENDIX FOUR

### DERIVATION OF DISCHARGE EQUATION (4.1) FOR AN ORIFICE METER

Consider the flow through the sharp edged pipe orifice shown in Figure A1.1<sub>(45)</sub>. Flow separation at the sharp edge of the orifice throat causes a recirculation zone to form. The mainstream flow accelerates from the orifice throat to form a vena contracta at section (2) and then decelerates to fill the pipe. At the vena contracta the flow area passes through a minimum, the streamlines are essentially straight, and the pressure is uniform across the pipe section.

The theoretical flow rate may be related to the pressure differential between sections (1) and (2) by applying the continuity and Bernoulli equations.

Bernoulli's Equation

$$P_1/\rho + V_1^2 + gz_1 = P_2/\rho + V_2^2 + gz_2$$

If we make the following assumptions:

1. Steady Flow
2. Incompressible Flow
3. Flow along a streamline
4. No friction
5. Uniform velocity at sections (1) and (2)
6. No streamline curvature at sections (1) and (2), so pressure is uniform across those sections
7.  $z_1 = z_2$

Then from Bernoulli's Equation:

$$\begin{aligned} P_1 - P_2 &= \rho/2(V_2^2 - V_1^2) \\ &= \rho V_2^2/2 [1 - (V_1/V_2)^2] \end{aligned} \quad (A1.1)$$

and from the continuity equation:

$$\rho V_2 A_2 - \rho V_1 A_1 = 0$$

or

$$V_1 A_1 = V_2 A_2 \quad \text{so} \quad (V_1/V_2)^2 = (A_2/A_1)^2$$

substituting into equation A1.1

$$P_1 - P_2 = \rho V_2^2/2 [1 - (A_2/A_1)^2]$$

solving for the theoretical velocity,  $V_2$ :

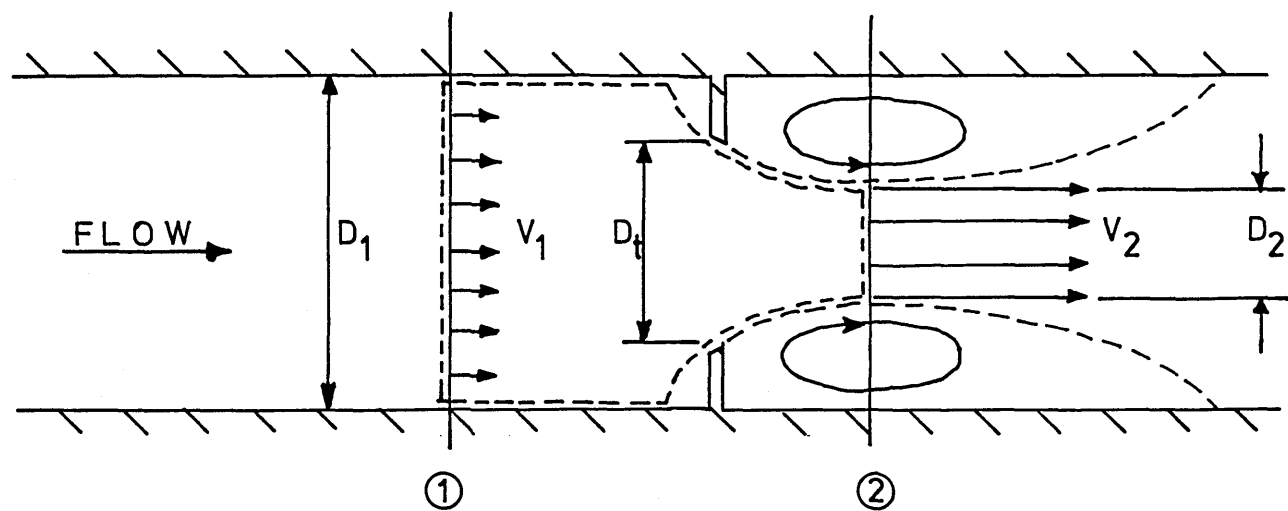
$$V_2 = [2(P_1 - P_2)/(\rho\{1 - (A_2/A_1)^2\})]^{0.5} \quad (A1.2)$$

The theoretical flow rate is then given by

$$m_{\text{theory}} = \rho V_2 A_2 = \rho [2(P_1 - P_2)/(\{1 - (A_2/A_1)^2\})]^{0.5} A_2$$

or

FIGURE A1.1



FLOW THROUGH AN ORIFICE METER

$$\dot{m}_{\text{theory}} = A_2 [2\rho(P_1 - P_2)]^{0.5} / [1 - (A_2/A_1)^2]^{0.5} \quad (\text{A1.3})$$

In order for the meter to be used to calculate the actual mass flow rate the theoretical equation must be adjusted, to account for the fact that the area at section (2) is unknown, the velocity profiles are not quite theoretical and frictional losses occur by using a discharge coefficient, K:

where:

$$K = (\text{actual mass flow rate}) / (\text{theoretical mass flow rate})$$

therefore with  $D_t/D_1 = \beta$ , and  $(A_t/A_1)^2 = (D_t/D_1)^4 = \beta^4$ :

$$\dot{m}_{\text{actual}} = KA_t [2\rho(P_1 - P_2)] / [1 - \beta^4]$$

If the term  $[1 - \beta^4]$  is included with the discharge coefficient then the constant term is called the velocity of approach factor, C, so

$$\dot{m}_{\text{actual}} = CA_t [2\rho(P_1 - P_2)]$$

For the flow of gases, an expansion factor Y, which accounts for the change in gas density as it expands from  $P_1$  to  $P_2$  is included and is given by<sup>(44)</sup>:

$$Y = 1 - [1 - (P_2/P_1)](0.41 + 0.35\beta^4)/k]$$

therefore:

$$\dot{m}_{\text{actual}} = YCA_t [2\rho(P_1 - P_2)] \quad (\text{A1.4})$$

or for the volume flow rate divide through by  $\rho$ :

$$Q_{\text{actual}} = YCA_t [2(P_1 - P_2)/\rho] \quad (\text{A1.5})$$

## APPENDIX FIVE

### CALIBRATIONS

Pressure Transducers - the pressure transducers used for the project were all manufactured by Bell and Howell. They were calibrated either by connecting the pressure gauge to a system containing a mercury manometer and measuring the millivolt output for a given pressure, as in the case of the 0-3 bars transducer and the differential transducer or by connecting to a system containing a pressure test gauge, in place of the manometer, as in the case of the 0-100 bars pressure transducer. The 0-3 bars (1.0 bar = 5.102mV) pressure transducer was used for measuring the stagnation pressure in pitot tubes. The differential (1.0 bar = 9.9285 mV) and 0-100 bars (1.0 bar = 4.4603mV) transducer were used on the orifice meter.

Wax Tank - As mentioned in Chapter 4 the wax tank was operated so that liquid flowed out the bottom of the tank when gas flowed into the top of the tank. This was experimentally investigated using water. The rotameter was calibrated so that the volume flow rate of air passing through the needle valve from the airline was known. The tank was then pressurized between 0.2 and 0.5 bars and the water flow rate out of the tank measured and the rotameter reading noted. It was found, provided the tank was full, that the water flow rate out of the tank was independent of the pressure in the tank and the volume flow rate of air was equal to the volume flow rate of water. Thus the wax flow rate could be determined by simply reading the rotameter.

APPENDIX SIX

DERIVATION AND STANDARD ERRORS OF ESTIMATES OF THE MEANS OF  
THE  
ROSIN RAMMLER AND LOG NORMAL DISTRIBUTIONS

# 1. ROSIN RAMMLER DISTRIBUTION

$$G(x) = 1 - \exp (-x/x_{rrm})^n \quad (A6.1)$$

or

$$\log \ln [1/(1-G(x))] = n \log x - n \log x_{rrm} \quad (A6.2)$$

Let

$$\log x = X$$

$$\log\{\ln[1/(1 - G(x))]\} = Y$$

Then from equations A6.1 and A6.2

$$Y = nX - n \log x_{rrm} \quad (A6.3)$$

If equation A6.3 is expressed in the form

$$Y = bX + a \quad (A6.4)$$

it follows that

$$x_{rrm} = 10^{(-a/b)} \quad (A6.5)$$

where  $n = b$  and  $-n \log x_{rrm} = a$

## Error Analysis

From the error equation

$$\text{var}(x_{rrm}) = [\partial x_{rrm} / \partial a]^2 \text{var}(a) + [\partial x_{rrm} / \partial b]^2 \text{var}(b)$$

it follows that

$$\begin{aligned} \text{var}(x_{rrm}) &= 10^{(-2a/b)} \ln^2 10 [ \text{var}(a)/b^2 + a^2 \text{var}(b)/b^4 ] \\ \text{var}(x_{rrm}) &= 5.3/b^2 10^{(-2a/b)} [ \text{var}(a) + a^2 \text{var}(b)/b^2 ] \end{aligned} \quad (A6.6)$$

where variance of the Rosin Rammler Distribution Parameter,  $\text{var}(n) = \text{var}(b)$ ,  $\text{var}(a)$  is the variation of the intercept  $a$ ;  $\text{var}(b)$  is the variance of the slope  $b$  as given from the regression analysis of the straight line equation A6.4. The mass mean diameter can be calculated from equation A6.2 substitute  $G(x) = 0.5$ . It follows than that

$$\begin{aligned} b \log x_{mmd} &= -0.1592 + b \log x_{rrm} \\ x_{mmd} &= x_{rrm} e^{-0.1592/b} \end{aligned}$$

The variance of the mass mean diameter can be calculated as before using the error equation. If we let  $0.1592 = k$  then

$$\begin{aligned} \partial x / \partial x_{rrm} &= e^{(-k/b)} \\ \partial x / \partial b &= x_{rrm} (k/b^2) e^{(-k/b)} \end{aligned}$$

therefore

$$\text{var}(x_{mmd}) = e^{-2k/b} \{ \text{var}(x_{rrm}) + [kx_{rrm}/b^2] \text{var}(b) \}$$

## 2. LOG NORMAL DISTRIBUTION

$$G(x) = 1/(\sigma_z [2\pi]^{0.5}) \int_{-\infty}^{\ln x} \exp - [(\ln x - \ln x_{mmd})^2 / (2 \sigma_z^2)] d(\ln x)$$

on substitution of:

$$u = (\ln x - \ln x_{mmd}) / \sigma_z \quad (A6.7)$$

one obtains

$$G(x) = 1/(2\pi)^{0.5} \int_{-\infty}^u \exp - [u^2/2] du \quad (A6.8)$$

This is the standardised form of the normal distribution, and the value of  $u$  can be obtained from tables of the normal distribution for each given value of  $G(x)$ .

Equation A6.7 is a straight line:

$$u = bX + a$$

where

$$b = 1/\sigma_z; a = -\ln x_{mmd} \sigma_z; \ln x_{mmd} = -a/b$$

From the error equation

$$\begin{aligned} \text{var}(x_{mmd}) &= (\partial x_{mmd} / \partial a)^2 \text{var}(a) + (\partial x_{mmd} / \partial b)^2 \text{var}(b) \quad (A6.9) \\ \partial x_{mmd} / \partial a &= \exp(-a/b) (-1/b) \\ \partial x_{mmd} / \partial b &= \exp(-a/b) (a/b^2) \end{aligned}$$

therefore

$$\text{var}(x_{mmd}) = 1/b^2 \exp(-2a/b) [\text{var}(a) + a^2 \text{var}(b)/b^2] \quad (A6.10)$$

and given that  $\sigma_z = 1/b$  then from the error equation

$$\begin{aligned} \text{var}(\sigma_z) &= (\partial \sigma_z / \partial b)^2 \text{var}(b) = (-1/b^2)^2 \text{var}(b) \\ \text{var}(\sigma_z) &= \text{var}(b)/b^4 \quad (A6.11) \end{aligned}$$

If the distribution is  $\log_{10}$  and not  $\ln$  then if we let the geometric standard deviation equal  $\sigma_g$  then  $\sigma_z = \ln \sigma_g$  thus  $\sigma_g = e^{-1/b}$

$$\text{The variance of } \sigma_g = 1/b^4 e^{(2/b)} \text{var}(b) \quad (A6.12)$$

## APPENDIX SEVEN

### CALCULATION OF PITOT TUBE SHOCK BEHAVIOUR

By following the same reasoning as used earlier, in Chapter 3 on gas flow, the position of the oblique shock wave can be calculated (the nomenclature followed is the same).

IN3/WM2 has the following properties:

$$A_* = 14.43 \text{ mm}^2 \quad A_e = 38.45 \text{ mm}^2 \quad A_e/A_* = 2.667$$

$$\text{therefore : } M = 2.51 \quad P/P_t = 0.05762$$

thus the driving pressure is 17.35 bars when the nozzle operates into ambient air of pressure 1 bar.

The angle between the pitot tube position and the exit,  $\theta$ , is  $\tan^{-1} 1.1025/2.29$ . Therefore  $\theta = 25.71^\circ$ .

Using the equations from section 3.12:

$$\begin{aligned} 2.51 \sin \theta &= M_{n1} = 2.51 \times 0.4400 \\ &= 1.1044 \end{aligned}$$

$$P_1/P_2 = 1.2565$$

$$M_{n2} = 0.9084$$

$$\begin{aligned} P_1 &= 0.05762 \times P_{\text{driving}} \\ &= 1/1.2565 = 0.7958 \end{aligned}$$

$$P = 13.8118 \text{ bars}$$

Thus the oblique shock should have been measured at pressures above 13.8 bars at a distance 2.29 mm from the exit plane.

However the results show (table 5.3.2) that the driving pressure was = 7.4 bar absolute when the stagnation pressure, measured by the pitot tube, first starts to drop and so the pressure drop cannot be caused by the oblique shock at the exit of the nozzle. The position of the oblique shock can be calculated as shown below:

$$P_1 = 0.05762 \times 7.4 = 0.4264 \text{ bars absolute}$$

$$M = 2.51$$

$$P_1/P_2 = 2.3453 \text{ as } P_2 = 1.00 \text{ bars}$$

$$M_{n1} = 1.4674$$

$$2.51 \sin \theta = 1.4674$$

$$\theta = 35.7763^\circ$$

$$M_{n2} = 0.7129 \quad T/T_o = 1.2985$$

$$M_{t2} = 2.51 \cos \theta \ (1.2985)^{-1/2} = 1.7871$$

$$M_2 = 1.9240$$

Thus the oblique shock is reflecting from a position  $1.1025/\tan \theta = 1.53$  mm from the exit plane. Therefore the pressure being measured by the pitot tube must be caused by the reflected shock. The angle between the reflected shock and the protrusion can easily be calculated:

$$M_{n2} = M_2 \sin (\theta - \delta)$$

$$M_{t2} = M_2 \cos (\theta - \delta)$$

therefore:

$$\tan (\theta - \delta) = 0.7129/1.7871$$

$$= 0.3989$$

$$\theta - \delta = 21.7478^\circ$$

$$= 14.0285^\circ$$

when  $\delta = 14.0^\circ$  at  $M = 1.924$  the angle  $\phi_2$  between the shock reflection and the incident wave is  $45.902^\circ$ . Thus the angle between the reflected shock and the protrusion side,  $\theta_2 = 45.902 - 14.0285 = 31.8731^\circ$

therefore:

$$M_{n2} = M_2 \sin \phi_2 = 1.924 \sin 45.902^\circ = 1.3817$$

$$M_{t2} = M_2 \cos \phi_2 = 1.924 \cos 45.902^\circ = 1.3389$$

$$M_{n3} = 0.7476 \text{ from normal shock tables}$$

$$M_{t3} = 1.3389 \times (1.243)^{-1/2} = 1.2009$$

$$M_3 = 1.4146$$

$$P_3/P_2 = 2.0604 \text{ thus as } P_2 = 1.00 \text{ then}$$

$$P_3 = 2.0604 \text{ bars}$$

## **APPENDIX EIGHT**

### **EXPERIMENTAL DETERMINATION OF VISCOSITY AND SURFACE TENSION**

## VISCOSITY

The viscosity of the waxes was measured using an Ostwald viscometer. This was placed in a paraffin bath at 100°C. The calibration of the viscometer was given as:

$$V = Ct$$

where:

$V$  = kinematic viscosity in  $\text{mm}^2/\text{sec}$

$C$  = 0.0923 (a constant of the viscometer)

$t$  = time in seconds

In order to change the viscosity of the wax, a polyethelene was added so that the wax contained 10% and 20% of the polyethelene by weight.

The wax and polypropylene were obtained from Kerax Limited. They were chosen to be as similar as possible to those used by Kim and Marshall<sup>(19)</sup>. The wax was Kerawax 508 and the polyethelene was Epolene N11.

The results of the viscometer tests are shown in Table A.8.1. The results obtained were as follows:

$$\text{Kerawax 508} = 15.28 \text{ mm}^2/\text{sec}$$

$$\text{Kerawax 508} + 10\% \text{ Epolene N11} = 25.94 \text{ mm}^2/\text{sec}$$

$$\text{Kerawax 508} + 20\% \text{ Epolene N11} = 30.20 \text{ mm}^2/\text{sec}$$

## SURFACE TENSION

The surface tension of waxes was determined using Sugden's Differential Method at 100°C.

The apparatus was checked for accuracy by first calibrating with distilled water, ethyl alcohol and acetone. The results obtained showed that the apparatus was very accurate.

Table A.8.2 shows the values obtained for Kerawax 508 and Kerawax 508/Epolene N11 mixtures.

N.B. The experimental methods used were based on those used as first year experimental practicals in the Materials Department.

TABLE A.8.1  
EXPERIMENTAL RESULTS OF VISCOSITY TESTS

| WAX<br>COMPOSITION            | TIME<br>s                        | AVERAGE<br>Time | KINEMATIC<br>VISCOSITY<br>mm <sup>2</sup> /s |
|-------------------------------|----------------------------------|-----------------|----------------------------------------------|
| KERAWAX 508                   | 168.0<br>164.4<br>164.0<br>165.7 | 165.525         | 15.278                                       |
| KERAWAX 508<br>+ 10 % EPOLENE | 292.0<br>285.2<br>278.0<br>269.0 | 281.05          | 25.941                                       |
| KERAWAX 508<br>+ 20 % EPOLENE | 328.9<br>326.2<br>327.9<br>329.4 | 328.10          | 30.284                                       |

**TABLE A.8.2**

**EXPERIMENTAL SURFACE TENSION RESULTS**

| wax<br>mixture           | $h_1$<br>mx10 <sup>2</sup> | $P_1$<br>Pa | $h_2$<br>mx10 <sup>2</sup> | $P_2$<br>Pa | Surface<br>Tension<br>J/m <sup>2</sup> |
|--------------------------|----------------------------|-------------|----------------------------|-------------|----------------------------------------|
| Kerawax 508              | 1.75                       | 171.68      | 3.85                       | 377.69      | 0.02416                                |
| Kerawax 508<br>+ 10% N11 | 1.75                       | 171.68      | 3.44                       | 337.46      | 0.01944                                |
| Kerawax 508<br>+ 20% N11 | 1.43                       | 140.61      | 3.55                       | 348.25      | 0.02435                                |

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