

MEASUREMENT OF VELOCITY PROFILES IN ULTRAFILTRATION

A Thesis

Submitted to the University of London for

the Degree of

DOCTOR OF PHILOSOPHY

and to the

Imperial College of Science and Technology (London)

for the

DIPLOMA OF THE IMPERIAL COLLEGE

by

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1985

To Professor Henry Sawistowski,

A brilliant educator and loyal patriot.

ACKNOWLEDGEMENTS

This list of acknowledgements must begin with thanks due to the late Prof. Henry Sawistowski who instigated and supervised this work, and to my other supervisor, Dr. Michael Streat who has encouraged and supported me, particularly in the later stages of this project. Practical assistance at Imperial College came principally from Austin Harrap and Chris Haddow but help from everyone in the Department of Chemical Engineering was appreciated.

Financial support came from the Science and Engineering Research Council and I.C.I. Organics Division. The latter also donated the Mono pump and Patterson Candy International supplied membranes and tubular modules. Rhône Poulenc provided flat membranes.

Dr. Malcolm Metcalfe (I.C.I.) provided excellent project direction and Dr. Alan Merry (P.C.I.) gave technical assistance. I do regret that while we more than succeeded in developing the necessary equipment, we did not have sufficient time to use it to repay all of the investment in the project.

Mr. M.J.Dyer gave me much useful advice on designing and constructing the membrane channel, and allowed me to use the machines in his firm - 'Engineering Services and Developments Ltd.'. This formed a useful part of my education. Finally, I cannot sufficiently thank his daughter, my wife Mary, for her patience, devotion and assistance in preparing and typing this thesis.

ABSTRACT

The thesis contains a description of the development of a laser Doppler anemometer suitable for velocity measurements close to solid walls and the design and construction of a membrane channel in which such axial measurements could be made.

Results are reported which validate and demonstrate the technique in this application. Subjectivity is removed from the results by a computer program which curve fits the velocity profile to force the 'no slip at the wall' boundary condition and plots the profiles on different axes.

Turbulent velocity profiles were obtained for both water and a 0.1 % w/w egg albumen suspension using impermeable and permeable films.

For water, the effect of feed flowrate, pressure, membrane use and membrane permeability on the velocity profile are determined. Only the former has an effect and can be described using dimensionless groups based on the wall shear stress. The dimensionless velocity profile is compared with the literature. Results have been obtained inside the traditional laminar boundary layer ($y^+ < 5$) with readings as low as $y^+ = 1.1$.

In order to investigate the possibility of turbulent bursts, velocity distributions were determined at various distances from the membrane. This showed that there were measurable variations in average Doppler frequency, even inside the traditional boundary layer. It remains to be

seen whether these variations are statistically significant.

For the egg albumen suspension, velocity profiles were evaluated. The dimensionless groups used for the single component system were unable to correlate the profile accurately, particularly in the buffer zone $5 < y^+ < 30$. This could be due to solute buildup at the membrane surface resulting from the total solute retention, thus forming a viscosity gradient.

Results are also reported of Scanning Electron Microscopy studies of commercial membranes and a study of the performance of different sections of commercial tubular membranes.

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CHAPTER 1 INTRODUCTION

The world wide membrane equipment market is very large, currently around \$500 million p.a., having started from essentially nothing in 1962. By implication, membranes form one of the principle separation technologies of the future.

A membrane will perform a separation on a multicomponent fluid once a driving force has been applied across it. The driving force may be either a pressure gradient, a concentration gradient or a charge gradient. Pressure gradients are by far the most commercially useful. The techniques are broken down into three categories, reverse osmosis, ultrafiltration and crossflow microfiltration.

Reverse osmosis (R.O.) is the most widely used technique and the usual pressure driving force is of the order of tens of bars. R.O. is primarily used in desalination, the separation of inorganic solutes from water. Ultrafiltration (U.F.) requires pressure driving forces of upto 10 bars and has a more diffuse range of applications. U.F. is used to concentrate or fractionate larger molecules up to submicron particles. The least used technique is microfiltration, where nominal pressure driving forces are used to retain particles of the order of microns. U.F., and to some extent microfiltration, offer new fractionation methods and hence new processes to a wide variety of industries, from foods to effluent treatment.

Concentration gradients are required to make dialysis work, although the process is relatively slow compared to pressure driven processes and hence of limited application to high value products such as pharmaceuticals. Electro-dialysis is also more expensive than pressure driven processes, but charge gradients do have unique applications, particularly in desalting.

The preferential rejection of a solute at the membrane surface leads to a solute buildup near the wall. This process is known as concentration polarisation and results in the loss of performance. The increased solute concentration near the membrane leads to an increase in viscosity which reduces the flow through the membrane. The solute concentration gradient across the membrane is also increased and hence solute passage through the membrane increases in proportion to the increased concentration driving force. Any extraneous material in the feed can settle on the membrane surface, since there is a transverse flow through the membrane. This process is known as fouling and there is a consequential loss in performance. Fouling can block areas of membrane and hence reduce the flow of solvent. Depending on the foulant-membrane-solute-solvent system, the proportion of solute passage through the membrane may be either increased or decreased. Concentration polarisation and fouling are the two major detrimental process phenomena preventing the wider application of membrane technology. The most common method of reducing these effects is to improve the mixing of the feed in the membrane channel. This implies either short length membrane channels or, more commonly, higher turbulent

Reynolds numbers in the channels.

This study aims to measure the axial velocity profiles over the top of, and as close to the membrane as possible, in order to lead to a better understanding of the turbulent limitation of concentration polarisation and fouling.

CHAPTER 2 LITERATURE SURVEY

2.1 Membrane Technology

Membranes are being used more and more in industry for separation processes since they do not require an energy intensive change of phase (1). Most membranes are used for desalination, which is the removal of salts to produce a potable or industrial water supply from sea or well water. In fact, by 1977, 20% of this was carried out by R.O. and this percentage is thought to be increasing by 20-30% per annum (2) 1979, (3) 1980. The bulk of the remainder is done by multistage flash distillation. Other uses of pressure driven membrane processes (R.O., U.F. only) are given in Table 2.1.

A recent review of membrane technology is given by Fane (35) who defines a number of terms in common use. The feed to the membrane is split into the permeate and the concentrate. The permeate is the stream that passes through the membrane and the remainder is called the concentrate. The flowrate of the permeate through the membrane is normalised per unit area of membrane and referred to as the permeate flux. The rejection of a particular solute i , normally expressed as a percentage, is defined by,

$$R_i(\%) = \left(1 - \frac{c_{p_i}}{c_{f_i}} \right) \times 100. \quad (2.1)$$

where c_p and c_f are the concentrations of the particular solute in the permeate and the feed respectively. It is a measure of the separation of solute i performed by the membrane, the higher the rejection, the greater the

TABLE 2.1 Applications of Reverse Osmosis and
Ultrafiltration

	Ref.
* Artificial kidneys	4
* Biotechnology	5
* Cheese and yogurt manufacture	6
* Cooling tower blowdown recycling	7
* Dyestuffs concentration	8
* Electrocoat paint wastewater recycling	9
* Electronics rinsewater manufacture	10
* Electroplating waste recycling	11
Fish farming	12
* Food industry	13
* Fruit juice concentration	14
* Gas separation	15
Helium recovery from natural gas	16
* Hydrogen recovery from purge streams	17
* Irrigation field drainage recycling	18
* Meat industry effluents	19
* Military water supply	20
* Milk concentration	21
* Molasses concentration	22
* Potato starch recovery	23
* Protein separation of the blood	24
* Pulp and paper industry	25
* Sewage treatment	26
* Soluble cutting oil recycling	27
Soya bean processing	28
Starch hydrolysis	29
* Sugar industry	30
Tanning industry	31
* Textile effluent recycling	32
* Ultrapure water for laboratory use	33
Wheat starch protein	34

(An asterisk indicates that at least one commercial plant is currently operating.)

separation.

The most comprehensive review of the technology is given in the patents listing by Keller (36). At present membrane research divides into two categories, improved membranes or improved processes.

Sometimes, the feed creates a dynamic membrane made up of solute and foulant, particularly when large solutes are used in U.F.. This dynamic membrane can then dictate the overall membrane performance, rather than the carefully constructed physio-chemical polymer membrane.

Membrane performance usually declines with time due to concentration polarisation and fouling. For a given membrane, the only way of overcoming this problem is to improve the process. Murkes (37) suggests that better processes provide more commercial benefit than better membranes.

2.2 The Effect of Axial Velocity on Membrane Performance

This section can logically be reviewed under four headings, i.e. experimental and theoretical examinations of fouling and concentration polarisation.

2.2.1 Fouling Experimental

A good recent review of fouling was given by Matthiasson (38). A descriptive senario of fouling was given by Velicangil (39) who broke the fouling process into three types occurring over different characteristic times. The initial phase consists of the plugging of large pores or

membrane defects, occurring over a time span of seconds, whereas a continuous fouling film forms over a period of minutes. The thickness of this film, and hence the permeability, will be primarily governed by the membrane flux, the axial velocity profile and membrane-foulant interactions. The third phase occurs over a period of hours. Velicangil's explanation was the polymerisation of the cheese whey protein in the gel layer (concentration boundary layer). Another more general reason would be the compaction and growth of the former phases.

Scanning electron microscopy has shown the existence of foulants on and inside used membranes (Livingstone (40) Matsumura (41) and Belfort (42)). Direct fouling thickness measurements were carried out by Carter (43) using ferric hydroxide doped brine in a perspex reverse osmosis rig. He predicted theoretically that,

$$\frac{\delta}{h} = \frac{\alpha r_d}{Re^{1.75}} \left(1 - \exp \left(\frac{-Re^{1.75} t}{\alpha h} \right) \right) \quad (2.2)$$

where δ is the foulant layer thickness, h is the half channel height, r_d the rate of foulant deposition, t the time from the start of the experiment and α a constant. His experimental work showed that, for infinite time experiments, the exponent on the Reynolds number was actually 1.43.

Since the flux will be roughly inversely proportional to the foulant thickness, and assuming the process is foulant layer controlled,

$$J_v \propto Re^{1.43} \quad (2.3)$$

Flux decline data usually fits the form

$$\frac{J_v(t)}{J_{v0}} = \left(\frac{t}{t_0} \right)^b \quad (2.4)$$

where $J_v(t)$ and J_{v0} are the prevailing and initial fluxes

recorded at the prevailing and initial times t and t_0 respectively. b is one exponent which was initially thought to be constant (Sheppard et al.(44), $b = -0.33$) but was later shown to have a system dependent form (Thomas et al. (45)). See Fig. 2.1. Sheppard et al.(46) suggest that

$$b \propto u^{-\frac{1}{2}} \quad u > u_t \quad (2.5)$$

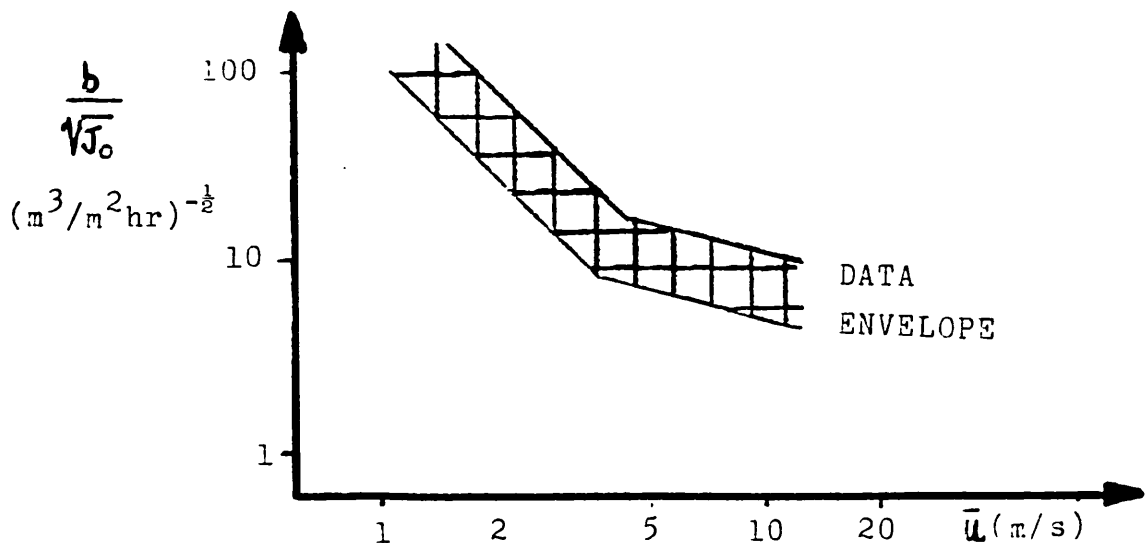
for river water. Various other plots of the exponent b have been used as a means of comparing long term comparisons between different commercial membranes and systems (Kunisada (47), Sammon (48)). However, the key point is the existence of a threshold velocity, u_t , above which flux decline is much less a function of increased Reynolds number. This leads to design criteria and some of these are listed in Table 2.2. The bounds on the virtues of increasing Reynolds number are set by increased pumping costs and, in some cases, although there is a threshold velocity, the separation performance decreases with increasing Reynolds number (45). This is believed to be due to a less effective "dynamic membrane" at high Reynolds numbers, i.e. the foulant layer is performing a separation.

The flux decline is in general more marked for highly permeable membranes (Lim et al.(53)) which is why fouling is very important in U.F.. Experimental work by Kimura et al. (54) shows that flux decline reaches a steady value after a period of days. However, this is not a commercial solution. Various techniques like chemical cleaning, oversized sponge balls (Loeb et al.(55)) etc. are used after a period of hours in order to regain as much of the initial flux as possible. These techniques essentially remove the film foulants and, to a lesser extent, the penetrated foulants.

TABLE 2.2 Recommended Axial Velocities or Reynold Numbers.

Reference	System	Recommendation
Sheppard et al. (46)	Water & brine using tubular R.O. membranes	$5 < u_t < 24 \text{ ft/s}$
Sheppard et al. (49)	River water using thin channel R.O. membranes	$Re > 10^4$
Jackson (50)	Brine and rust using tubular membranes	$Re > 10^4$
Tsuge et al. (51)	1/2" I.D. tubular membranes	$u > 1 \text{ m/s}$
Pepper et al. (52)	1/2" I.D. tubular membranes	$u > 2.5 \text{ m/s}$

FIGURE 2.1 Effect of Axial Velocity of Primary Sewage
on Flux Decline of Cellulose Acetate Membranes.
(Thomas et al.(45).)



It is for this reason that flux recovery is not usually total. Cleaning techniques have been reviewed by Belfort (56). Partial flux recovery can be effected by increasing the axial velocity (Jackson (50) and Sheppard (44)).

There are many authors who just deal with the relationship between J_v and u . Two U.F. applications are noteworthy. Using activated sludge, Fane et al. (57) initially found that,

$$\ln J_v \propto u \quad (2.6)$$

However, in the long term, the system became more sensitive to the axial velocity,

$$\ln J_v \propto u^{2.4} \quad (2.7)$$

Polymer lattices also benefit from increasing u (Shen et al. (58)).

$$J_v \propto u^s \quad s > 1 \quad (2.8)$$

Shen gives the reason for $s > 1$ as the pinch effect.

Particles experience a lift away from the wall due to the velocity gradient. The higher the axial velocity, the steeper the velocity gradient and hence the greater the particulate lift away from the wall. The theory of the pinch effect has been considered relevant to membrane technology by Porter (59) but has not been pursued. Wagner (60) suggests that particles less than $50\mu\text{m}$ do not affect the fouling rate because of the pinch effect. This is wishful thinking. If there are no particles in any region, the proposed L.D.A. system will not work. However, the pinch effect does exist and is covered later on.

Two methods of flux improvement which impinge on the use of axial velocities are as follows. Fane et al. (57)

added additional fibres (about $5\mu\text{m}$ long) to an effluent to give a degree of scouring. Flux increases of upto 270% were recorded. The second method relies on creating a dynamic membrane on another membrane. The dynamic membrane can then be removed on cleaning and another formed for the next operation. In this case, high axial velocities are not necessarily a good thing. Flux increases of upto 230% are reported (Belfort (61)) with a corresponding reduction in rejection by as much as 50%.

In summary, it is clear that increased Reynolds numbers lead to higher and more stable fluxes although rejections may be impaired. This may be due to scouring, the pinch effect and/or some other phenomenon not covered in the literature.

2.2.2 Concentration Polarisation Experimental

The bulk of experimental work on concentration polarisation has used inference or non-quantifiable methods because the concentration boundary layer is, in most cases, smaller than the momentum boundary layer. This work aims at developing equipment to quantify the momentum boundary layer in order to place an understanding of the concentration boundary layer on a stronger footing.

The ratio of the two thicknesses of boundary layer is normally given as the Schmidt number to some power less than 1. For laminar flow over an infinite, impermeable, flat plate the exponent is $1/3$ and can be derived analytically. (Kays (62)) Using this result, the ratio of momentum to

concentration boundary layer thickness δ_m/δ_c is illustrated in Table 2.3.

In 1966, Brian (63) suggested that concentration polarisation could be reduced by increasing axial velocity, an obvious but important idea. Conceptually though, an infinite axial velocity, and hence infinitesimal boundary layer, would still leave the membrane polarised in the pores. This concept has been explored by Thomas et al.(64) and Shor et al.(65). However, concentration polarisation in the membrane channel dominates that in the pores for practical axial velocities. The more permeable and solute rejecting the membrane, the more the channel is polarised, so this has a tempering effect on the ratio of boundary layer thicknesses. The results in Table 2.3 are for an impermeable wall with a homogenous solution. When the wall is semi-permeable, the concentration boundary layer increases in thickness. The momentum boundary layer thickness will only increase if the increased solute concentration leads to an increase in viscosity.

The bulk of the data records the observed rejection as a function of axial velocity. The observed rejection, $R_{obs.}$, is derived from the feed and permeate measured concentrations. The proportionality observed is

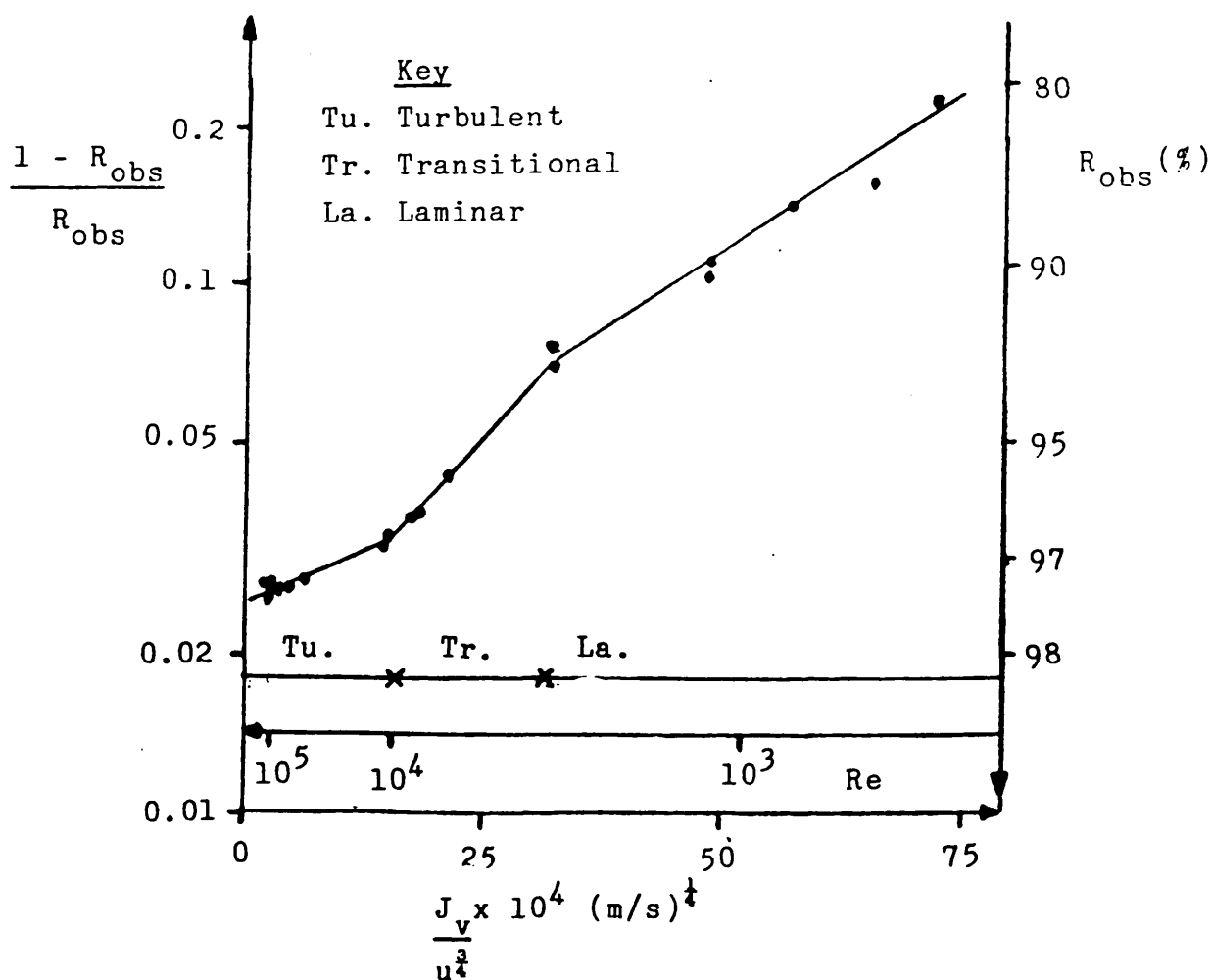
$$\ln\left(\frac{1 - R_i}{R_i}\right) \propto \left(\frac{J_v}{u}\right) \quad (2.9)$$

The actual curve has been plotted in Fig. 2.2. Many papers have been written expanding this proportionality further (Shor et al.(65), Sheppard et al.(49)(44)(66) and Thomas et al.(64)). A slight variation in exponent has been proposed by Jonsson et al.(67)

TABLE 2.3 Ratio of the Momentum to Concentration Boundary Thickness (δ_m/δ_c) for Laminar Flow over an Infinite, Impermeable Flat Plate for Two Solutes

	Sc.	δ_m/δ_c
Sodium Chloride Solution (1M)	745	82
Sucrose Solution (1M)	2230	171

FIGURE 2.2 The Effect of Axial Velocity on the Observed Rejection. (Sheppard et al. (46))



$$\ln\left(\frac{1 - R_1}{R_1}\right) \propto \left(\frac{J_v}{u}\right)^{0.8} \quad (2.10)$$

The only paper that really sticks out is given by Kimura et al.(54) which correlates the bulk and gelling concentrations c_b and c_g thus.

$$\ln\left(\frac{c_g}{c_b}\right) \propto u^{0.8} \quad (2.11)$$

The difficulty is that the gelling concentration is not a directly measurable quantity.

Mass transfer coefficients can be derived for membrane systems and hence attempts at more generalised correlations have been made. Table 2.4 summarises some of these dimensionless correlations.

There have been attempts to measure the actual concentrations of solute near the membrane. The most quantitative work has been done by Hendricks et al.(68), who made two conductivity probes, one of 20 μ m diameter and the other of 50 μ m. The closest the probes came to the surface was 30 μ m, with an estimated error of $\pm 50\mu$ m in the position of the probes relative to the membrane. Although the probes were intrusive and significant in size compared to the distance from the wall, the solute concentration was found to decrease exponentially with distance from the membrane for $130 < Re < 1400$.

Less quantitative work has been carried out using shadowgraphs and other types of interferometers. For example, buoyancy instabilities can be observed when the membranes are uppermost (71)(72). A series of papers by Belfort (73) and Mahlab (74)(75), attempt to derive theories

TABLE 2.4 Membrane Mass Transfer Correlations

Ref.

67 (2.12)	$Sh \propto Re^{0.8} Sc^{0.33}$	Thin channel Inorganic salts $1000 < Re < 2500$
62 (2.13)	$Sh = 0.332 Re^{0.5} Sc^{0.33}$	Flat plate Laminar flow
69 (2.14)	$Sh \propto Re^{0.55} Sc^{0.33}$	Stirred cell, laminar flow.
(2.15)	$Sh \propto Re^{0.75} Sc^{0.33}$	Stirred cell, turbulent flow
(2.16)	$Sh \propto Re^{0.33} Sc^{0.33} \left(\frac{x'}{L}\right)^{0.33}$	Thin channel and tube laminar flow.
(2.17)	$Sh \propto Re^{0.8} Sc^{0.33}$	Thin channel and tube turbulent flow.
70 (2.18)	$Sh = \text{const.}$	Far downstream laminar flow
(2.19)	$Sh \propto Re^{0.5} Sc^{0.33} \left(\frac{x'}{L}\right)^{0.5}$	Developing laminar flow.

Sh = Sherwood number

L = Channel/pipe length

 x' = Characteristic flow dimension e.g. diameter of tube.

relating the interference pattern fringe spacings and the concentrations of dilute solutions. However, these theories are not tested in experiments. Vilker et al.(76)(77) have produced a simplified theory and used interferometry down to within $200\mu\text{m}$ of the membrane in an unstirred batch cell. Extrapolated experimental concentration gradients to the membrane predict surface concentrations of upto 580 g/l of BSA with bulk concentration of 100 g/l. Such a high surface concentration would have significant effects on both solute and solvent permeability. Due to the approximations made to derive the theory, there remains the question of whether these predictions are real or not.

An unusual set of observations were made by Madsen (78) who found that iron dextran and haemoglobin settle out in reproducible patterns with laminar flow over a flat membrane. When pressure transducers were fixed to the back of the membrane, pressure waves at a frequency of 100-500 Hz were noted. Strain gauges detected membrane movements of amplitude $50\mu\text{m}$ and frequency around 100 Hz. These results are claimed to have influenced the design of the DDS Type 35 modules. It is a shame that similar results are not reported by other authors. However, if this is the case, one could reasonably expect the polymer membranes to work harden. Amplitudes of $50\mu\text{m}$ are significant with active membrane surfaces only a few hundred microns thick.

The axial velocity is probably the easiest parameter that can be practically used to control concentration polarisation. Other techniques that have been tried experimentally are turbulence promoters, (79),(80),pulsating

flow, (81), rotating flow, (82), and membrane heating, (83). However, as pointed out earlier, observations of concentration polarisation have involved only bulk measurements, for example, the effect of turbulence promoters given in Fig. 2.3.

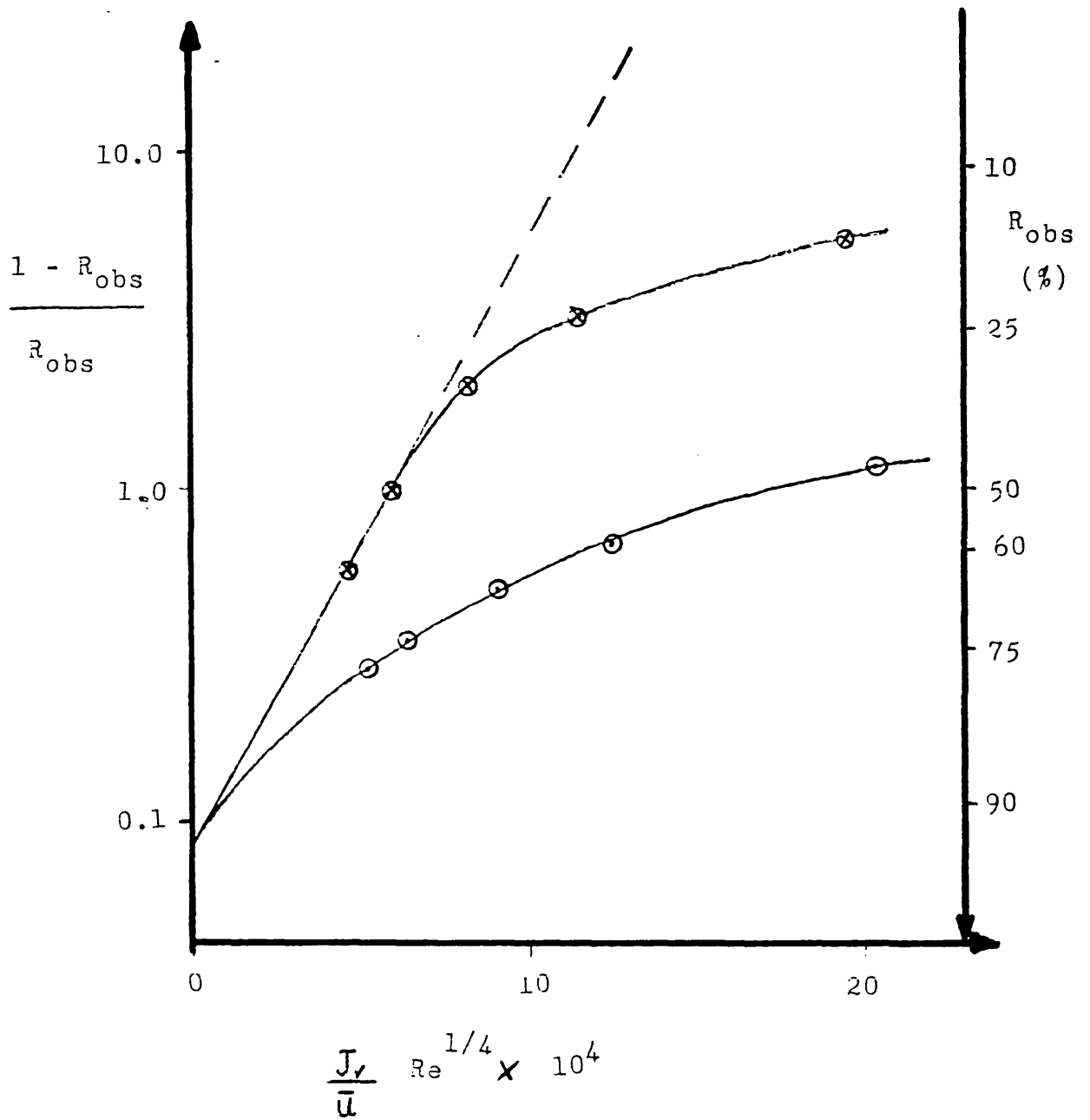
Concentration polarisation is clearly influenced by axial velocity although its effect is hard to quantify. The increased solute concentration at the membrane increases the solute concentration gradient across the membrane and decreases the osmotic pressure gradient. This normally has the effect of reducing the solvent flux and decreasing the rejection coefficients. However, there may be morphology changes which may increase the rejection such as dynamic membranes.

2.2.3 Fouling Theoretical

This section may conveniently be broken down into three processes, foulant transport to the membrane, foulant-membrane cohesion and foulant transport away from the membrane. Foulant-membrane cohesion is, to a large extent, axial velocity independent and will not be covered here. Foulant transport, however, is highly dependent on axial velocity and the direction of the foulant flow may be considered to be related although not totally symmetric.

A simple model of drag, electrostatic and Brownian movement forces acting on particles entering a vertical tubular membrane showed membrane permeation to be the dominant factor in particle deposition, (84). Given the

FIGURE 2.3 Effect of Turbulence Promoters on Rejection Coefficients. (Thomas et al.(80))



⊗ No Turbulence Promoters

⊙ Detached Turbulence Promoters

0.01M Magnesium Chloride at 600 psig.

assumptions of the model, this result is expected. However, the presence of a velocity profile, and, in this case of turbulent flow, eddies, have significant effects on deposition.

The pinch effect has already been mentioned. Due to the velocity gradient in the channel, particulates have different fluid velocities flowing past them which define tangential lift forces and, as a consequence, drag forces. The effect thus defines an 'equilibrium radius' in the channel where particles of a given size, shape and density would prefer to be, for a given fully developed flow regime. This work has been presented by Molerus et al.(85) and Blauckhage (86) and applied to membrane systems by Green et al.(87). Green's model correctly predicts a relationship first correlated by Thomas et al.(88) relating the 'threshold velocity, u_t ,' above which the rate of fouling is reduced and the membrane flux J_v .

$$u_t \propto J_v^{\frac{1}{2}} \quad (2.20)$$

The model though, contains many approximations and hence the authors were only able to claim order of magnitude predictions of fouling parameters.

Streamline flow is clearly a requisite for theoretical modelling of the pinch effect. Turbulent flow has further complications for particle deposition and entrainment. In a brilliant set of papers by Cleaver et al(89,90,91), the effects of turbulence bursts on particle movement were modelled. Cleaver et al believed these bursts to be pockets of fluid within the near wall boundary layer moving away from the wall. This, unfortunately, does not give a

mechanism. Eddies in the turbulent core have a kinetic energy spectrum. Some of these eddies have sufficient momentum in the direction of the wall to disturb the laminar boundary layer. In so doing, there must be an equal and opposite reaction which leads to Cleaver's starting point. Cleaver's papers estimate the spacing diameter and frequency of such bursts leaving the wall as functions of the fluid kinematic viscosity and the wall shear velocity. These terms are defined in Section 2.3. The model is compared with a small amount of experimental data for gas solid flow and the agreement was described as 'satisfactory'. This analysis has never been applied to membranes.

There are a number of intuitively based theoretical fouling models such as Fane's (69) scour model.

$$J_v \propto u_b^i c_b^j \quad (2.21)$$

but these might as well have been derived directly from experimental results.

Little theoretical work has been done to relate the effect of axial velocity to membrane fouling. The pinch effect and turbulence bursts are likely to be the important processes in such a study. The bulk of the theoretical papers on fouling deal with solute membrane interactions, which, unfortunately, are very system specific. Nor is there likely to be significant progress in this area in the near future because systems using impermeable channels have to be modelled first, without the complicating factor of transverse velocities.

2.2.4 Concentration Polarisation Theoretical

Of the four sections, this has by far the most papers written under its heading. In a multivariable system such as in membrane technology, it has been relatively easy to make various simplifying assumptions and obtain results from basic equations. However, few workers have compared their models comprehensively with experimental data and even fewer consider axial velocity as a basic parameter governing concentration polarisation. Strictly, velocity is a vector quantity and a function of position another vector. It is easy to understand why it has been neglected.

Two notable reviews on this subject are those of Gill et al (92) and Liu et al (93). Although these only cover the period upto 1971, most of the existing models had been completed due to massive U.S. government funding of membrane technology. Only one paper was found which derived an analytical expression for the concentration boundary layer thickness, δ_c , having assumed the most common velocity profile, a linear relationship. The near wall velocity profile equation from the Karmen Boulter Martinelli relations described in Section 2.3 gave

$$\frac{\delta_c}{h} = 25.2 \text{Re}^{-7/8} \text{Sc}^{-1/3} \quad (2.22)$$

where h is the channel half height (94). This equation highlights some of the failings of other relationships. For example, it is independent of solute rejection, and, at an infinitesimal flowrate, the concentration boundary layer thickness would encompass at least the whole of the channel independent of the membrane flux.

Previous theoretical work looking at concentration polarisation rarely includes the velocity profile as an important parameter. Due to the simplifications required to get any results, these papers do not have anything to offer this thesis although that is not to say they will fail to bear fruit at some future date.

2.3 Turbulent Axial Velocity Correlations

A number of correlations have been based on wind tunnel experimental measurements, particularly those obtained by Eckert (96). From dimensional analysis of turbulent flow, the velocity profile can be plotted in terms of u^+ and y^+ .

$$y^+ = \frac{y \cdot u_\tau}{\nu} \qquad u^+ = \frac{u}{u_\tau} \qquad (2.23)$$

where u_τ is the wall shear velocity, y is the distance from the wall and ν is the kinematic viscosity. Eckert shows one result as close as $y^+ = 2$ and two results at $y^+ = 3$ for $Re > 8000$. The experimental values fall onto a well defined curve on u^+ , y^+ coordinates, independent of Reynolds number. The data so plotted was correlated by Martinelli (98) with some physical reasoning into the following;

Laminar Sublayer	$y^+ < 5$	$u^+ = y^+$	(2.24)
Buffer Layer	$5 < y^+ < 30$	$u^+ = -3.05 + 5.00 \ln y^+$	
Turbulent Core	$y^+ > 30$	$u^+ = 5.5 + 2.5 \ln y^+$	

Martinelli's paper also shows a few experimental points on the same curve by Reichardt (99), who obtained one data point as close as $y^+ = 1.7$.

Deissler (100), sought to get a better fit for the same experimental data.

$$\begin{aligned}
 y^+ < 26 \quad y^+ &= \frac{1}{n'} \operatorname{erf}\left(\frac{n' u^+}{\sqrt{2}}\right) \sqrt{\frac{\pi}{2}} \cdot \exp\left(\frac{1}{2} (n' u^+)^2\right) \\
 y^+ > 26 \quad u^+ &= \frac{1}{k'} \ln y^+ + c
 \end{aligned} \quad (2.25)$$

where $n = 0.109$, $k' = 0.36$, $c = 3.8$. The data on which the correlation was based was said to be accurate to $\pm 5\%$ and the correlation fitted the experimental data to within $\pm 5\%$ over the whole range. Deissler's correlations, although fitting the data better than Martinelli's, are not as simple to use. Spalding (101), suggested a series type correlation for the whole curve.

$$y^+ = u^+ + \frac{1}{E} \left\{ e^{ku^+} - 1 - ku^+ - \frac{(ku^+)^2}{2!} - \frac{(ku^+)^3}{3!} - \frac{(ku^+)^4}{4!} \right\}$$

where $k = 0.407$, $\frac{1}{E} = 0.0991$. (2.26)

The overall accuracy of this equation was put at $\pm 10\%$.

A recent paper by Snijders et al (102) reporting some hot wire anemometry results for air over a flat plate, show Spalding's equation to be too high in its evaluation of u^+ for $y^+ > 30$. A better fit for their data is attributed to Hinze (103).

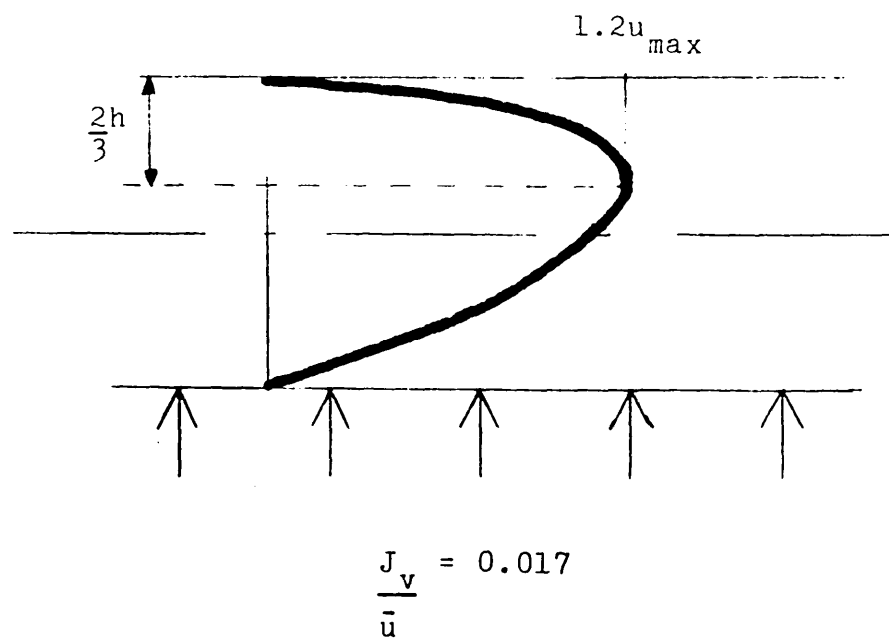
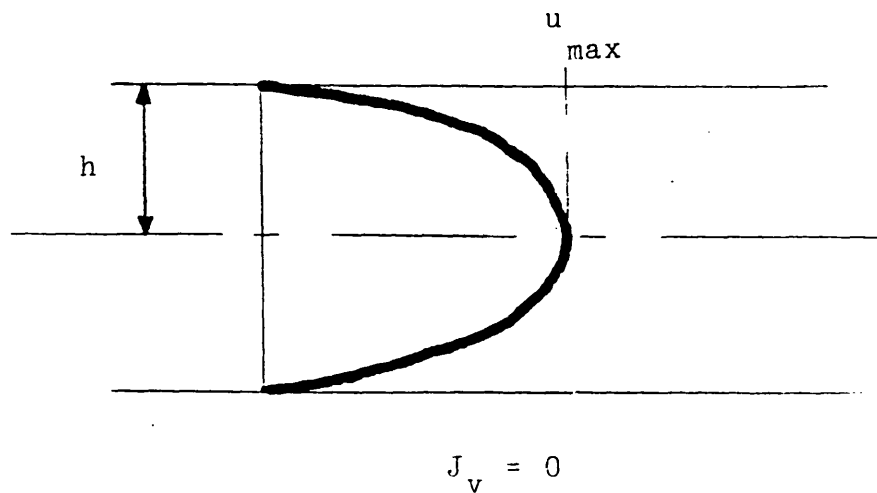
$$u^+ = 2.44 \ln y^+ + 4.90 \quad \text{for } y^+ > 30 \quad (2.27)$$

Using this result, Snijder et al suggested that values of $k = 0.41$ and $1/E = 0.1342$ were better parameters for Spalding's equation. The closest results to the wall observed by Snijder et al were down to $y^+ = 8$ in a 0.5m diameter wind tunnel.

As well as making measurements in impermeable wind tunnels, Eckert et al (104), made pitot tube velocity measurements for 'uniform' air injection from the walls to the bath. The air injection flowrate was varied from nil to $0.017 \bar{u}$ in the 0.6" x 3" cross-section tunnel. The closest experimental result was at 0.03" (750 μ m). It was found that wall friction decreased with increasing wall injection flowrate and thus it was believed to have aeronautical applications. A schematic presentation of one of the results is given in Fig. 2.4. (These results may still have an aeronautical application following an advertisement by McDonnell-Douglas for commercial launch at the end of 1983 (105))

Another recent paper by Hirata et al (106), used a pitot tube to obtain velocity measurements of air in a porous tube to within 0.6mm from the wall for a flow of entrance Reynolds number of 2.1×10^4 . The suction and injection velocity ratios were -4.97×10^{-3} to $+2.77 \times 10^{-3}$ based on the permeable and tube entrance average velocities. However, since the porous wall to entrance area was roughly 100:1, the suction and injection volumetric flowrate ratios became -0.5 to +0.3. The measurements were carried out at a range of distances downstream and the effect of porous flow on the axial velocity, friction coefficient, etc. are easily detectible. For the U.F. system, the suction volumetric flowrate ratio will be at least three orders of magnitude smaller than this experimental case. The velocity profile was observed to fit a logarithmic profile because no measurements could be made close to the wall.

FIGURE 2.4 Schematic Diagram Showing the Effect of Air
Injection Through One Wall of a Rectangular
Wind Tunnel on the Velocity Profile (Eckert 104)



A recent paper by Thomas (107) proposing a turbulent burst model for turbulent boundary layers gives the following,

$$y^+ < 52.45 \quad (2.28)$$

$$u^+ = 14.93 - 0.01196 \sinh\left(\frac{y^+}{14.94}\right) - 0.8929 \sinh\left(\frac{52.45 - y^+}{14.94}\right)$$

$$y^+ > 52.45$$

$$u^+ = 5.0 + \frac{\ln y^+}{0.41}$$

The equations are derived from a surface renewal model of the turbulent boundary layer with three constants being fixed by experimental data using hot wire anemometry in a wind tunnel (108).

The correlations mentioned are the most common but are not exhaustive. There are many others, some of which are mentioned in the following section reviewing their application to membrane technology.

2.4 Axial Velocity Correlations used in Membrane Technology Theory

In most cases, the axial velocity^{Profile} is ignored as a parameter in concentration polarisation. This is normally done by considering the case of an unstirred batch cell, i.e. no flow parallel to the membrane surface.

2.4.1 Laminar Flow Correlations

Many of the models where axial velocity profiles are considered use theory derived by Berman (95). Starting

with the steady state laminar flow form of the Navier Stokes equations, he modelled an incompressible fluid flow between two infinite, flat, equally porous walls. The velocity components were transformed into stream functions and, by assuming a polynomial expression for the transverse velocity component throughout the channel, he formed a perturbation solution. The wall flux was assumed constant and independent of position. The resulting axial velocity profile was flatter in the bulk and steeper near the walls than Poiseuille's capillary equation. The results also suggested that the permeable walls actually reduce the pressure drop across the channel compared with an impermeable channel. Berman's final results may be summarised by,

$$u(x, \bar{\lambda}) = \left[\bar{u}(0) - \frac{J_v x}{h} \right] \left[\frac{3(1 - \bar{\lambda}^2)}{2} \right] \left[1 - \frac{w(2 - 7\bar{\lambda}^2 - 7\bar{\lambda}^4)}{420} \right]$$

$$\frac{v(\bar{\lambda})}{J_v} = \frac{\bar{\lambda}(3 - \bar{\lambda}^2)}{2} - \frac{w}{280} \bar{\lambda}(2 - 3\bar{\lambda}^2 + \bar{\lambda}^6) \quad (2.29)$$

where $w = \frac{h J_v}{\nu}$

h = half channel height

$$\bar{\lambda} = y'/h$$

A similar analysis for heat rather than mass transfer was given by Sparrow (109).

Berman's relations for laminar flow between flat plates were first used in membrane technology by Dresner (110). He approximated the axial velocity to be proportional to distance from the wall for conditions near the inlet. Sherwood et al. (111) first used the results in full, but they required further analytical work to yield a

non-numerical solution. Their results gave the spacial concentration of salt, C , as

$$C(\epsilon', \bar{\lambda}) = \sum_{n=0}^{\infty} \beta_n Y_n(\bar{\lambda}) [1 - f\epsilon']^{(2/3)\beta_n - 1} \quad (2.30)$$

where β_n & $Y_n(R)$ are the eigen values in the solution of

$$\frac{d}{d\bar{\lambda}} \left[\frac{v}{J_v} Y_n - \frac{D}{J_v h} \frac{dY_n}{d\bar{\lambda}} \right] = \beta_n (1 - \bar{\lambda}^2) Y_n \quad (2.31)$$

with the boundary conditions,

$$\frac{dY_n}{d\bar{\lambda}} = 0, \text{ at } \bar{\lambda} = 0 \quad (2.32)$$

$$\frac{D}{J_v h} \frac{dY_n}{d\bar{\lambda}} = Y_n, \text{ at } \bar{\lambda} = 1$$

$\epsilon', \bar{\lambda}$ are the dimensionless distances with respect to the channel half height, h . D is the Diffusion coefficient of solute and $f = J_v / \bar{u}$.

Gill et al.(112) used an approximated form of Berman's relations for laminar flow in a thin parallel membrane channel.

$$\frac{u}{\bar{u}} = \frac{3}{2} (1 - f(0)\epsilon)(1 - \bar{\lambda}^2) \quad (2.33)$$

$$\frac{v}{J_v(0)} = \frac{\bar{\lambda}(3 - \bar{\lambda}^2)}{2} \quad (2.34)$$

where $f(0) = \frac{J_v(0)}{\bar{u}(0)}$, $\bar{\lambda} = y'/h$, $\epsilon = x/h$

$\bar{u}(0)$ = entry average bulk velocity

The same authors (92) formed an even simpler set of equations for laminar flow,

$$u = 2\bar{u}(1 - (y/R)^2) \quad \text{for porous tubes} \quad (2.35)$$

$$u = \frac{3\bar{u}}{2}(1 - (y/h)^2) \quad \text{for porous parallel plates} \quad (2.36)$$

These are very similar to the normal laminar flow velocity profiles and are independent of transverse flow. This is a good approximation since $\bar{u}/J_v \approx 10^3$.

Doshi et al.(113) used Berman's initial flow equations and did not impose the uniform wall flux condition for laminar flow between parallel flat plates. A numerical solution was obtained for the following set of equations.

$$u^*(x^*, y^*) = \left[1 - \int_0^{x^*} J_v^* dx^* \right] \frac{\partial f}{\partial y^*}(x^*, y^*) \quad (2.37)$$

$$u^*(x^*, y^*) \approx \left[1 - \int_0^{x^*} J_v^* dx^* \right] \frac{3y^*}{\mu^*(x^*, y^*)} \quad (2.38)$$

$$u^* = 3y^* \left(1 - \frac{y^*}{2} \right) \quad \text{at } x^* = 0 \quad (2.39)$$

$$v^* = 0 \quad \text{at } x^* = 0 \quad (2.40)$$

$$y^* = 0, \quad u^* = 0, \quad v^* = \frac{-\beta_1}{Sc} (1 - \beta_2 c_w^*) = -J_v^* \quad (2.41)$$

β_1, β_2 are constants, f is a stream function to be specified and

$$\begin{aligned} x^* &= \frac{x}{hR}, & y^* &= \frac{y}{h}, & u^* &= \frac{u}{\bar{u}}, & J_v^* &= \frac{hJ_v}{\bar{u}} \end{aligned} \quad (2.42)$$

Doshi et al's velocity profiles were correlated by Probstein et al.(114) for laminar flow over a porous wall.

The following series solutions were obtained

$$u = 3\bar{u}(1 - S(x))\left[\frac{y}{h} - \frac{1}{2}\left(\frac{y}{h}\right)^2 + \dots\right] \quad (2.43)$$

$$v = J_{vlim}(x)\left[1 - \frac{3}{2}\left(\frac{y}{h}\right)^2 + \dots\right] \quad (2.44)$$

$$\text{where } S(x) = -\int_0^x \frac{J_{vlim}(x)}{u_h} dx \quad (2.45)$$

J_{vlim} = limiting membrane flux where the concentration boundary layer is fully developed.

Other models used for porous channels in laminar flow include the following.

Dresner (110) used a modified Leveque approach (linearised axial velocity profile) in a semi-infinite system to obtain the following truncated Taylor series;

$$\left. \begin{aligned} u &\approx 3\bar{u}(1 - y^*) \\ v &\approx J_v \end{aligned} \right\} \quad \text{for } u \gg \frac{J_v x}{h} \quad (2.46)$$

$$(2.47)$$

He used these to obtain closed form solutions for the entrance and downstream sections of a membrane channel.

Yuan et al.(115) started with the two dimensional steady state Navier Stokes equations for laminar flow in a porous pipe. They then proposed the following stream function.

$$ru = \frac{\partial \Psi}{\partial r}, \quad -rv = \frac{\partial \Psi}{\partial x} \quad (2.48)$$

$$\Psi = \left(A + \frac{Bx}{R}\right)f(q) \quad (2.49)$$

where $q = (r/R)^2$, A and B are constants. r and R refer to the spacial and wall radii respectively and $f(q)$ is

approximated by an n^{th} order polynomial. Yuan et al's velocity profile equations were first applied to tubular laminar flow by Fisher et al.(116).

Srinivasan et al.(117) used the following equation for laminar flow in a tubular membrane duct,

$$\frac{u}{\bar{u}} = \frac{2y}{R} - \left(\frac{y}{R}\right)^2 \quad (2.50)$$

For laminar flow in a curved porous duct, Srinivasan used the following velocity profile which was described as only approximate.

$$v_{\phi}^+ = -D' \cos \phi \left[\left(\frac{-12 + 6}{\delta^+} \right) g + \left(\frac{24 - 9}{\delta^+} \right) g^2 + \left(\frac{-12 + 4}{\delta^+} \right) g^3 \right] \quad (2.51)$$

$$v_{\theta}^+ = v_{\theta}^+ \delta^+ (2g - g^2) + \frac{\delta^+ c^+ \sin \phi (g - g^2)}{D'} \quad (2.52)$$

$$\text{where } K = 2 \operatorname{Re} \kappa^{\frac{1}{2}} \quad (2.53)$$

$$D' = 0.9656 K^{\frac{1}{2}} + 1.65 \quad (2.54)$$

$$\delta^+ = \frac{4.6311}{K^{\frac{1}{2}}} - \frac{0.7659}{K} \quad (2.55)$$

$$v_{\theta \delta^+}^+ = \frac{1}{1 - \frac{2\delta^+}{3} + \frac{\delta^{+2}}{6}} \quad (2.56)$$

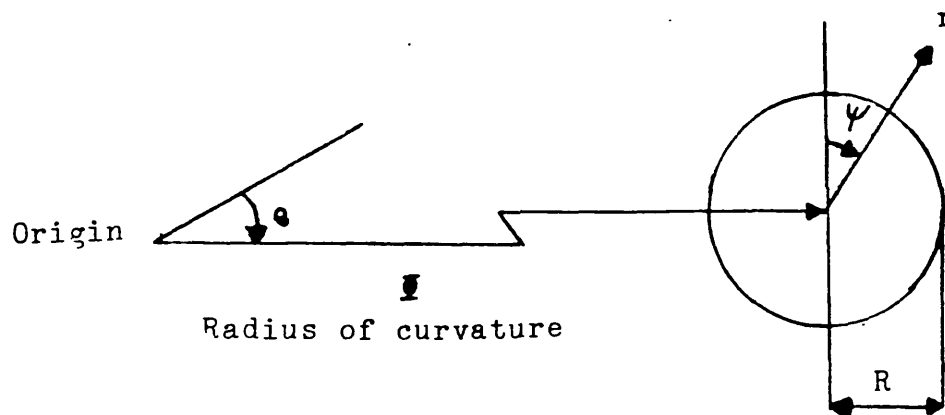
$$c^+ = \frac{4 \operatorname{Re} v_{\theta \delta^+}^+}{\delta^+} \quad (2.57)$$

$$\kappa = \frac{r}{\bar{r}} \quad g = \frac{y}{R \delta^+} \quad (2.58)$$

The coordinate system used is shown in Fig. 2.5.

Another obscure laminar velocity profile was given by Tsao (119). This considered the case of the external of

FIGURE 2.5 Coordinate System Used in a Model to Describe
Concentration Polarisation in a Curved
Tubular Membrane. (Srinivasan 118)



a tube either horizontal or vertical in a stationary surrounding fluid. The practical case would be a reverse osmosis rig submerged in sea water. The velocity profile used was

$$u = P(x) \frac{y'''}{\delta'''} \left(1 - \frac{y'''}{\delta'''} \right)^2 \quad (2.59)$$

where δ''' is the diffusion boundary layer thickness, y''' the radial and x the axial coordinates and $P(x)$ is a velocity function. From conservation of species,

$$\text{Vertical Tube} \quad (2.60)$$

$$\frac{1}{105} \frac{d}{dx} (P(x))^2 \delta''' = -\frac{y''' P(x)}{\delta'''} + \frac{\rho_b y''' \delta'''}{3 \rho} \left(\frac{\rho_w}{\rho_b} - 1 \right)$$

$$\text{Horizontal Tube} \quad (2.61)$$

$$\frac{1}{30} \frac{d}{dx} \left(P(x) \delta \left(\frac{\rho_w}{\rho_b} - 1 \right) \right) = \frac{2x}{\delta'''} \left(\frac{\rho_w}{\rho_b} - 1 \right)$$

$$\text{Boundary Conditions, } x = 0, \frac{\rho_w}{\rho_b} = 1, P = 0. \quad (2.62)$$

where ρ_b and ρ_w are the densities of salt and water respectively. $P(x)$ can be found by numerical integration. Using a similar mathematical approach, Bellucci et al.(120) used

$$\frac{u}{\bar{u}} = \text{erf} \left(\frac{y}{h(x)} \right) \quad (2.63)$$

for laminar flow in an infinite width porous channel. $h(x)$ has to be determined. To get a closed form, $h(x)$ was taken to be

$$h(x) = (9.66x)^{\frac{1}{2}} \quad (2.64)$$

2.4.2 Turbulent Flow Correlations

Fan (94) used the following expression for a porous plate,

$$u = \frac{\tau_w}{\rho} y \quad (2.65)$$

where τ_w is the wall shear stress. This is the most common model for a fully developed laminar boundary.

Gill (121) and Liu (122) coupled this equation with

$$v = J_v - \frac{1}{\mu} \frac{d\tau_w}{dx} \frac{y^2}{2} \quad (2.66)$$

to totally specify the two dimension flow. Liu also gives an expression for the wall shear stress

$$\tau_w = \alpha' \bar{u}_x^{\frac{3}{2}} \left(\frac{3n-1}{2} \right) \sqrt{\left(\frac{n+1}{2} \right) \rho \mu} \quad (2.67)$$

where α' is a constant and $n = 0$ for a flat plate and $n = 1/3$ for an infinite width channel.

An equation developed by Deissler (100) for the eddy viscosity has been used for turbulent flow in porous channels. (Deissler went on to use his result to form a good velocity profile correlation for turbulent flow. This was described in Section 2.3.) The eddy viscosity was given by

$$\epsilon = m u^+ y^+ [1 - \exp(-m u^+ y^+)] \quad (2.68)$$

where ϵ = eddy viscosity and $m = 0.0154$

$$u^+ = \frac{u}{u_\tau}, \quad y^+ = \frac{u_\tau y}{\nu}, \quad u_\tau = \sqrt{\frac{\tau_w}{\rho}} \quad (2.69)$$

Sherwood et al.(111) used this to derive a reasonably simple result for a turbulent flow, parallel flat plate, totally rejecting membrane system.

$$\frac{c_w}{c_b} = \exp \left\{ \frac{8.96 J_v Sc^{\frac{2}{3}}}{\bar{u}} \sqrt{\frac{2}{f}} \right\} \quad (2.70)$$

where f = Fanning friction factor.

They also used another approximation for the eddy viscosity which was proportional to $\bar{u}^3$ and gave the final result as

$$\frac{c_w}{c_b} = \exp \left\{ \frac{J_v Sc^{\frac{2}{3}}}{\bar{u}(f/2)} \right\} \quad (2.71)$$

This latter result was adapted by Brian (123) for a membrane providing a rejection of solute R_i to produce

$$\frac{c_w}{c_b} = \frac{\Omega}{R_i + (1-R_i)\Omega} \quad (2.72)$$

$$\text{where } \Omega = \exp \left\{ \frac{J_v Sc^{\frac{2}{3}}}{\bar{u}(f/2)} \right\} \quad (2.73)$$

It is important to note that concentration polarisation builds up exponentially^{with flux.} However, the simplifications used by these authors to give an ordinary conservation of species differential equation do not take time or axial length into account. Hence, their applicability is limited to academic interest only.

Another author to use Deissler's velocity profile was Srinivasan et al.(124) for a porous flat duct.

$$y^+ < 26 \quad u^+ = \int_0^{y^+} \frac{dy^+}{1 + (0.124)^2 u^+ y^+ (1 - \exp(-(0.124)^2 u^+ y^+))} \quad (2.74)$$

$$y^+ > 26 \quad u^+ = u_1^+ + \frac{1}{0.36} \ln\left(\frac{y^+}{26}\right) \quad (2.75)$$

$$\text{where } u_1^+ = u^+ \Big|_{y^+=26} \quad (2.76)$$

Gill et al.(92) suggest the use of the Prandtl mixing length, l , for turbulent flow

$$u' = l \frac{du}{dy} \quad (2.77)$$

but don't expand the analysis. u' is the fluctuational velocity defined by

$$u' = u - \bar{u} \quad (2.78)$$

The aim of this section was to show the variety of velocity profiles used for the theoretical study of membranes. The potency of this study is that it should provide a technique for measuring the velocity profile over a flat plate and thus remove one uncertainty from the membrane system modelling.

2.5 Turbulence Bursts

The concept of turbulence bursts has been introduced earlier. This section seeks to give a brief literature review of the experimental data backing the existence of turbulence burst phenomena.

One of the earliest experimental papers suggesting such a phenomena was given by Kline et al.(125). When a large number of hot wire anemometer and visual experiments using dye injection and hydrogen bubbles were carried out

in the laminar sublayer of turbulent flow in a 10" channel, it was noted that low speed streaks very near the wall gradually lifted away from the wall until $y^+ \sim 30$. At this point, some form of instability occurred. It was suggested that upto 80% of the turbulence in the core could be attributed to this factor.

Corino et al.(126) used a high speed cine camera moving on an 8ft long flat bed to observe the flow of colloids in a channel down to $y^+ = 2.5$. In the region $y^+ < 5$, velocity fluctuations of small magnitude and intrusions of bulk elements from the core were noticed. In the region of $5 \leq y^+ \leq 70$ turbulent bursts increase in intensity with increasing distance from the wall, having originated in the region $5 < y^+ < 15$ and interacted with each other in the region $7 < y^+ < 30$. For the region $y^+ > 70$, a reduced intensity of velocity fluctuations and a large dimension scale of turbulence was observed. Turbulent bursts or ejections as this paper calls the phenomena, occurred randomly with respect to time and position in a given parallel plane to the wall. The intensity and frequency of the bursts were dependent on flow conditions.

Blackwelder et al.(127) made a grid of 10 hot wire anemometers to cover the range $15 < y^+ < 100$, with the closest measuring point from the wall being equivalent to 550 μ m. At Reynolds numbers of about 2500, there was some evidence of spanwise movement down to $y^+ = 15$ although the scale decreased as the wall was approached.

Van Maanen et al.(128) have constructed an ingenious turbulent flow channel which enables L.D.A. measurement to

be made down to a distance of $y^+ = 18$ from the tubular wall. The complex channel and processing electronics allow axial and radial velocity fluctuations to be recorded and processed on a computer. It should be noted that the distinction between Doppler bursts and 'noise' is not precise. However, the results seem to fit a Random Surface Renewal Penetration model proposed in a sister paper by Fortuin et al.(129). The model was applied to such phenomena as polymer drag reduction with noticeable success and a model for the axial velocity profile over a flat plate was given by

$$u^+ = 18(1 - e^{-y^+/18}) \quad \text{for } 10^4 < Re < 10^5 \quad (2.79)$$

This is at least a first order approximation of the observed axial velocity profile data reported in the last section.

2.6 Laser Doppler Anemometry

2.6.1 Introduction

In order to measure fluid velocities at small distances from solid walls, the measurement technique must be either unobstructive or produce infinitesimally small changes. L.D.A. is an unobtrusive technique, using only light to form the measuring volume. Yeh et al.(130) were the first to demonstrate the technique in 1964. Using coherent light beams, they were able to measure local instantaneous velocities as low as 0.07 mm/s.

A short intense review of the subject was given by

Goldstein (121), while for the most part, the comprehensive text by Durst et al.(132) was predominantly consulted in this study. There are many other reviews of this subject and Table 2.5 lists some of the applications of L.D.A.

Tables 2.6 and 2.7 show the system parameters for the optical volume size and the closest measuring distance from the wall recorded in the papers.

2.6.2 Laser Doppler Anemometry Basics

Unless otherwise specified, this section has been based on the material of Durst et al.(132).

There are three basic forms of laser Doppler anemometers. These are schematically defined by Fig. 2.6. It can be inferred from the diagram that the fringe mode has the ability to form a smaller precise optical volume with the observed signal not being swamped by the unscattered laser beam. The fringe mode involves splitting the laser beam in two, and recombining these beams to form interference fringes at the beam intersection. The fringes are parallel to the bisector of the beams. A solid light scattering particle of size similar to the beam spacing will produce scattered light directly related to its position in the fringes. If the particle has a velocity component perpendicular to the fringes, the scattered light will be modulated as a function of the particle's speed and the beam spacing. The particle velocity can be assumed to be the same as the local fluid surrounding it, provided that the only significant force acting on the particle is

TABLE 2.5 Applications of Laser Doppler Anemometry.

	<u>Reference</u>	
Turbulent Water Flow	Mccomb et al	133
	Berman	134
Oscillatory Water Flow	Denison et al	135
Turbulent Pipe Flow Drag Reduction using Dilute Polymer Solutions.	Rudd	136
Laminar Water Flow	Kawata et al	137
	Mishina et al	138
Combustion Flow	Baker et al	139
Supersonic Air Flow	Pfeifer et al	140
Recirculating Air Flow through a Sharp Expansion.	Durst et al	141
In Vitro Blood Flow	Le-Cong et al	142
In Vitro Blood Vessel Flow	Vlachos	143
Fluidised Bed Flow	Bernard et al	144
Particulate Flow to Enhance Heat Transfer.	Zisselmar et al	145
Evidence of Turbulence Bursts	Van Maanen et al	128

TABLE 2.6 Laser Doppler Anemometer Smallest Optical Volume
Sizes Recorded in the Literature.

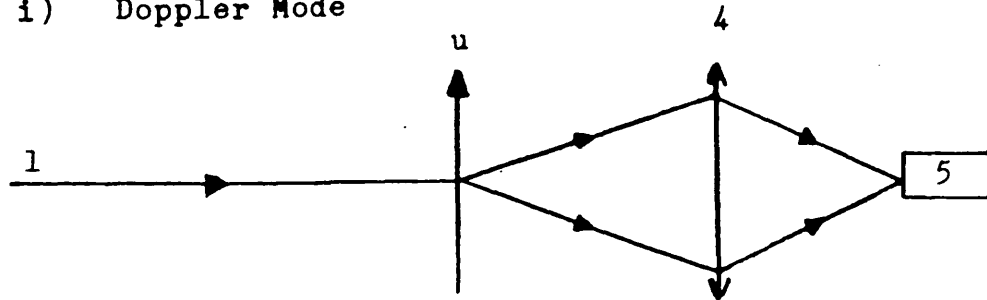
<u>Reference</u>	<u>f</u>	<u>Optical Volume</u>	<u>Pinhole</u>
Rudd	136	10x100x1000 μm	
Mishina et al	138	10x1000x1000 μm	
Baker et al	139	300mm 0.12mm diameter	250 μm
Pfeifer et al	140	0.8x0.8x5 mm	
Durst et al	141	0.18x0.18x1.4 mm	
Bernard et al	144	0.4mm diameter	
Vlachos	143	20x20x30 μm	200 μm

TABLE 2.7 Closest Measurements to a Wall Recorded by
Other Authors.

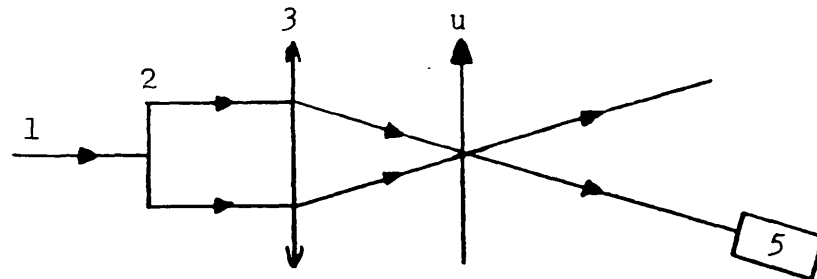
<u>Reference</u>		<u>Distance</u>
McComb et al	133	$y^+ > 15 \sim 2\text{mm}$
Rudd	136	50 μm
Kawata et al	137	500 μm
Mishina et al	138	100 μm
Durst et al	141	$\sim 1\text{mm}$
Bernard et al	144	$\sim 1\text{mm}$
Zisselmar et al	145	$\sim 50 \mu\text{m}$
Van Maanen et al	128	$y^+ = 18$
Vlachos	143	Blood vessels $\sim 100 \mu\text{m} \varnothing$

FIGURE 2.6 Modes of Laser Doppler Anemometry

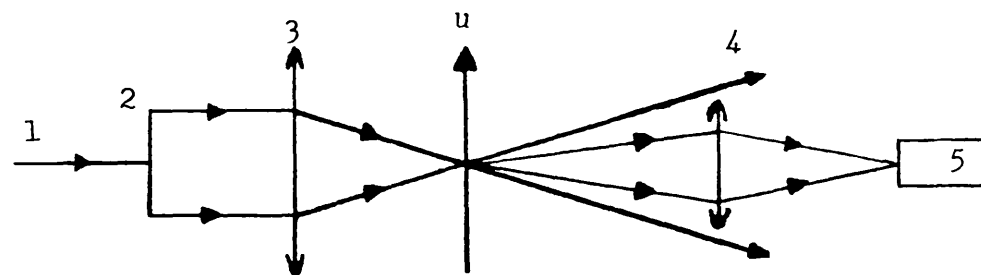
i) Doppler Mode



ii) Reference Beam Mode



iii) Fringe Mode



Key

- 1 Laser beam
- 2 Beam splitter
- 3 Front lens
- 4 Receiving lens
- 5 Photomultiplier tube
- u Measured velocity component

that due to the momentum of the surrounding fluid. This implies that the particle must be small and that there are no external forces such as wall effects.

Referring to Fig 2.7, the beam spacing Δx is given by

$$\Delta x = \frac{\lambda}{2 \sin \theta_t} \quad (2.80)$$

where λ is the wavelength of the light and θ_t is the beam bisector angle. From trigonometry

$$\theta_t = \tan^{-1} \left(\frac{d}{f_t} \right) \quad (2.81)$$

where f_t is the focal length of the transmission lens.

The Doppler frequency ν_D is then related to the velocity component of the particle moving perpendicular to the fringes, u , by

$$u = \Delta x \nu_D \quad (2.82)$$

The dimensions of the intersection of the beams is given by

$$l_t = \frac{5 \lambda f_t}{\pi d_B \sin \theta_t} \quad (2.84)$$

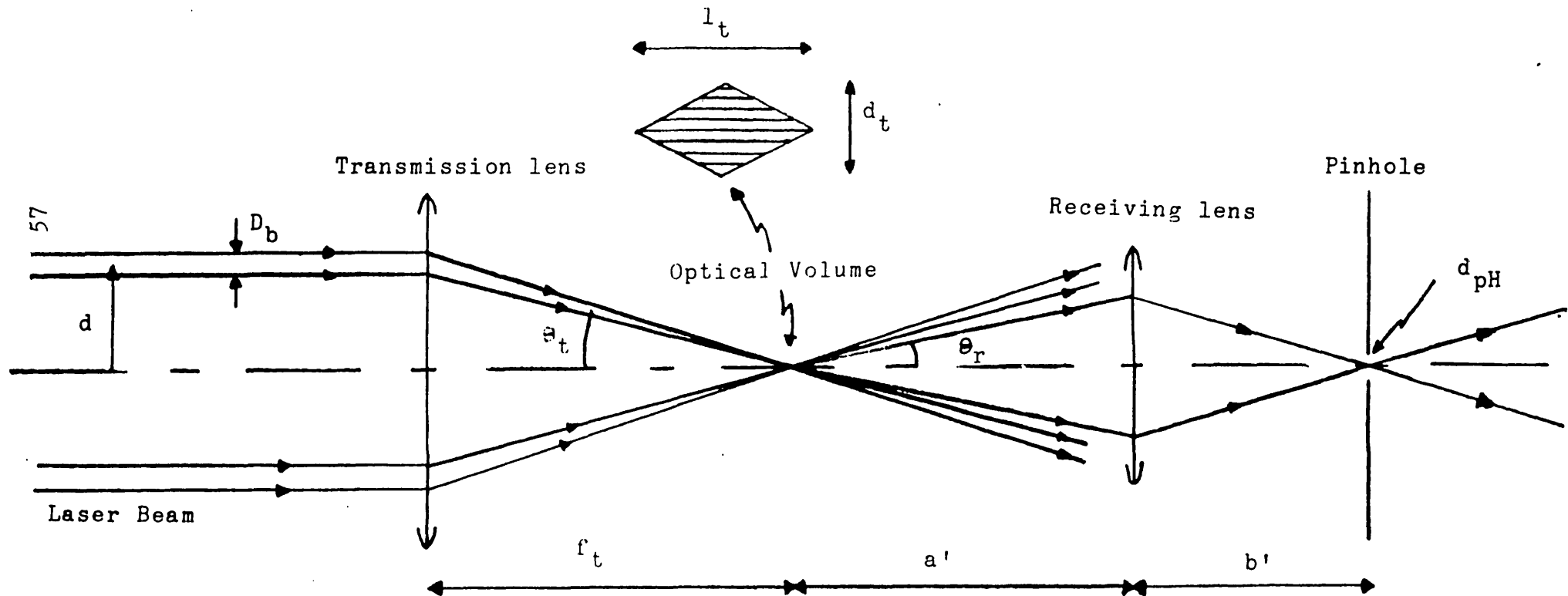
$$d_t = \frac{5 \lambda f_t}{\pi d_B \cos \theta_t} \quad (2.83)$$

$$\text{combining 2.81 and 2.83} \quad d_t = \frac{5 \lambda f_t}{\pi d_B \cos \left(\tan^{-1} \left(\frac{d}{f_t} \right) \right)} \quad (2.85)$$

This result is important because, in order to have a high resolution close to the wall, the optical volume must be small. For d_t to be small, f_t must be small while d_B and d are large.

The laser beam has a Gaussian intensity distribution in cross-section. The beam diameter of the locus d_B refers to

FIGURE 2.7 Diagram of a Fringe Mode Laser Doppler
Anemometer System using the Symbols Defined
in the Text.



the diameter of the locus in which the beam intensity, I , is related to the maximum beam intensity, $I_{\max}$.

$$I = I_{\max} e^{-1} \quad (2.86)$$

Similarly, the scattering intensity also has a distribution in polar coordinates known as the Azimuthal Distribution and is of the form shown in Fig. 2.8. The exact form is dependent on many factors including the particle size. Provided that the receiving optics collection angle (θ_r in Fig. 2.7) is small, the received scattered light intensity is close to its maximum.

The receiving optics can be focused onto the optical volume and the portion of the optical volume actually observed, d_r , is determined by

$$d_r = \frac{a' \sin \theta_r}{b' \sin \theta_t} d_{pH} \quad (2.87)$$

$$\text{and } \frac{1}{f_r} = \frac{1}{a'} + \frac{1}{b'} \quad (2.88)$$

The symbols have again been defined by Fig. 2.7. Therefore, for a small observed optical volume, a' , θ_r and d_{pH} are to be small and b' to be large.

A limitation on all these equations is the need to have a reasonable intensity of scattered light from the optical volume. Formulae do exist for the received laser power (132).

The particle size, d_p , is also important and reference 132 suggests

$$\frac{d_p}{2} < \Delta x < 2d_p \quad (2.89)$$

2

The same reference gives the ratio of the formed optical

FIGURE 2.8 A Typical Azimuthal Distribution for Scattered Light.

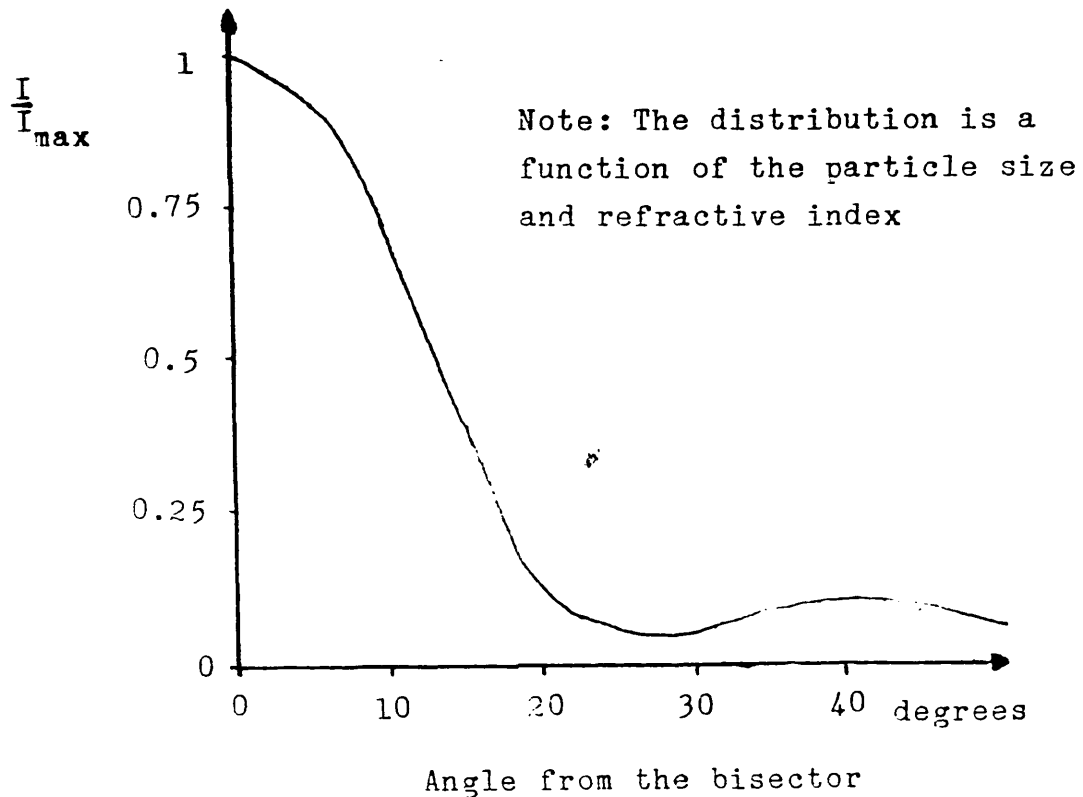
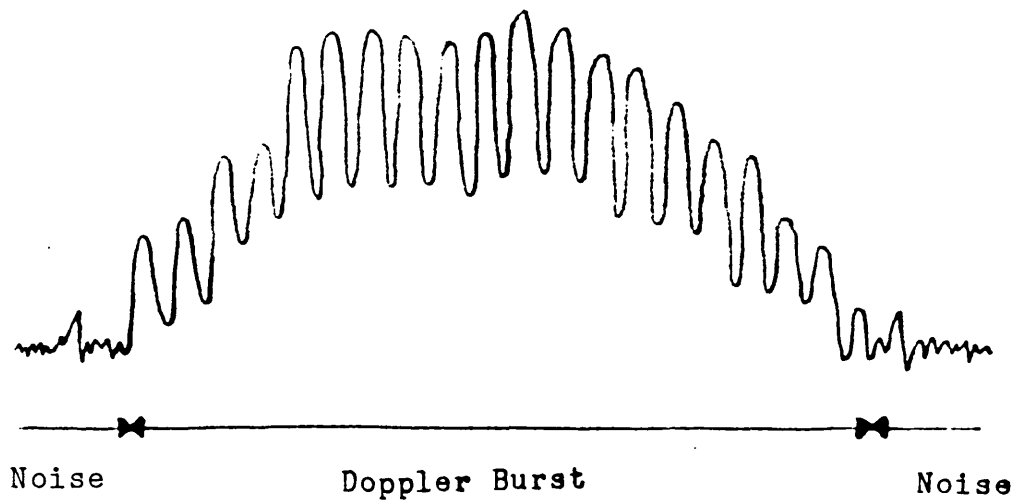


FIGURE 2.9 Schematic Representation of a Doppler Burst in the Output of a Photomultiplier.



diameter to that observed.

$$\frac{d_r}{d_t} \sim \frac{4}{5} \quad (2.90)$$

The signal being observed by the photomultiplier is typically of the form shown in Fig.2.9. Plate No.4 shows an electronically processed section of the Doppler burst. The wave has a clearly defined fixed frequency.

2.6.3 Errors in Laser Doppler Anemometry

From equation 2.82, it was shown that the Doppler frequency is only proportional to velocity of the particle in the direction perpendicular to the bisector for a given optical system. The signal may, however, vary in frequency due to any of the following:-

- a) Optical Noise Broadening. This broad heading covers all changes in the optical system such as;
 - i) vibration of the optical bench
 - ii) changes in the laser beam characteristics
 - iii) refractive index changes e.g. due to temperature change
 - iv) scattered extraneous light
 - v) imperfect alignment of the laser beams so that the fringes are not exactly parallel.
- b) Electronic Noise. Another broad heading which includes;
 - i) shot thermal noise from the photomultiplier tube
 - ii) extraneous or imperfect signal processing
- c) Velocity Gradient Broadening.

The preceding factors can be reduced to a negligible amount with experimental care. However, the velocity gradient

broadening is due to the fact that the laser Doppler anemometer observes a finite optical volume. When the optical volume is close to a solid wall, such that there is a significant velocity gradient across it, the average Doppler frequency measured will be dependent on where the particles moved through the optical volume.

To illustrate this point, consider an optical volume in which there exists a linear velocity gradient, (Fig.2.10). The particles passing through the optical volume are in such planes equidistant from the centre that their velocities are u and $2u$. For a uniform particle concentration, there will be twice as many particles passing through the plane corresponding to $2u$ than for the u plane. Thus the average velocity observed will be

$$u_{\text{obs}} = \frac{(u + 2(2u))}{3} = \frac{5}{3} u \quad (2.91)$$

and not the average of the fluid velocities across the optical volume of

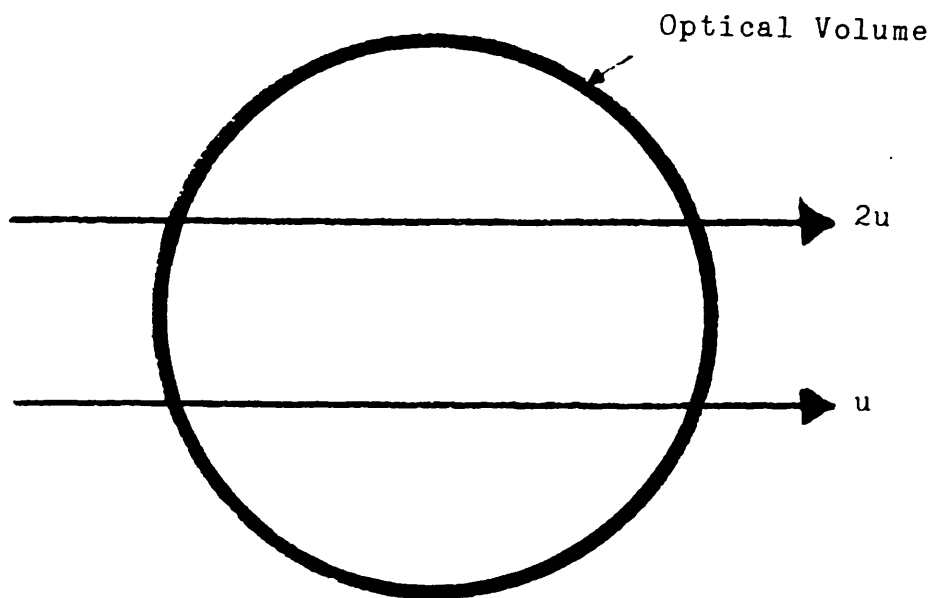
$$u_{\text{act}} = \frac{Nu + N \cdot 2u}{2N} = \frac{3}{2} u \quad (2.92)$$

It is important to note that the individual particle velocities are measured correctly. It is the finite spacial nature of the optical volume that creates an error in the observed velocity.

A complete treatment to correct the observed data for velocity gradient broadening is given by Edwards et al.(146) for the case of a parabolic laminar velocity profile.

The complexity, though, can be demonstrated by the following. For a velocity gradient and particle planar

FIGURE 2.10 Diagram Associated with the Explanation of
Velocity Gradient Broadening.



position probability distribution

$$u = u(y) \quad (2.93)$$

$$p = p(u(y)) \quad (2.94)$$

The observed mean velocity is given by

$$\bar{u} = \int_{y_1}^{y_2} u(y)p(u(y))dy \quad (2.95)$$

This equation requires $p(y)$, which is not known, but can be modelled using a random number generator with an assumed weighting dependent on $u(y)$, which is the aim of the experiment. The solution for $u(y)$ is extremely complex.

d) Concentration Gradient Broadening. It has been implicit that the concentration of particles used for scattering is uniform. (The particle size in this experiment are of the order of $1\mu m$ and are not to be confused with solute used in the membrane channel e.g. albumen.) If the concentration of particles is non-uniform, then the particle planar position probability distribution will be a more complex function of concentration

$$p = p(u(y), C(y)) \quad (2.96)$$

In order to reduce velocity and concentration gradient broadening effects, the observed optical volume should be as small as possible. Turbulent flow should also reduce particle concentration phenomena.

e) Transit Time Broadening. This error is due to particles taking a finite time to cross the optical volume. The optical volume is an ellipsoid with more intense fringes towards the centre, due to the Gaussian intensity distribution in the initial laser beam. Thus any particle travelling in the bisector plane will pass through more

fringes that are more intense than a particle passing through the edge of the optical volume. Hence, it is more likely that the central particle will be observed by the electronic processing than the fringe particles, given that the processor has a choice of either.

Transit time broadening can, however, negatively compound the errors encountered in velocity and ^{concentration} gradient broadening by another mechanism. Referring to the previous hypothetical model of particles passing through two planes equidistant from the bisector plane, with velocities u and $2u$ respectively, although there are twice as many particles passing through the plane corresponding to $2u$, suppose that every alternate $2u$ particle passes completely through the optical volume when the u particle is being tracked by the processor. The observed velocity will then be

$$u_{\text{obs}} = \frac{u + 2u}{2} = \frac{3}{2} u \quad (2.97)$$

Remember that the particle travelling at u takes twice as long to pass through the optical volume as the particle travelling at $2u$. It is assumed, as is usually the case, that the optical volume is symmetric about the bisector plane.

Transit time broadening can be reduced by suitable criteria in electronic signal processing. For example, the processor may only need a fixed number of wave fronts before the frequency is evaluated. The processor may then be forced to look for another signal even though the original particle is still scattering light at the original Doppler frequency.

There are several parameters involved in transferring the Doppler frequency data obtained to a point velocity in the flow. These are mainly due to the fact that the optical volume is finite. However, it should be remembered that intrusive methods such as hot wire and pitot tube anemometry suffer from similar effects as well as diverting the flow. Two of the papers listed earlier have evaluated the total error in the laser Doppler anemometer velocity results c.f. fluid mechanics theory.

Denison et al.(135) claimed an error of no more than $\pm 1.4\%$ between the measured velocity and the computed velocity for oscillatory water flow. While Durst et al.(141) stated that L.D.A. measured velocities had an accuracy of $\pm 0.5\%$ in laminar air flow through a 1:3 sharp edged expansion. The velocity was measured down to 1mm from the surface in a 12mm diameter channel.

Whilst L.D.A. is subject to numerous errors, these appear to be small, particularly with reference to other obtrusive techniques. L.D.A. error correction has, as far as the author is aware, only been carried out for laminar flow measurements. However, by changing parameters such as beam diameter, focal lengths and electronic averaging times and sensitivity when observing the same flow it should be possible to examine their effects.

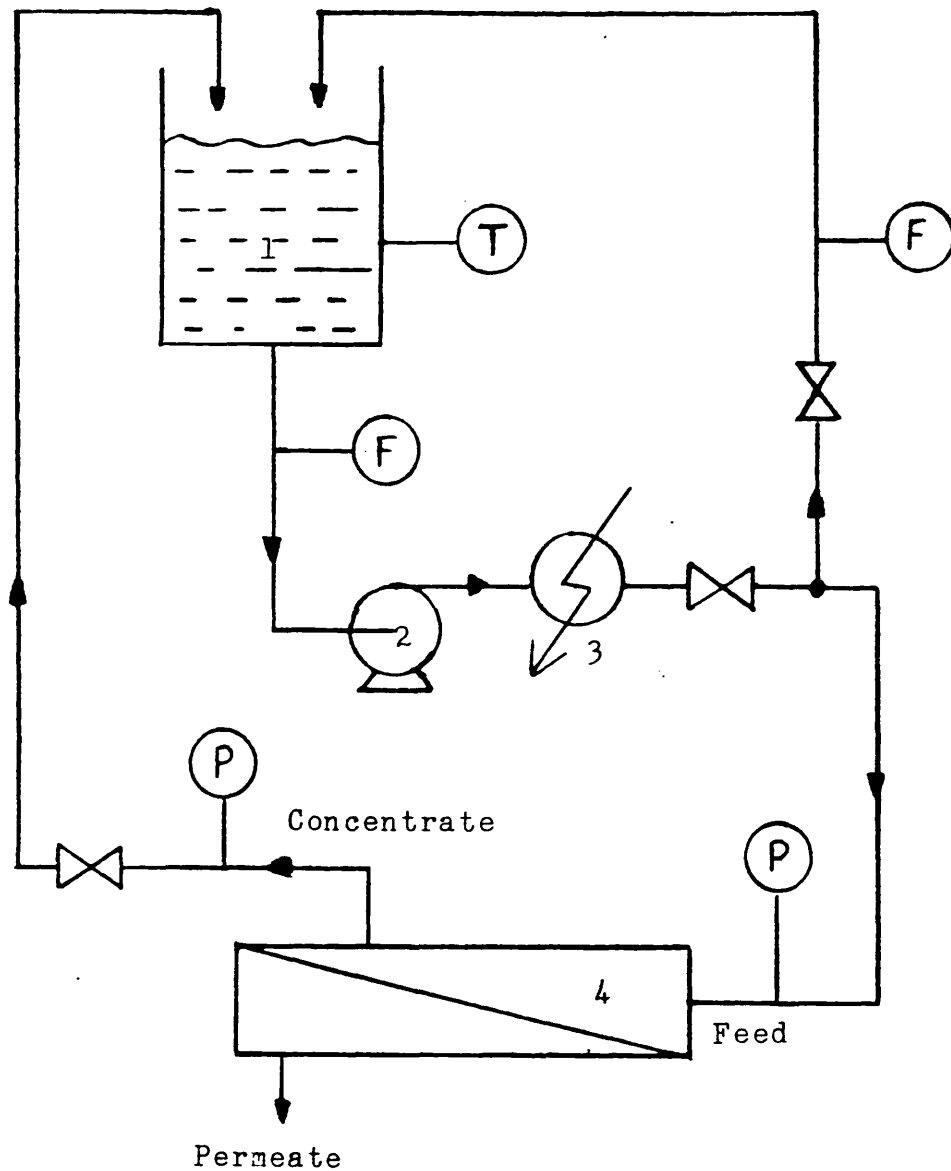
CHAPTER 3 EQUIPMENT

3.1 Process Plant Layout

A diagram of the layout is shown in Fig. 3.1. The fluid flows from the tank to the pump via a rotameter, which is used to measure the flowrate through the membrane channel. The pump then discharges through the coiled heat exchanger which keeps the recycled fluid at a constant temperature. After flowing through a control valve, the fluid is split into the membrane channel feed and a direct return to the holding tank. The flowrate in this return is measured by a rotameter and controlled by a valve so as to vary the flowrate through the channel at a constant pressure. (A more stable though tedious method of achieving the same result is to leave the bypass return closed and adjust the remaining two valves.)

Bourdon gauges are used to measure pressures at the inlet and outlet of the membrane channel. The inlet gauge contains a high and low pressure trip to the pump motor relay. Before returning to the holding tank, the fluid is throttled by a valve and it is this valve that essentially determines the system pressure.

The residence time of fluid in the tank is about two minutes, and, provided low solubility solutes are premixed, the return lines from the pump provide sufficient mixing.

FIGURE 3.1 Process Plant Line Diagram**Key**

- 1 Holding tank (25 l)
- 2 Mono pump (3 phase, 4.5 kW, 40 l/min @ 3.0 barg.)
- 3 Coil heat exchanger (0.015 m^2 heat transfer area process tube side.)
- 4 Membrane channel
- F Rotameter
- P Bourdon pressure gauge
- T Thermometer

3.2 Membrane Channel

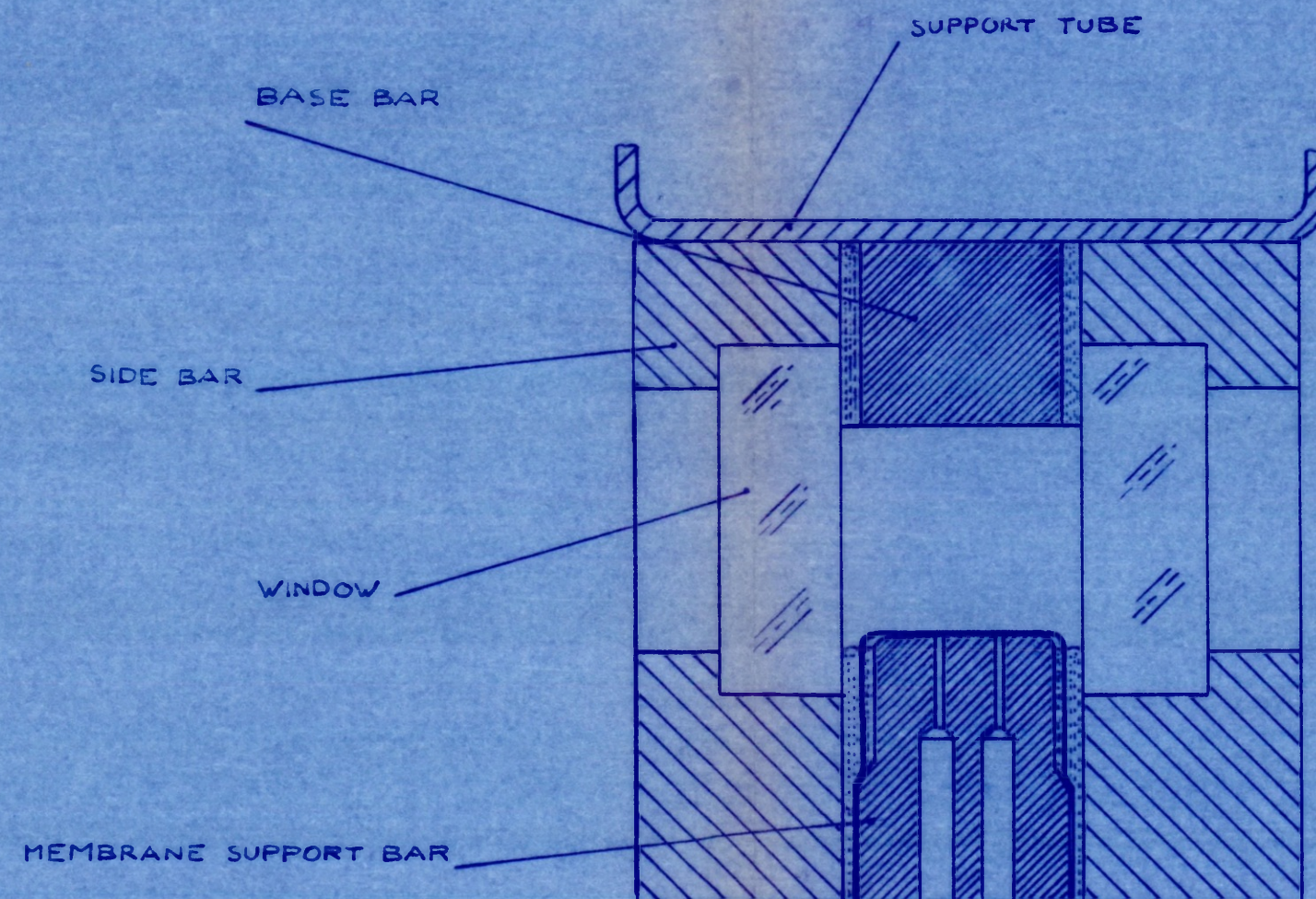
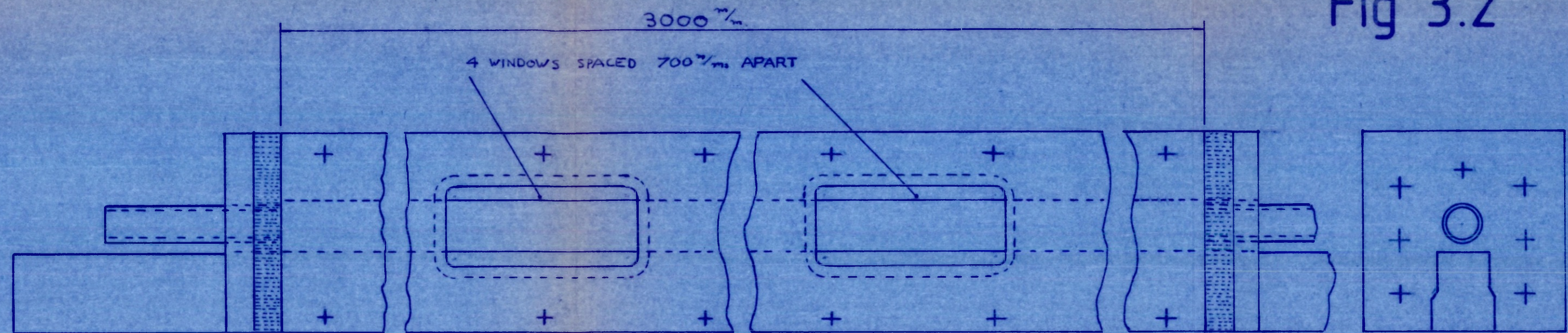
The channel consists of four bars of Delrin each 3m long. The two smaller bars of $1" \times 1\frac{1}{4}" \times 3m$ and $1\frac{1}{4}" \times 1\frac{1}{2}" \times 3m$ fit between the two wall bars each of $1\frac{1}{4}" \times 3\frac{3}{4}" \times 3m$ leaving a roughly $1" \times 1"$ cross-sectional channel in the centre.

Delrin, a polyacetal resin, was chosen for its solvent resistance and machinability. Although stainless steel was the first choice, the smallest sizes of ^{channel} ~~tube~~ commercially available would have dictated a pump capacity at least an order of magnitude larger to obtain turbulent Reynolds numbers in the channel. Unfortunately, all plastic materials possess an inherent deformation on extrusion. The manufacturer was prepared to accept a 3° maximum deflection specification on the material, but, on delivery, none of the bars came anywhere near this standard, the worst having an 18° deflection. Although the sales company offered to replace them, long manufacture and delivery times and abysmal quality control dictated that the bars in hand be used.

All of the bars had to be straightened and clamped prior to machining. Despite months of extra work, this was to cause severe channel sealing problems at a later date.

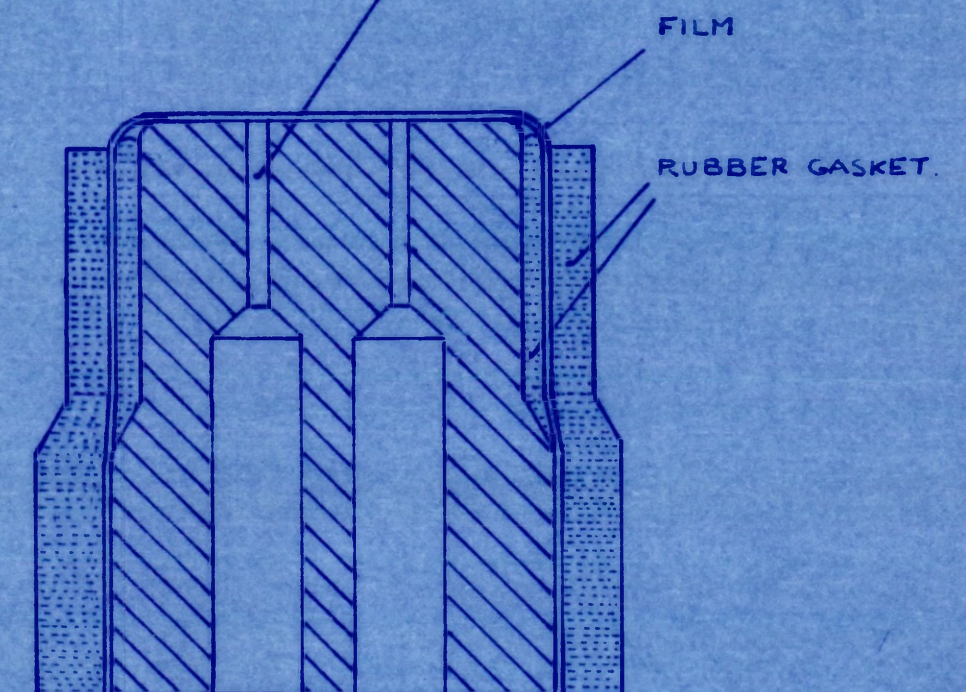
The channel cross-section is shown in Fig. 3.2. The smallest bar, at the top of the diagram, is fixed onto a 4" square tube and acts as a base. The other small bar is

Fig 3.2



SECTION THROUGH CHANNEL

PERMEATE DRAIN HOLES
SPACED $\frac{3}{4}$ APART ALONG BAR.

SECTION THROUGH MEMBRANE
SUPPORT BAR

GENERAL ARRANGMENT OF MEMBRANE CHANNEL

milled in a wedge shape, so that when the membrane is placed on top of it and pushed into the female gap, the wedge has the effect of tightening the membrane on the bar. 1mm diameter permeate holes were drilled through the top of the bar on a $\frac{3}{4}$ " square pitch. These holes are relieved from the other side by 6mm diameter holes. Optimal perforation spacing is discussed by Winograd et al (147). The spacing here conforms to the pitch used by Patterson Candy International.

The remaining two bars have the female section of the membrane support bar and holes for the eight 4" x 2" x $\frac{3}{4}$ " crown glass windows machined into them. (Fig. 3.3)

The windows have been coated by MgCl_2 to give a reflectivity of less than 1% of transmitted radiation. They also have a surface finish of better than a tenth the wavelength of the helium neon laser so as to minimise laser beam deformation.

These windows are flush with the inside face of the side walls and were originally to have been sealed with an adhesive. Silicone rubber lasted for about an hour under 2 bar gauge pressure, and although various other adhesives were tried, none gave a good watertight seal. Only the silicone rubber bonded well to the glass. After much experimentation, (See Appendix 4) the final solution has been to construct rubber gaskets for the window-Delrin restraining lip interface which leave the window 30 to 50 thou. proud prior to assembling the channel. These compress on assembly to give a watertight seal.

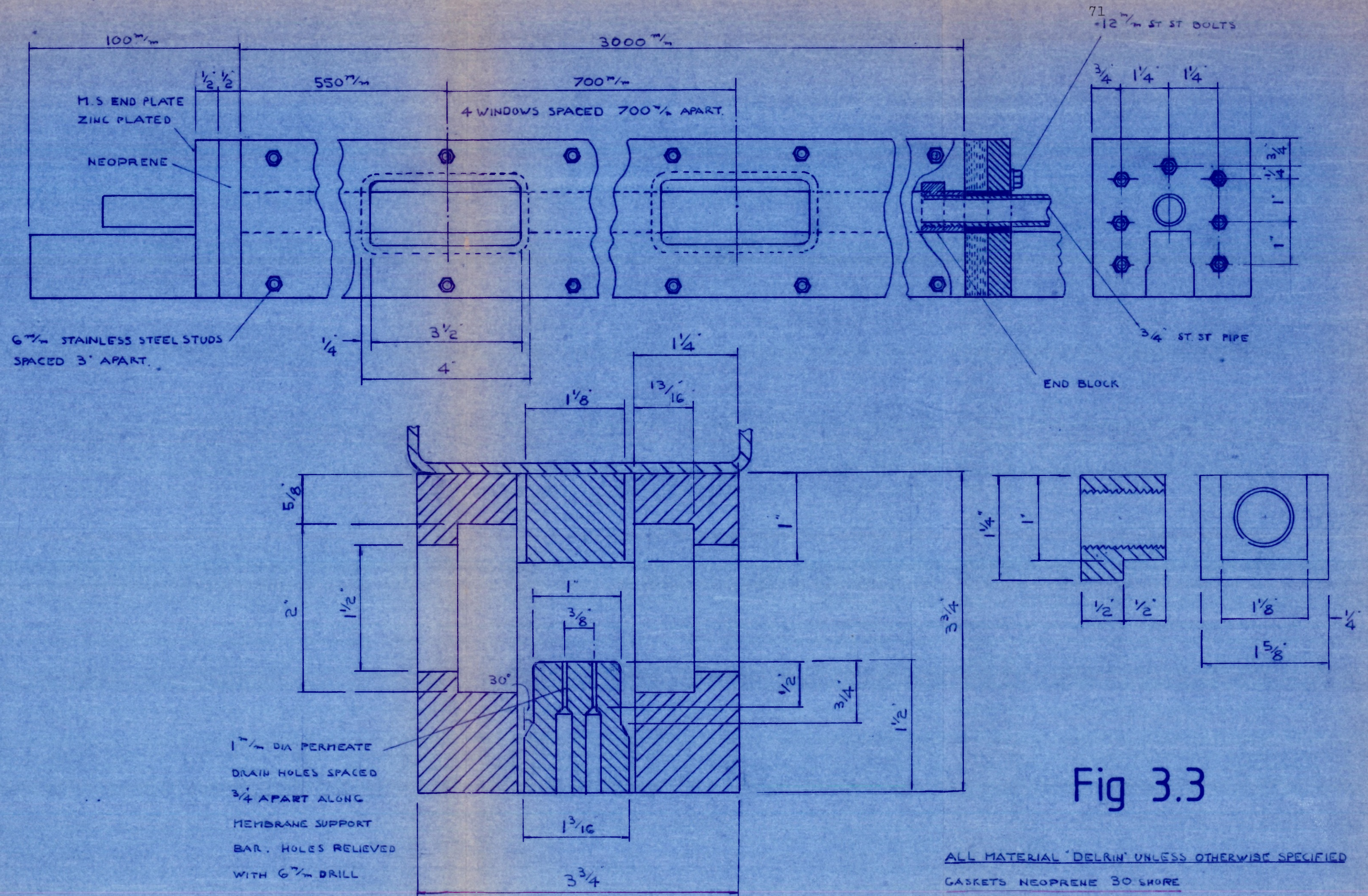


Fig 3.3

ALL MATERIAL 'DELRI' UNLESS OTHERWISE SPECIFIED
GASKETS NEOPRENE 30 SHORE

DETAILS OF THE CONSTRUCTION OF THE MEMBRANE CHANNEL

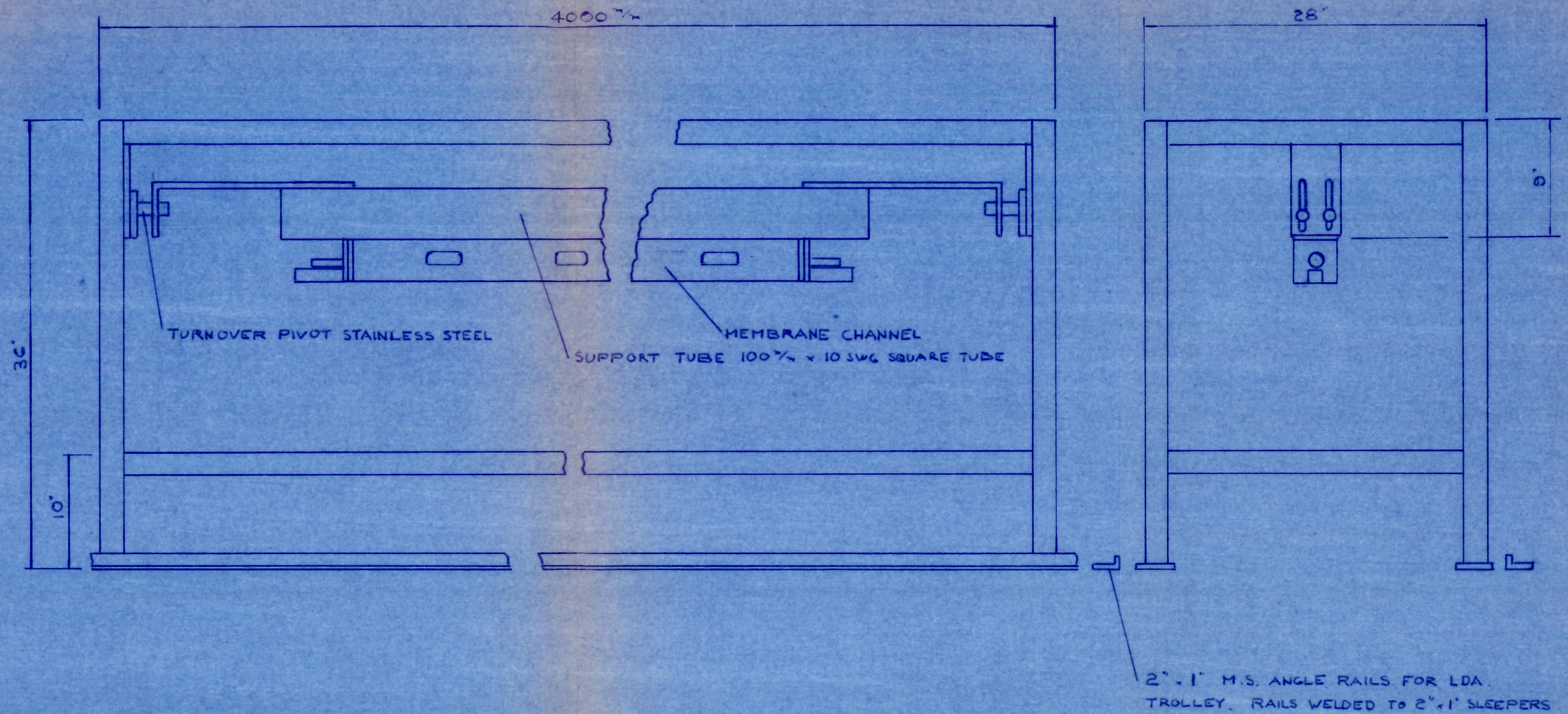
The flexure in the Delrin was probably the main cause for the failure of the adhesive bond.

All four bars are held together by nuts, washers and studding through the side walls and either the top or bottom bars. These are spaced at roughly a 3" square pitch along the channel length.

Originally, the channel was to be sealed by four strips of 'O' rings, one let into each side of the smaller bars, in contact with the side walls. Various sizes, types and seating arrangements for the 'O' rings were tried, all to no avail. Essentially, the 'O' ring in cross-section represented a point contact seal which was not sufficient to overcome the deflections of the Delrin. The solution has been to use tailor-made black steam quality rubber gaskets. These have been balanced to $\pm \frac{1}{32}$ " so that the side walls are parallel to effect a perfect seal.

The ends of the channel are shown in Fig. 3.3. A block, let into the base by a half inch lip, is sealed with silicone rubber and backed up by a neoprene gasket and backing plate. A $\frac{3}{4}$ " I.D. stainless steel pipe has been tapped into the block and let through the gasket and backing plate.

The whole channel on its four inch steel tube base is mounted on a rigid frame and can be axially twisted through 360° about an 8" radius from the axis. It is connected to the mono pump only by 5' lengths of 1" I.D. P.V.C. glass reinforced pipe so as to reduce system vibrational effects to a minimum. (Fig. 3.4)



WELDED CONSTRUCTION USING 50 mm x 10 SWG SQUARE TUBE
STOVE ENAMELED HAMMER FINISH.

Fig 3.4

The Delrin has a very smooth finish on the extruded bars so the final machining was taken slowly and sanded to give a visibly equivalent smoothness, especially on all sections in contact with the fluid.

3.3 L.D.A. Optics System

A 5mW helium neon laser is used as the light source. It can be accurately moved in all directions and rotated within a horizontal locus but with less precision.

The transmission optics was constructed in house, based on an old optical unit. It has two functions, firstly to split the beam and secondly to bring the new beams to a focal point in the channel.(Fig. 3.5)

The specifications for all the home built optical components is a surface roughness no more than a tenth the wavelength of the helium neon laser and a transmissive reflectivity of less than 1% by MgCl_2 coating. The former criteria is at least a factor of two better than that specified in the literature.

The beamsplitter consists of two right-angled prisms whose faces are stuck together by a partially reflecting coating. This coating increases in thickness towards the top of the interface so that the relative beam intensities of the two beams could be changed by moving the beamsplitter relative to the beam.

After leaving the beamsplitter, the beams are displaced outwards from the original beam axis by a set of prisms. The

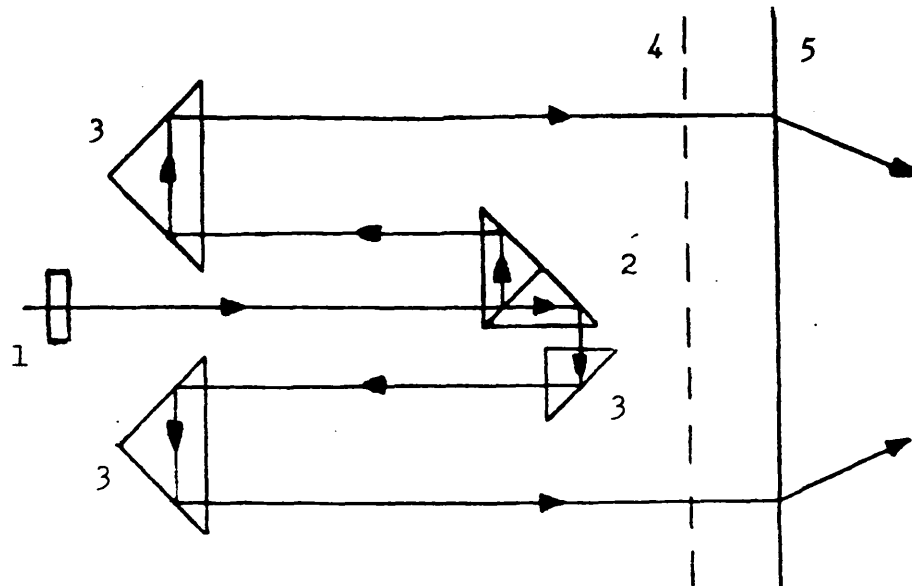


FIGURE 3.5a Transmission Optics

Key

- 1 Polarising filter
- 2 Beam Splitter
- 3 Redirecting prism
- 4 Plane of beam displacer
- 5 Front lens

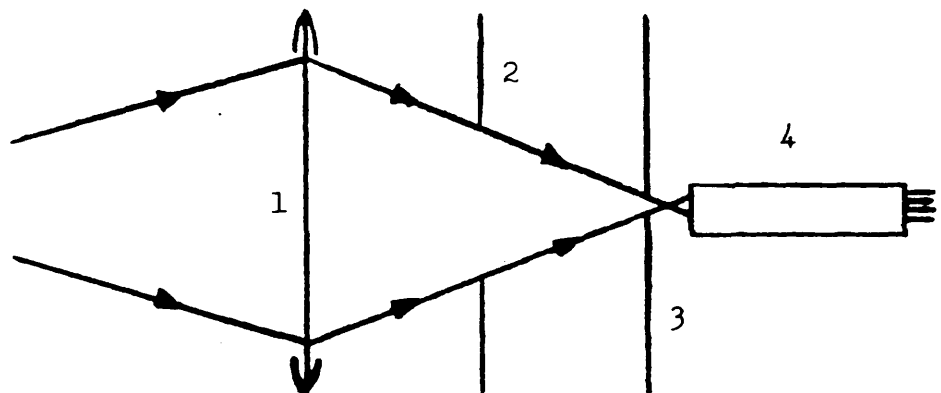


FIGURE 3.5b Receiving Optics

Key

- 1 Front lens
- 2 Variable aperture
- 3 Pinhole
- 4 Photomultiplier tube

beams are retained for three crossings of the optical chamber to have the option of frequency shifting the beams. (This method allows the measurement of low and reversing velocities by forcing the interface fringes to travel in the direction of the flow at a known frequency. The detection equipment measures the increased total frequency, subtracts any imposed frequency shift electronically and hence gives the actual frequency.)

Each of the prisms is mounted on a spring loaded table which can be moved and held relative to the frame by a series of Allen screws, twenty six in all.

The two beams, now 80mm apart, pass into a unit of four prisms which can alter the beam spacing to 40 or 20 mm if desired. The emergent beams are focused by either a 280mm, 90mm or 70mm crown glass lens.

All of the above are fixed rigidly together into one unit. The whole transmission optics can be moved in any direction by adjustment screws, and can be rotated about the unit's axis.

The receiver optics is a Cambridge Consultants unit consisting of a 0.2m - ∞ focal length lens of variable aperture and a 50 μ m pinhole. The image at the pinhole is viewed by an eleven stage Centronic Type 4283 photomultiplier with trialkali photocathode and optically flat end window.

The receiving optics can be moved in the vertical plane and twisted about an axis perpendicular to the receiving optics body axis.

3.4 L.D.A. System

The system diagram is given in Fig. 3.6. The laser is a 5mW polarised helium neon laser producing a 1mm diameter beam. This beam passes through a 1:2.8 variable beam expander into the transmission optics described in the last section.

The P.M.T., also described previously, looks at the beam's focus in the membrane channel and feeds the observed signals to the Doppler signal processor. The P.M.T. was powered by a VG. Instruments Model M2.5k1 high voltage supply which could be varied from 0 to 3400 Volts. The Doppler signal processor was a Cambridge Consultants CC04 unit.

In simplistic terms, the processor uses a voltage controlled oscillator (V.C.O.) to produce a continually varying frequency proportional to the voltage. This varying frequency covers the frequency range set roughly 3 million times a second. Meanwhile, the incoming Doppler signal is compared with the V.C.O. signal. When the two signals have the same frequency, the processor holds the V.C.O. generated signal to validate the Doppler signal. Depending on the control setting, if the V.C.O. and Doppler signals have exactly the same frequency for, typically 10 waves, the signal is validated. The voltage supplied to the V.C.O. is recorded by the processor and the V.C.O. continues to sweep the frequency range for another signal.

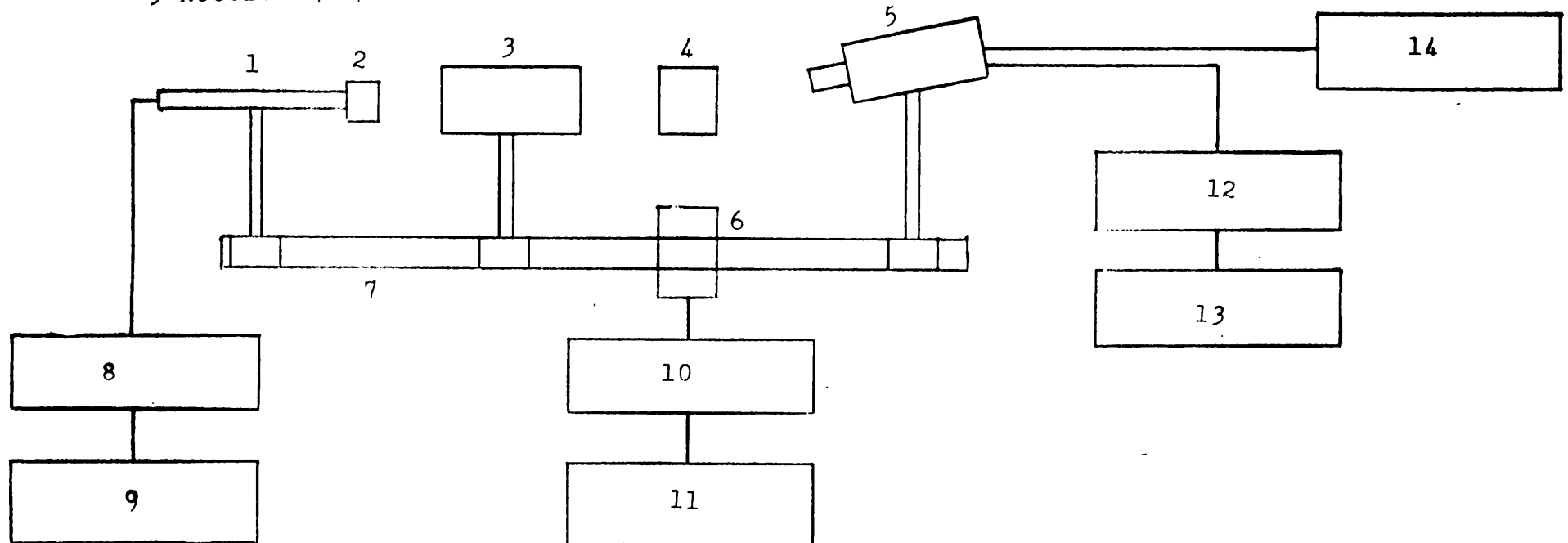
FIGURE 3.6 Laser Doppler Anemometer System

Key

- 1 Laser
- 2 Beam Expander
- 3 Transmission optics
- 4 Membrane channel
- 5 Receiving optics

- 6 Clamp
- 7 Optical bar
- 8 Laser H.V. supply
- 9 Laser safety interlock
- 10 Stepper motor traverse assembly

- 11 Stepper motor indexer
- 12 Frequency tracker
- 13 Oscilloscope(s)
- 14 Photomultiplier H.V. supply



The voltage pulses, (proportional to Doppler frequencies), which are recorded after validated results have been received, are then averaged over times set by the user. These averaging times are only based on the times in which Doppler signals are being observed. Typically, these correspond to 10^3 to 10^5 different frequencies being tracked and validated, each derived from a different particle.

The processor contains several settings which need to be altered to suit the system in question. They are described in the Cambridge Consultants CC04 manual or briefly by DURST F. et al (132). The combined errors of the instrument are rated at no more than $\pm 0.5\%$ of the full scale reading.

The signals from the Doppler signal processor were observed on two oscilloscopes. These can be used to give single particle Doppler frequencies and can be compared to the signal processor results.

The optical system is fastened rigidly to a traverse table system which can be accurately adjusted in all three planes. In the horizontal plane lead screws allow an accuracy of $\pm 10\mu\text{m}$ and in the vertical direction a stepper motor drive allows an accuracy of $\pm 1\mu\text{m}$.

The traverse table system, including the optics, and all the associated electronics are positioned on a trolley which can move the whole 3m length of the membrane channel. The axis of the trolley track and membrane channel were parallel.

CHAPTER 4 EXPERIMENTAL METHODS

4.1 Assembly of the Membrane Channel

The membrane channel consisted of 593 separate components. The construction method has evolved over 60 assemblies and is described in detail in Appendix 3. Useful observations made during the development of the channel are described in Appendix 4.

4.2 Laser Doppler Anemometer Alignment

The optical components were first cleaned with a photography lens brush and then by the use of analytical grade acetone soaked tissues. The laser was set up on the optical bar and the beam expander screwed onto the front. (Appendix 5 covers the safe use of lasers.) The single beam was observed on a diffuse screen at a distance of 4m whilst altering the magnification of the beam expander, to check for a uniform Gaussian distribution laser beam. Various screw adjustments were available on the laser should there have been any problem.

The transmission optics were placed on the bar so that the laser beam entered the 5mm entrance window cleanly and the frame was parallel to the optical bar. This could be done by rotating the transmission optics and ensuring the image on the beam splitter was independent of rotation. The optics were then removed and, without adjusting the laser, a plane mirror was firmly set up at some 4m distance so that the reflected laser beams re-entered the laser at its

exit point. The mirror was a 360° rotatable screw adjustment mirror with a surface finish better than half the wavelength of the laser light. The optics were gently replaced on the bar with the same alignment procedure. This was followed by many weeks of work altering the transmission optic adjustment screws to obtain horizontal space parallel laser beams at the exit. To do this the front lens of the optic was removed and the screw crudely adjusted to allow the split laser beams to exit through the drilled holes in the frame. Final adjustment was required to make the exit beams reflect off the plane mirror previously set up in the perpendicular plane of the laser beam and back onto the exit holes in the transmission frame.

The mirror was realigned daily during the process. Since the adjustment is very sensitive, it was thought advisable to record the effect of small, say $1/16$ th turns of the screws so that the 26 screw system could be adjusted towards an optimum solution of space parallel beams. The best solution obtained had one beam returning on target and the other returning perfectly in the vertical direction but about 1mm off in the horizontal direction. This was equivalent to the beams being space parallel in the vertical plane and about 0.4 minutes of an arc from space parallel in the horizontal plane. Subsequently, only the angle adjustment screw on the prism next to the beam splitter was turned for realignment. This prism has the effect of adjusting the relative vertical position of the beams, and is the only one susceptible to vibrational effects because it is only side-mounted. All the others are base mounted and spring loaded.

The front lens was screwed on the transmission optics, and a microscope eyepiece carefully positioned at the focus of the two beams. The image of the focus on the microscopic lens was displayed on a white screen some 2m distant. The fringes were parallel and very sharp. The image of the 280mm lens was essentially circular whereas those of the 90 and 70mm lenses were increasingly elliptical with the fringes perpendicular to the major diameter. The focus diameter of the beams was so small for the low focal length lenses in relation to the microscopic lens radius, that positioning of the microscope was very sensitive. At this stage, the optical bar was clamped onto the traversing tables on the rig with extreme care not to knock the aligned optics. The photomultiplier was added to the other side and the whole bar balanced by a weight over a pulley on the laser side, so that any moment about the tables was less than 0.5Nm. This was done by calculation to ensure free running of the accurate stepping motor on the traversing tables.

4.3 Laser Doppler Anemometer Use.

(The following procedure was repeated at the start of each day and more frequently if necessary.)

A visual check was made to ensure that the two beams were equal. Any necessary adjustment was achieved by altering the height of the beam splitter relative to the incoming beam and hence the reflectivity/transmissibility of the prism coatings. The laser beams from the transmission optics were focussed on the screen inside the

relevant channel window. This was done by checking that the laser beams were in the same horizontal plane using the angle adjustment screw on the prism next to the beam splitter. The impinging beams were brought together at a point on the screen by winding the optical bar on the traverse perpendicular to the channel. This was checked by repeatedly blanking off one beam momentarily whilst observing the remaining beam.

After making the room as dark as possible, the photomultiplier was focussed on the image on the screen. To do this, the receiving window was first checked for stray laser beams using a white screen, making sure that the high tension supply to the tube was off. A stop was pushed into position between the pinhole and the tube. The angular microscope for looking at the pinhole was pushed into the receiving optics and focussed on the pinhole. The lens cover was then removed and the aperture fully opened. The whole tube was moved so that it was at least 0.5m from the screen at an angle to the laser beams and the image inside the tube fell roughly near the pinhole. By focussing the lens, the beam image on the pinhole plate was made as small and intense as possible. The micrometer screws attached to the pinhole plate were adjusted until the beam image centre coincided with the pinhole centre. The aperture was then reduced to minimise the observation of stray radiation but still allowing any radiation arising in the optical volume of the beam focus to be seen by the photomultiplier tube. The microscope was removed, the lens and microscope hole covers replaced and the stop in front of the tube retracted. The beams were moved by the traverse tables to the required

vertical measuring plane and then into the channel the required distance from the window.

The flow was started and the electronics switched on. From prior calculation, the order of magnitude of the expected Doppler bursts was known and the oscilloscopes were set accordingly. The room was darkened and the lens cover on the photomultiplier removed. The voltage applied to the photomultiplier was cautiously increased until Doppler bursts in its output could be seen on the oscilloscope. The voltage was further increased until the maximum of the Doppler bursts was no more than 30mV r.m.s. on the oscilloscope screen. The processed signal was connected to another oscilloscope for quality control. Generally, the following settings in TABLE 4.1 were used to process the bursts to give average Doppler frequencies on the tracker. Brief explanations and alternatives are also given.

The frequency range dial and output switch settings depended on the situation being measured. Almost every reading was taken with the longest averaging time setting so that the frequency recorded corresponded to the average of many 1000s of different validated signals.

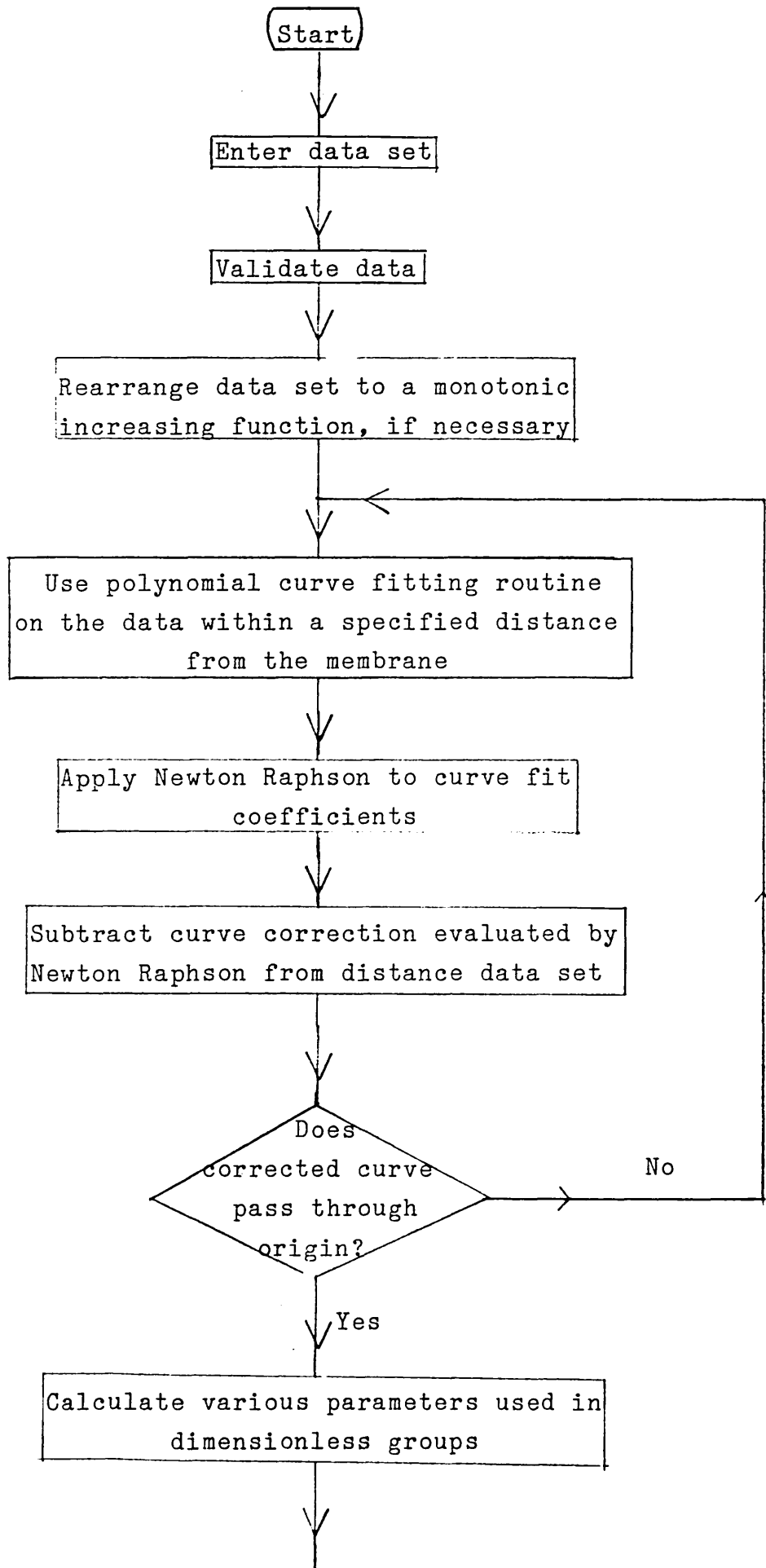
4.4 Computer Processing of the Results.

The 60 to 120 data points of relative distance versus average Doppler frequency for each velocity profile were typed into a computer. They were then processed using a program whose basic flowsheet is shown in Fig. 4.1. This program can operate on upto nine data sets at a time, but,

TABLE 4.1

TRACKER SETTINGS

Processor Section	Normal Setting	Comments
Mode	Tracker Mode	Instrument can be used as a Spectrum Analyser
Gain	After the Doppler signal has been adjusted to 30 mV rms max. set Gain to Reset for 20s and then to Peak.	a) If Doppler signal is continuous, Reset alone can be used. b) If the capture rate of Doppler signals becomes poor (slower) during a run, or the light scattering characteristics or the PMT voltage is changed, the Gain must be set to Reset for another 20s and back to Peak.
Capture	Full Scan Off	a) If the signal possesses a lot of noise, select 3% ie. track the signal only if it is within 3% of the last valid signal b) If the tracker finds it hard to track signals, Ramp Scan On allows the frequency of the first validated Doppler signal recorded to be displayed.
Tracking	Fast	For a stable, laminar flow situation select slow.
Dropout	Gated	Only validated signal will be recorded.

FIGURE 4.1 FLOWCHART

Transform data set into dimensionless data sets

Use polynomial curve fitting routine on the dimensionless data set

Print coefficients

Plot linear graph of velocity profile

Plot linear graph of the data points used in the Newton Raphson convergence routine

Transform dimensionless distance to log of the same

Use polynomial curve fitting routine on the semi-log data set over sections of the plot

Validate the data points on the semi-log plot

Any discrepancies?

Yes

Record points

No

88

Plot semi-log graph

Print correlations,
standard deviations, etc.

Transform the data set to log-log
coordinates

Plot log-log graph

Stop

because of excessive output, this was cut to just one set. Average computing time was about 2 Central Processor Unit seconds.

The first part of the program checks the inputs and forces the velocity profile to pass through the origin by use of Newton Raphson. The second part plots and correlates the experimental data into useful forms. The data files and programs were stored on floppy discs, each program being equivalent to around 25 k bytes of storage and data files, around 5 k bytes for each profile. Further details are contained in Appendix 7.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Technique Validation

5.1.1 A Typical Velocity Profile

The first velocity profile obtained on the apparatus which was typical is given in Fig. 5.1. It was obtained with an impermeable channel at a Reynolds number of 7200 and only covers a distance of 6mm from the impermeable wall. It is important to remember that Doppler frequency is directly proportional to velocity. ($1 \text{ kHz} \equiv 2.24 \times 10^{-3} \text{ m/s}$)

The velocity profile begins at the first data point of 13.2 kHz, at an initial displacement of $0 \mu\text{m}$. The displacement points are accurate to within $\pm 0.0025\%$ relative to this. There is, however, a zero error that has been correlated by computer so that the 'no slip at the wall' condition is obeyed. This simply involves a translation of the velocity profile along the ordinate axis. The translated profile is given in Fig. 5.2. It shows the closest data point to be $88 \mu\text{m}$ from the wall. Each point represents Doppler frequencies observed over 1s. Since each signal typically requires 10 waves from each particle, the point on the curve represents $\frac{10000 \times 1}{10}$ ie. 1000 particles for Doppler frequencies of about 10 kHz. At frequencies of about 100 kHz, the point typically represents 10000 particles. Most of the curves given later use an averaging time of 10 s and hence require the averaging of an order of magnitude more particles.

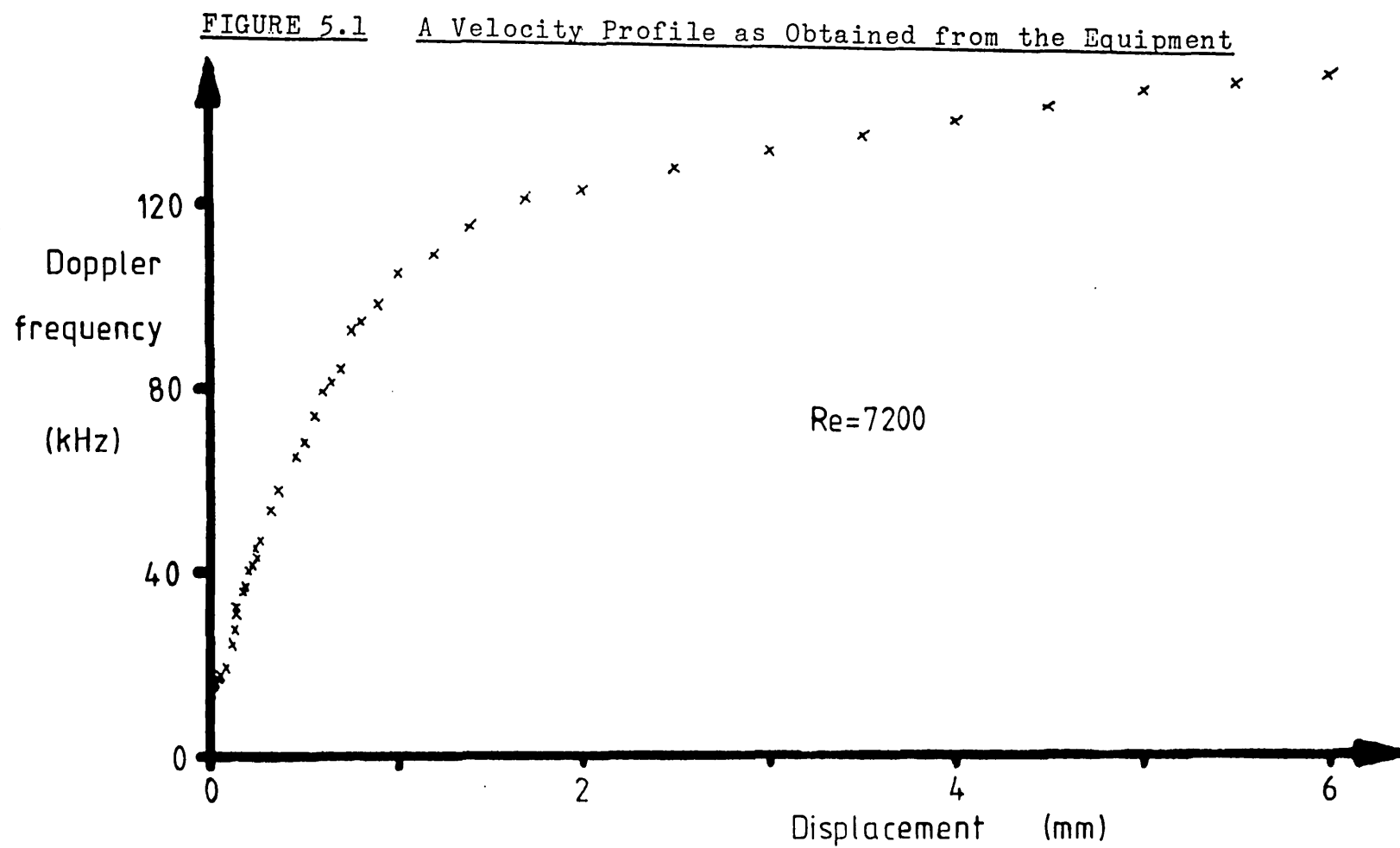
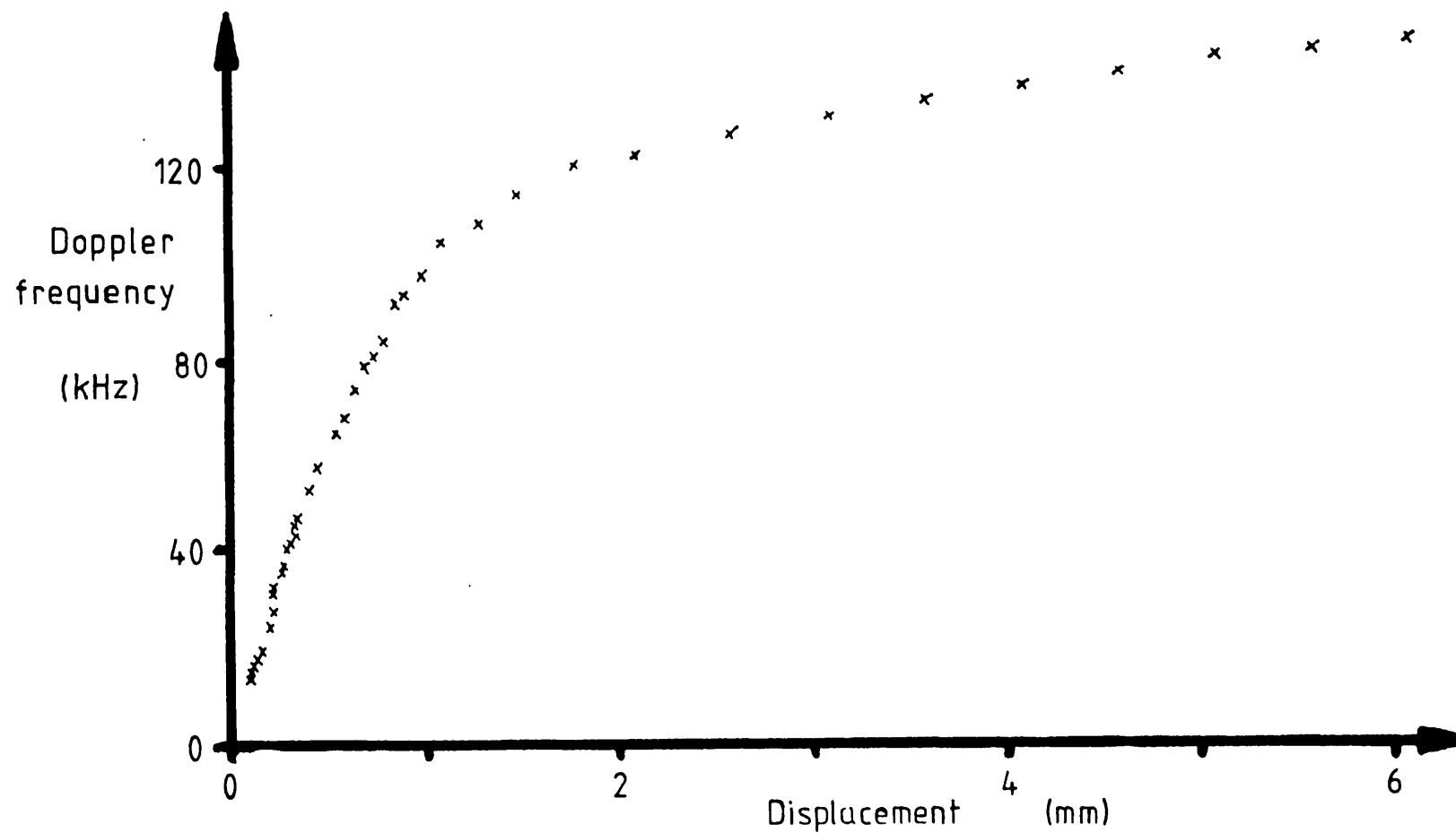


FIGURE 5.2 The Velocity Profile Given in Fig. 5.1 with the Computer Corrected Zero Error



One way of looking at the variation in velocities of single particles is to record two or more readings at each location. The full table of results used for the curve given in Fig. 5.1 is tabulated in Table 5.1. The greatest variation in Doppler frequencies at the same point occurs closest to the wall. The major reason for this is that the velocity gradient is greatest across the optical volume of the L.D.A. at the same time as the processor requires its lowest number of observed particles for one result. Even so, the velocity profile is well defined.

The maximum percentage variation at each data point is given in the same table. Throughout the whole range, turbulence provides the main reason for the variation. Superimposed on the bulk velocity is a fluctuating component which can be in the same or opposite direction to the bulk flow. The optical volume and number of particles are finite, and the processor is simply recording the variation. The variations can also be seen by observing the Doppler signal on an oscilloscope. The frequencies observed compared well with the processor average values.

The processor was checked against a quartz crystal signal generator prior to its use on the L.D.A. equipment. There was no detectible difference between the desired generating signal frequency and the processor measured frequency, ie. any error in processing is less than 0.01%.

5.1.2 Hysteresis

One test of the equipment carried out very early on,

TABLE 5.1 A Typical Velocity Profile

Displacement (μm)	Doppler Frequency (kHz)			Maximum % Difference Between the two readings
	1	2	Average	
0	11.8	14.6	13.2	24.0
20	15.3	15.0	15.2	2.0
40	15.6	15.3	15.5	2.0
60	17.1	17.7	17.4	3.5
80	19.2	18.8	19.0	2.1
100	24.2	24.6	24.4	1.6
120	28.3	27.0	27.7	4.8
140	32.1	30.3	31.2	5.9
160	33.7	31.9	32.8	5.6
180	35.2	33.3	34.3	5.7
200	35.6	38.1	36.9	9.8
220	40.3	40.8	40.6	1.2
240	41.4	42.1	41.8	1.7
260	45.0	45.9	45.5	0.9
280	42.5	44.7	43.6	5.1
300	47.5	48.1	47.8	0.6
350	54.6	52.2	53.4	4.6
400	60.2	55.9	58.1	7.7
450	65.7	64.4	65.1	2.0
500	67.1	69.2	68.2	3.1
550	74.6	73.8	74.2	1.1
600	81.2	77.3	79.3	5.0
650	83.0	79.5	81.3	4.4
700	86.4	82.8	84.6	4.3
750	91.3	94.2	92.8	3.2
800	96.5	92.3	94.4	4.6
900	99.2	98.8	99.1	0.3
1000	106.6	104.5	105.6	1.8
1200	105.9	112.6	109.3	6.3
1400	113.7	117.3	115.5	3.2
1700	123.0	120.1	121.6	2.4
2000	124.0	123.5	123.8	0.4
2500	128.4	128.6	128.5	0.1
3000	132.0	130.8	131.4	0.9
3500	133.5	135.4	134.5	1.4
4000	137.6	137.3	137.5	0.2
4500	141.2	139.9	140.6	0.9
5000	144.5	143.5	144.0	0.6
5500	144.8	145.9	145.4	0.5
6000	147.7	148.5	148.1	0.5

was a hysteresis type experiment. The velocity profile should be independent of the direction of movement of the L.D.A. equipment. Fig. 5.3 shows one of the curves obtained. The flow was essentially laminar at a Reynolds number of 2100. When the L.D.A. equipment was moved both towards and away from the impermeable wall, the velocity profiles obtained were essentially the same.

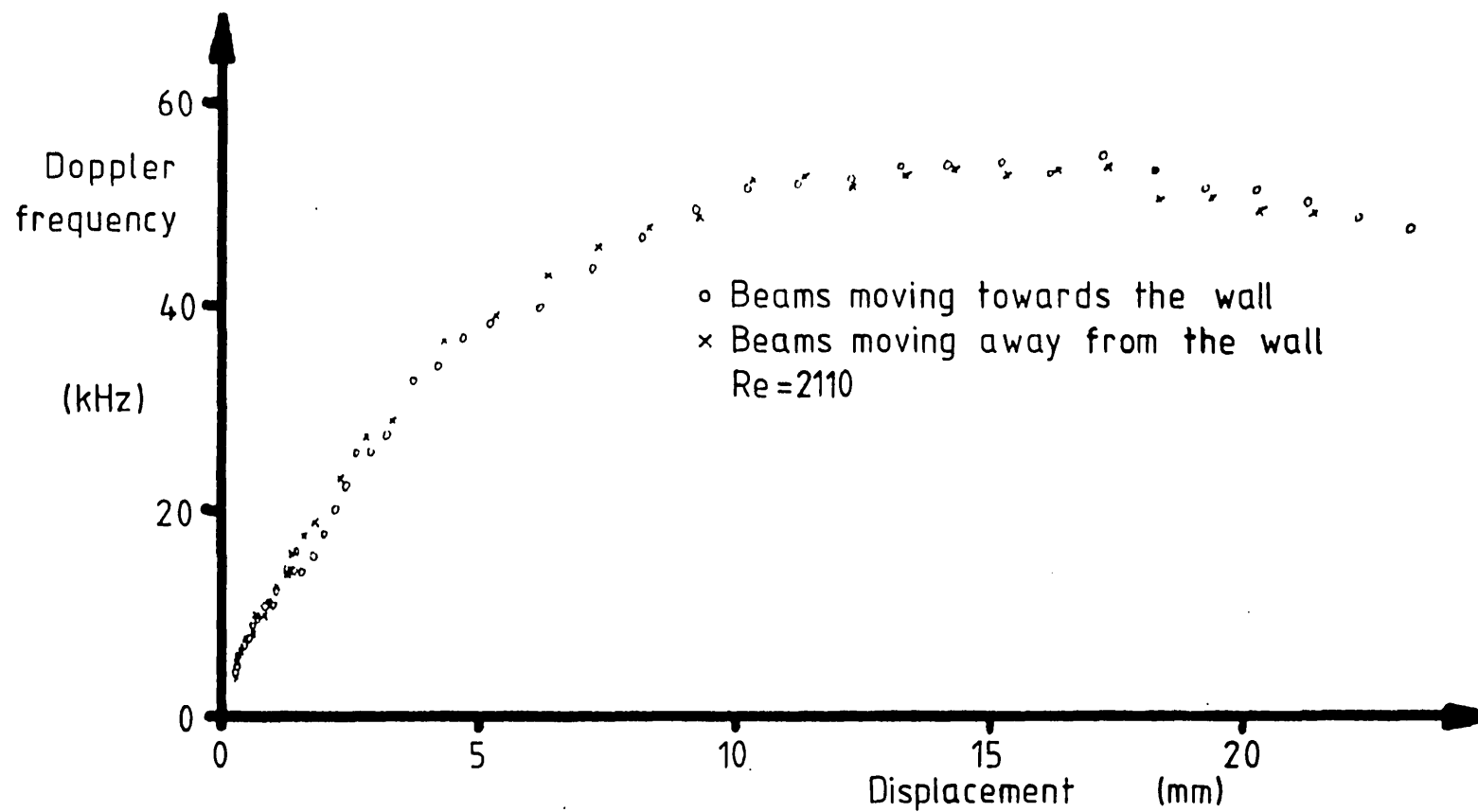
The velocity profile changes rapidly close to the wall, particularly for turbulent flow. Although it made no quantitative difference which way the L.D.A. approached, most of the data was obtained by moving it away from the wall. The incremental transverse movements could then be increased as one observed smaller changes in frequency, rather than estimating when to decrease the movements because a substantial decrease in frequency was expected.

5.1.3 Membrane Channel Movement

A systems error was spotted by observing the Doppler frequency at a given point in the channel close to the impermeable or permeable wall. Over the initial period (1 - 2 hours), the velocity at a given point increased. After a great deal of systematic detective work, the increasing velocity with time was ascribed to the membrane covered wall moving away from the rigid support plate. The L.D.A. intersection was fixed relative to the support plate.

The two end sets of windows lay 0.30 m and 0.55 m from their respective ends. A travelling microscope was rigidly positioned in the central plane of one set of windows and

FIGURE 5.3 A Typical Hysteresis Loop Pair of Velocity Profiles



the L.D.A. system aligned at the other, i.e. 0.335m and 0.585m from each end. The pump was started and the displacement from the membrane support channel was calculated by curve fitting the velocity profile measured after this experiment.

Figs. 5.4 and 5.5 show the movement of the membrane support with time, relative to its long term stable position. Fig. 5.4 has the travelling microscope at the entry window pair and the L.D.A. system at the exit. Fig. 5.5 has the converse.

As can be seen, the support bar moves away from the channel by just over 0.8mm at an internal pressure of 5.1 bara. This pressure is equivalent to 3.2×10^3 kg at terrestrial gravity acting on the membrane support bar. From the symmetry of the two experiments, the whole bar moves away en masse at more or less the same rate. There is more than enough slack in the system to account for the slip. The maximum tolerance on the stud holes is 1.7mm (See Fig. 5.6) assuming the holes are the same size as the drill. This is an underestimate.

There is, however, a difficulty in explaining the reversible nature of the defect. The displacements were almost completely restored after a long period of time with the motor stopped. Table 5.2 gives the net displacement not recovered. One explanation is that this may be due to the force compressing the bars due to the row of studs. This has the effect of compressing the inside of the bars relative to the outer regions of the channel during the

FIGURE 5.4 Measurements of Membrane Channel Movement

Outlet Pressure = 60.0 psig.

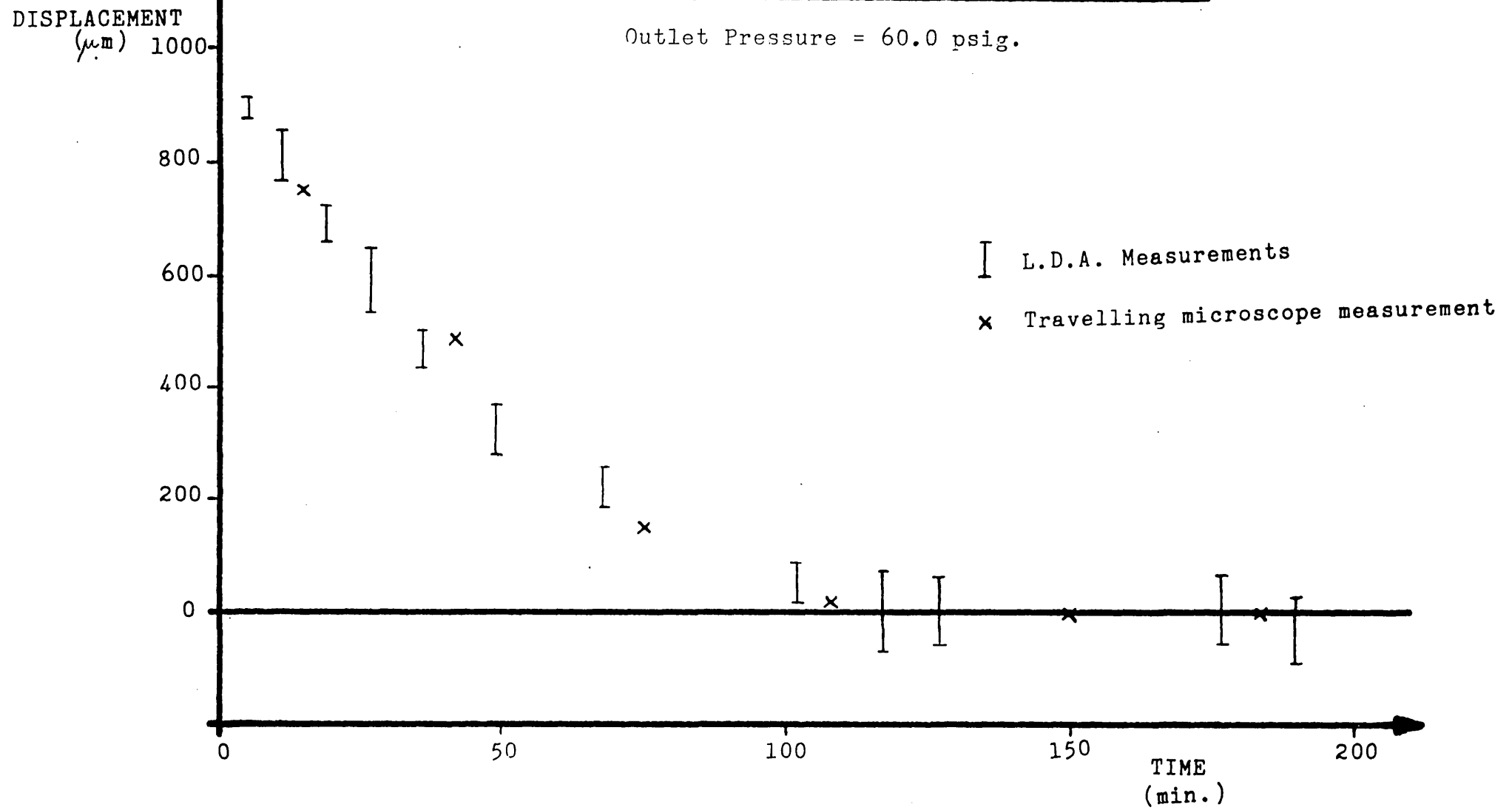


FIGURE 5.5 Measurement of Membrane Channel Movement

Inlet Pressure = 32.5 psig.

Outlet Pressure = 30.0 psig.

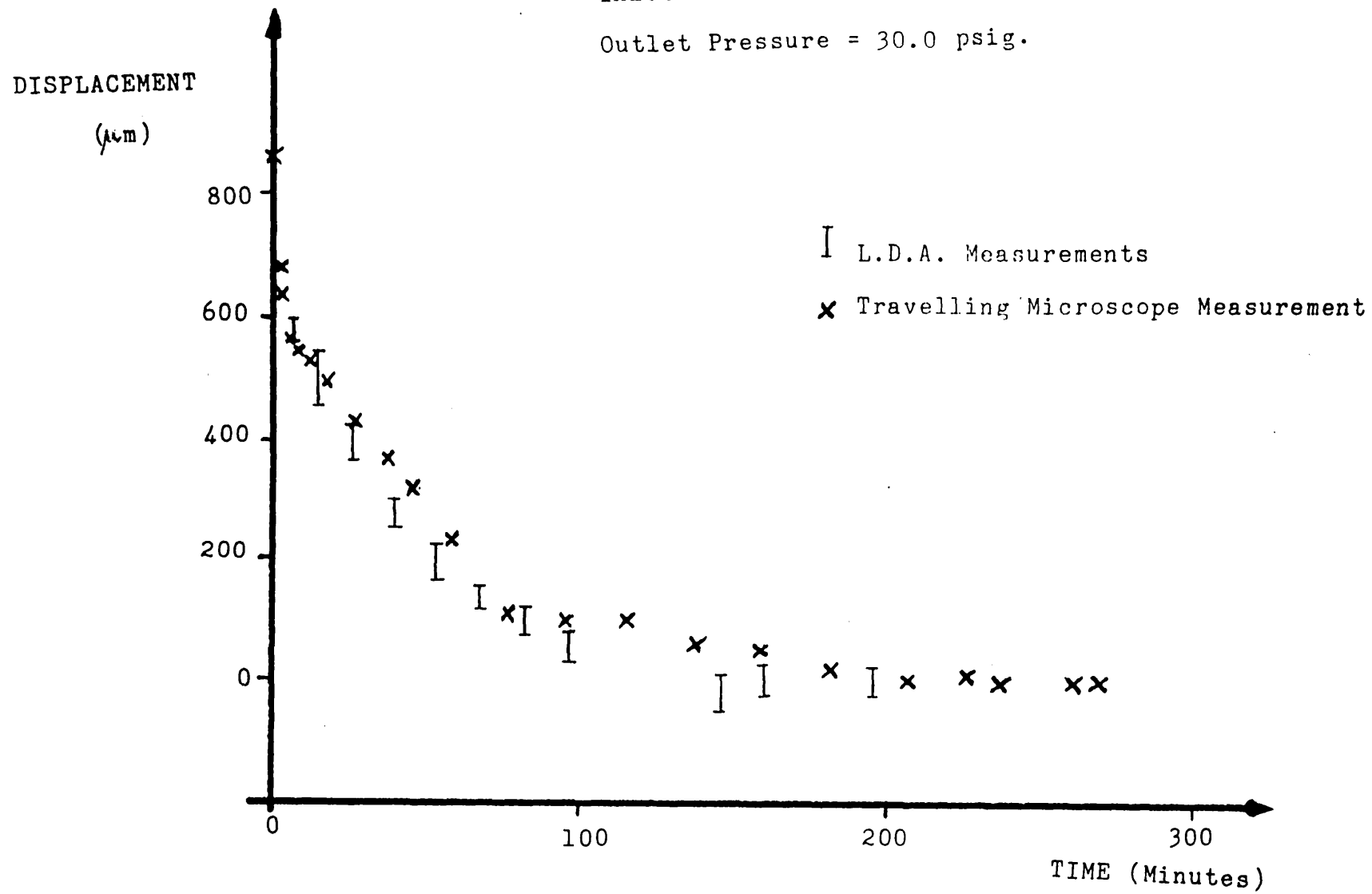
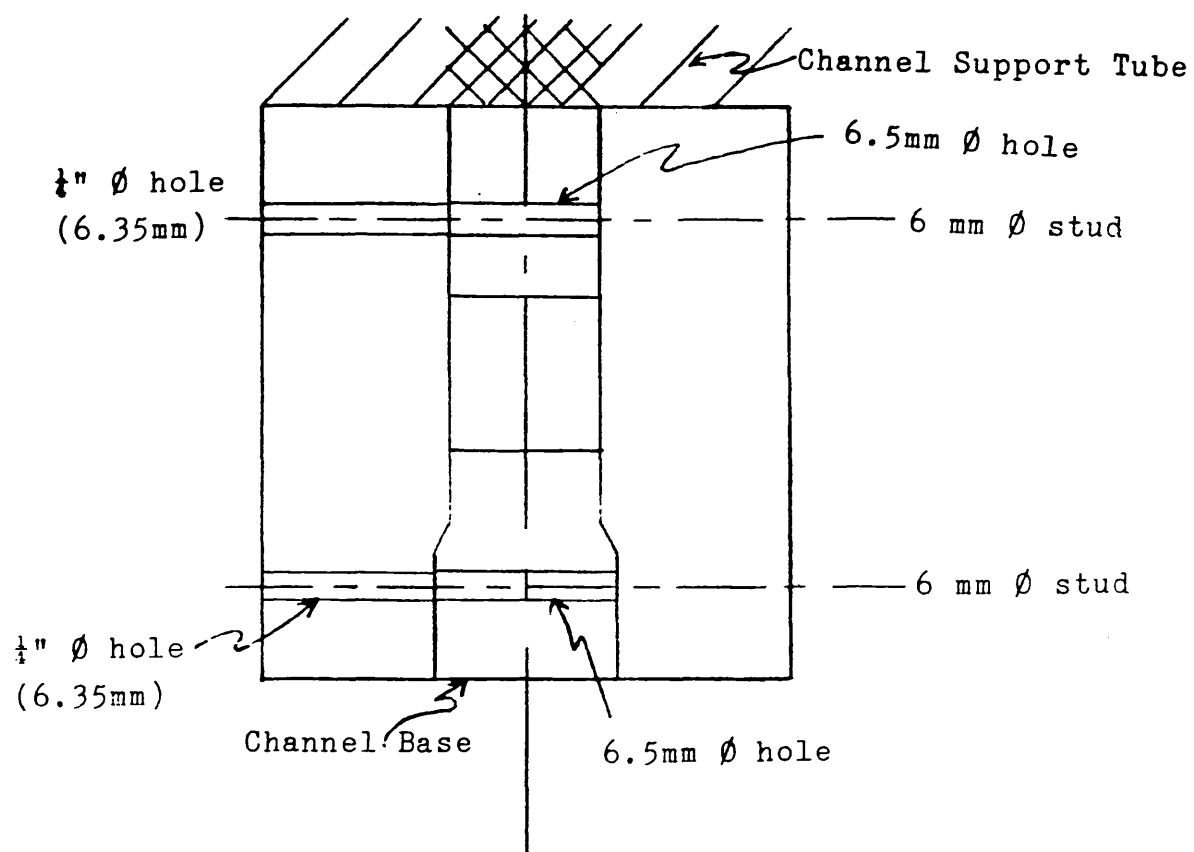


FIGURE 5.6 Tolerances in the Cross-section of the Membrane Channel.



Maximum movement of the channel base relative to the channel support tube = $2 \times (6.5 - 6) + (6.35 - 6) \times 2 = 1.7 \text{ mm}$

TABLE 5.2 Long Term Data Showing the Elastic Nature of the Membrane Deflection.

Case	Time after motor stopped (min.)	Net Displacement (microns)	Stable Displacement with motor on (microns)
Fig.5.4	970	-70	-890
Fig.5.5	1110	-20	-860

condition of internal pressure. (Fig. 5.7) When the internal pressure was released, the stud compression pinched the channel back in shape.

The larger error bars on the L.D.A. measurements on Fig. 5.4 compared with Fig. 5.5 are simply due to differing initial displacements from the membrane support bar.

Fig. 5.8 shows the travelling microscope readings based on the displacement of a bolt fixed beneath the membrane support bar and the membrane on top. The two curves were measured on separate days, and hence could not be expected to be totally identical. The magnitude of the displacement was different from Figs. 5.4 and 5.5 because the membrane had been reassembled. The two curves show that the displacement was not due to membrane or bar compression.

The conclusion from this work was that velocity profiles should only be measured about two hours after starting the pump, so that the displacement has already occurred. Two hours was considered adequate because velocity points on a good alignment required only about 10s per reading, 30s at the outside, before moving the L.D.A. further. Hence, the results frequency of order 0.1 Hz per $10\mu\text{m}$ movement was very much greater than any further support movement of order $10\mu\text{m}$ per hour ($3 \times 10^{-4}\text{Hz}$). In addition, the support movement is physically limited by the studding assembly, and from all the experiments, appears to reach this limitation after at most 3 hours.

As an aside, the back calculation of membrane movement from L.D.A. velocity measurements could be a useful

FIGURE 5.7 A Possible Mechanism for the Elastic
Nature of the Membrane Channel Movement.

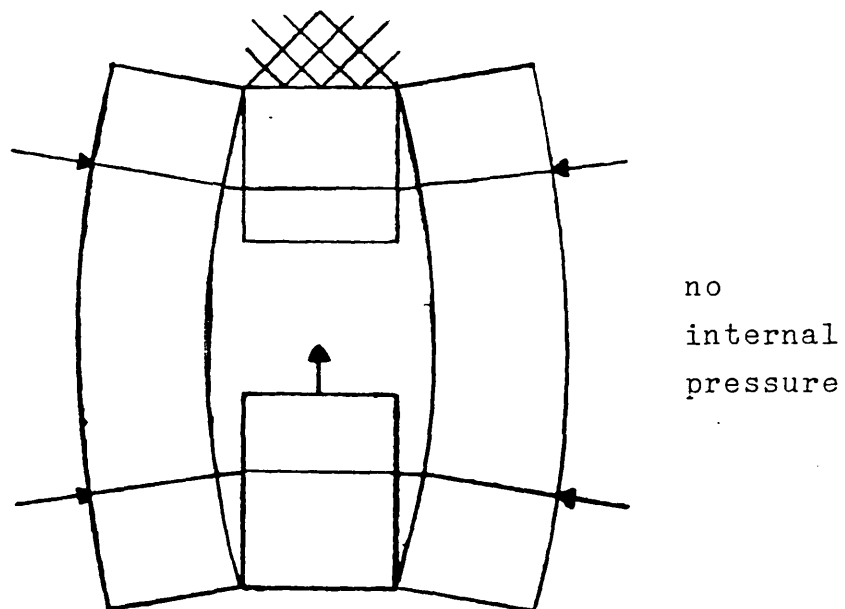
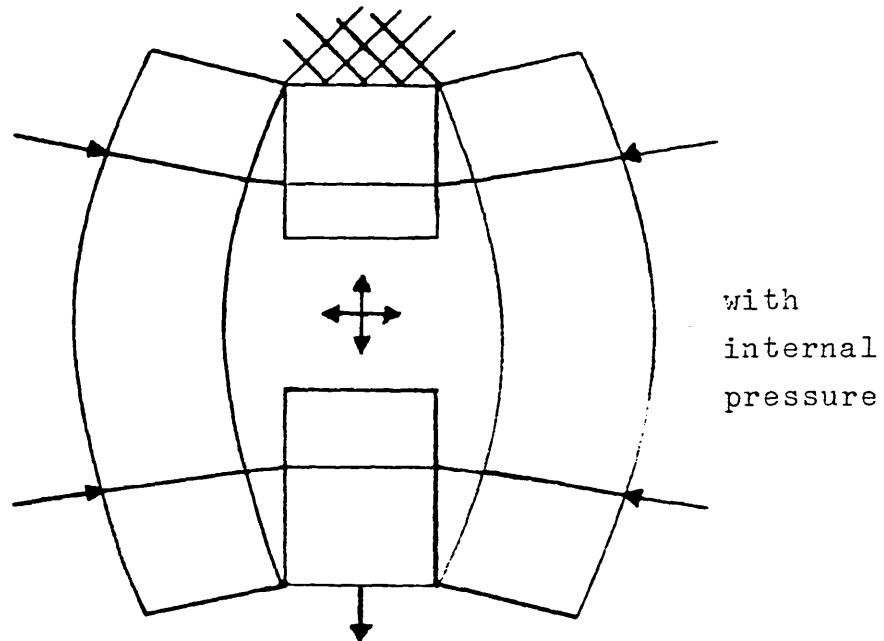
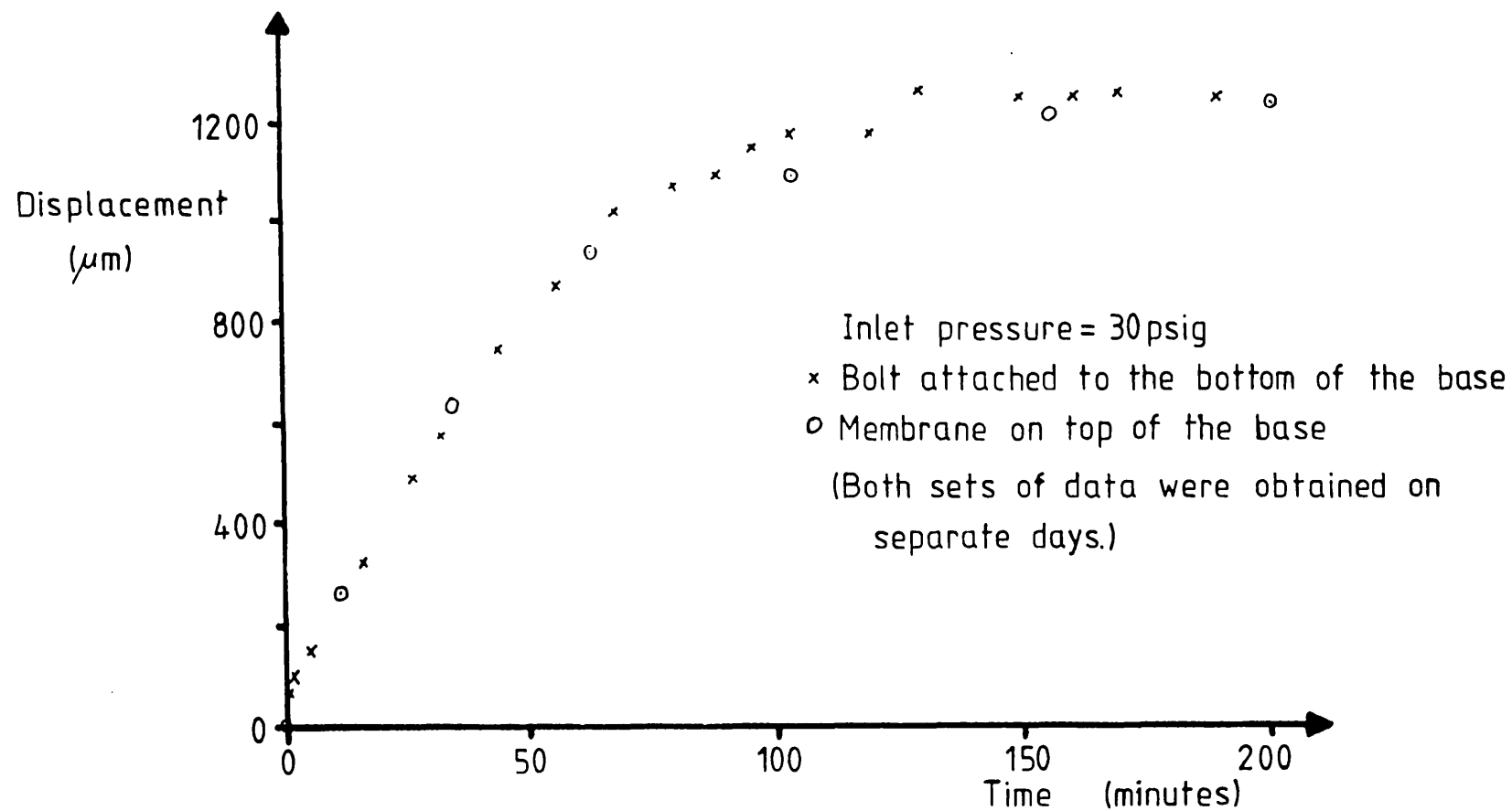


FIGURE 5.8 Displacement Measurements using a Travelling Microscope on the Base of the Channel and a Bolt on the Base of the Base Bar



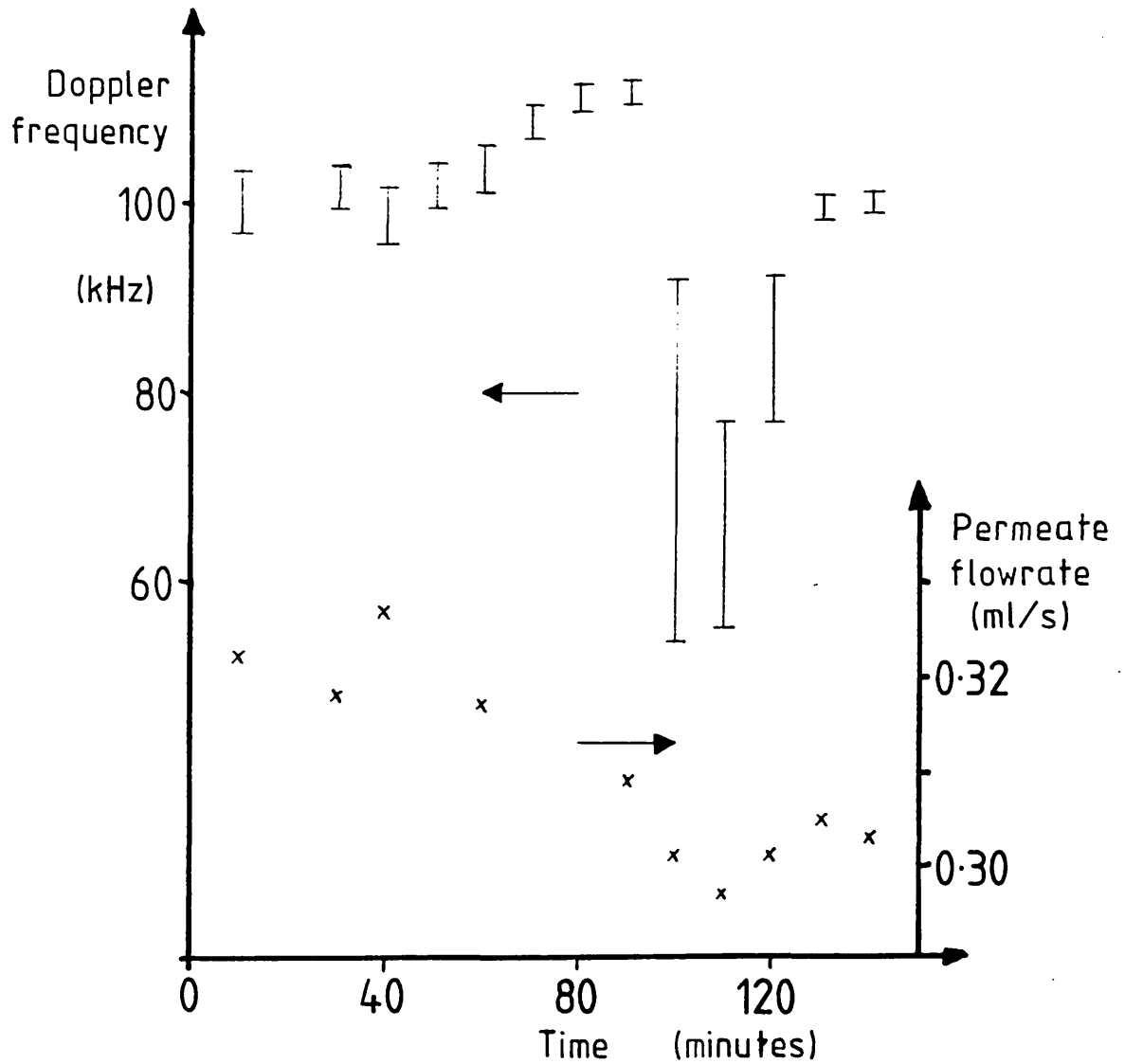
technique for movements of the order $10\mu\text{m}$ or greater, provided that the refractive indices of the system could be assumed unaffected e.g. the effect of pH extremes on membrane compaction rate. Two examples are given in Fig.5.9 and 5.10. The Doppler frequency of a point was observed whilst carrying out a teepol and sodium hypochlorite wash respectively.

Clearly, many different effects occur simultaneously. Any detailed study would require several controls to check that variations were significant. The most significant effect was the elastic nature of the membrane support bar movement. Each rinse required the motor to be switched off because of the rig's inability to provide sufficient back pressure on the filtered water feed. When the motor was switched back on, the support bar soon returned to its initial position. (See Fig. 5.9) The sudden continuing decline in Doppler frequency in Fig. 5.10 was due to the pump being switched off at 60 minutes.

5.1.4 Average Velocity Data

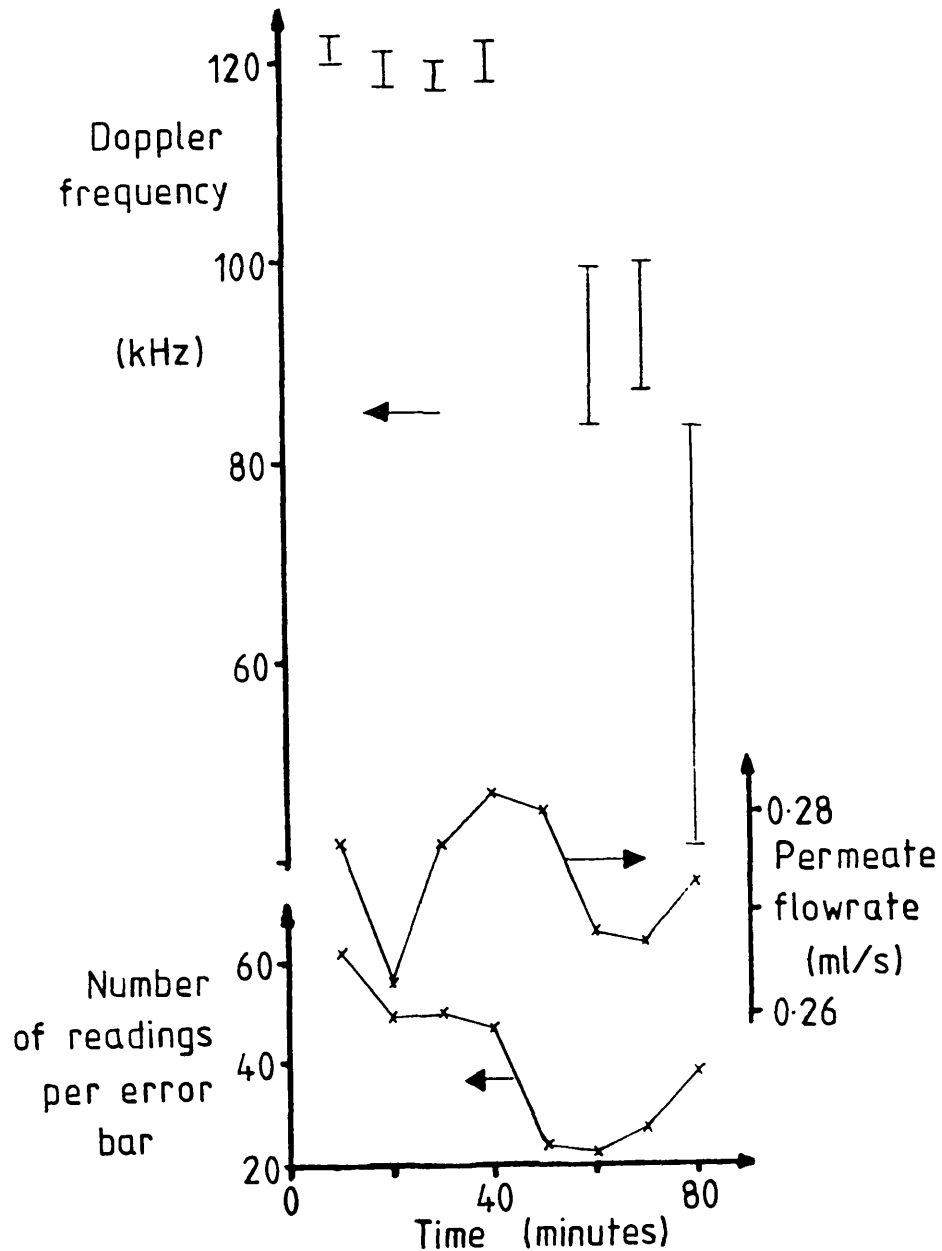
A good way of validating the experimental velocity profiles is to compare the evaluated channel average velocity with that calculated from measuring the flowrate by the rotameter. There were two ways of comparing this with measured data. The first involved measuring the velocity profile over many planes in the channel, curve fitting the data and computing the average. The second involved finding a theoretical solution to the Navier Stokes equations and evaluating the theoretical velocity profiles in the same

FIGURE 5.9 Doppler Frequency Measurements at a Fixed
Point During a Teepol Cleaning Cycle



- 10 mins - 5 ml Polystyrene Latex added as a light scatterer
- 30 mins - 20 ml Teepol added
- 60 mins - Stop motor and rinse with filtered water
- 90 mins - Once through rinsing stopped. Motor restarted and 5 ml of Polystyrene Latex added

FIGURE 5.10 Doppler Frequency Measurements at a Fixed
Point During a Sodium Hypochlorite
Sanitisation Cycle



- 10 mins - Add 500 ml Sodium Hypochlorite (5% w/w)
- 20 mins - Rinse with filtered water using pump
- 60 mins - Stop pump. Maintain same flowrate using filtered water
- 90 mins - Doppler signal lost due to the disappearance of the beam intersection

plane as the experimental curve.

There were a number of problems with the former method. As the channel height was 26.8 mm, and the elevating table could only travel a 25 mm range, not all of the channel velocity profile could be measured. It might be reasonable to measure upto, say half the channel height, and then use the symmetry of the profile. Mathematically, the curve fitting function would be erroneous since one is attempting to force the function of velocity for the half channel to be zero on three out of the four boundaries and symmetric about the mid plane. It would also have required more time than was available, and it was for this reason that this method was not chosen. The other problems would have been surmountable.

The second possibility was chosen using a solution for laminar flow found in a paper by Lundgen et al (149). For the coordinate system given in Fig.5.11, the velocity

profile is given by

$$u(y,z) = \frac{-1}{2\mu} \frac{dP}{dx} \left[\frac{h^2}{2} - y^2 + \frac{4}{h} \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{N_n^3} \frac{\cosh(N_n z)}{\cosh(N_n a)} \cos(N_n y) \right] \quad (5.1)$$

$$\text{where } N_n = \frac{(2n+1)\pi}{2h} \quad (5.2)$$

$$\text{and } \frac{-1}{\mu} \frac{dP}{dx} = \frac{Q}{\frac{4ah^3}{3} - \frac{8}{h} \sum_{n=0}^{\infty} N_n^{-5} \tanh(N_n a)} \quad (5.3)$$

The symbols are also defined in Fig. 5.11.

The series converged very quickly; seven terms always being adequate to satisfy the condition.

$$f_i < 10^{-6} \sum_{n=0}^6 f_n \quad \text{where } i \geq 6 \quad (5.4)$$

The term N_i^{-5} was always dominant and rapidly decayed relative to the hyperbolic functions.

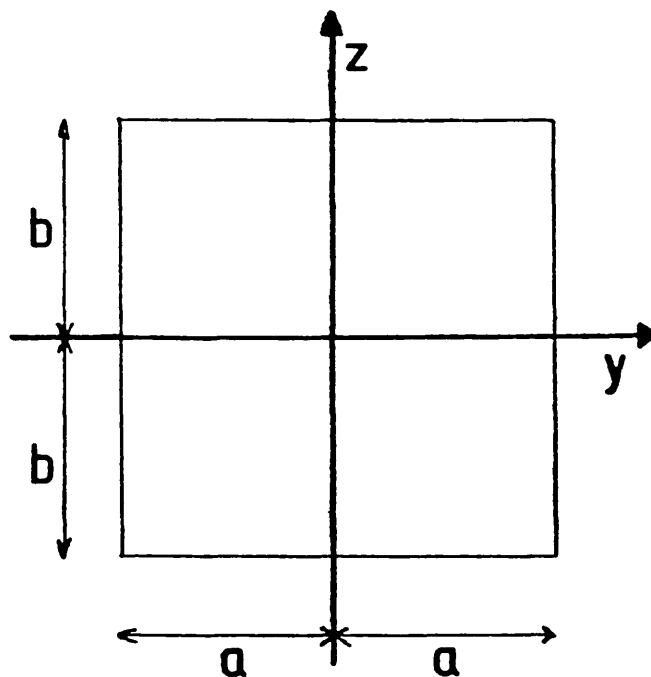
TABLE 5.3 Convergence of the Series Solution

Re = 990

Flowrate = $34.5 \times 10^{-6} \text{ m}^3/\text{s}$

No. of points considered per plane.	No. of nodal points per quadrant	Predicted Flowrate m^3/s
6	36	36.72
8	64	35.90
10	100	35.44
12	144	35.14
14	196	34.93
16	256	34.77
18	324	34.66
20	400	34.57

FIGURE 5.11 Coordinate System used for the Theoretical
Laminar Rectangular Velocity Profile.
(Lundgen et al (149))



As well as the usual computer dry run, a quadrant of the channel was broken down into a grid. The nodal velocities were evaluated and averaged. This allowed the computer modelled flowrate to be checked against the flowrate used as one of the initial pieces of data. The results in Table 5.3 show that the series solution conserves mass satisfactorily. In addition, for $a = b$, the velocity profile was symmetric to within 1% in u about $y = 3$.

The computer model was then set to give the velocity profile in the same plane as an experimental profile. A set of curves are given in Figs. 5.12 to 5.15. They were obtained in a plane 12.00 mm from the laser beam entry windows at different Reynold numbers.

For Reynolds numbers of 990 and 1510, the agreement is excellent. For the low Reynolds number of 640 the agreement may be described as good and for the highest Reynolds number of 2060 the agreement is poor. The reason for the latter case is simply that the flow is transitional rather than laminar, so the theoretical equations do not apply. It is interesting to observe that there is a higher centre line velocity at a Reynolds number of 1510 than for a Reynolds number of 2060.

For the two extremes in Reynolds numbers, mass appears to be conserved bearing in mind that the profile is only one plane through the channel. This means that the channel average velocity and flowrate is weighted towards the boundary, i.e. a larger proportion of the fluid is travelling close to the wall than near the centre line. A

FIGURE 5.12 The Comparison between Lundgen's Model
(solid line) and Experimental Data at
 $Re = 640$

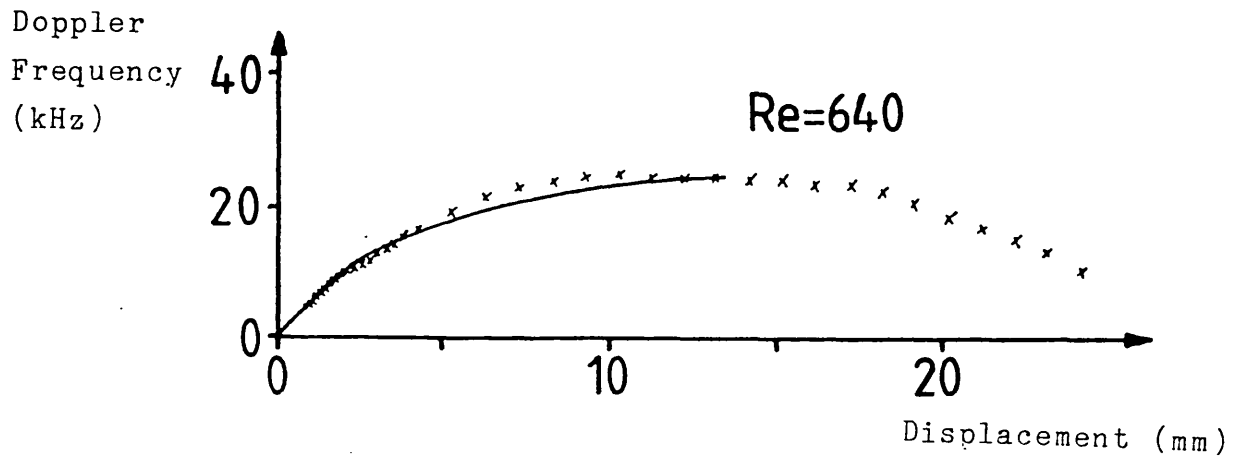


FIGURE 5.13 The Comparison between Lundgen's Model
(solid line) and Experimental Data at
 $Re = 990$

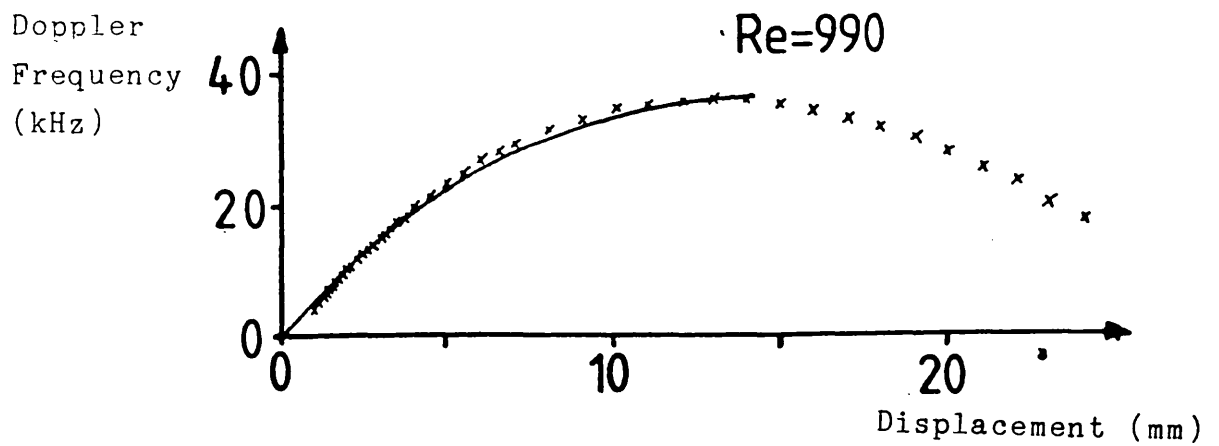


FIGURE 5.14 The Comparison between Lundgen's Model
(solid line) and Experimental Data at
 $Re = 1510$

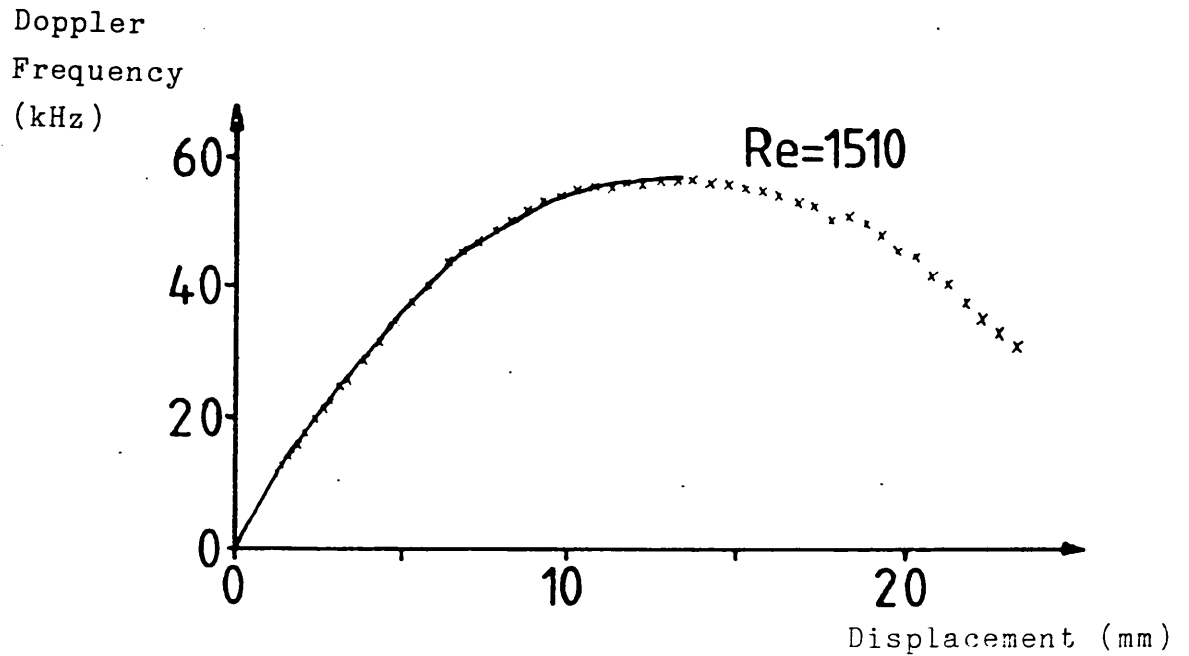
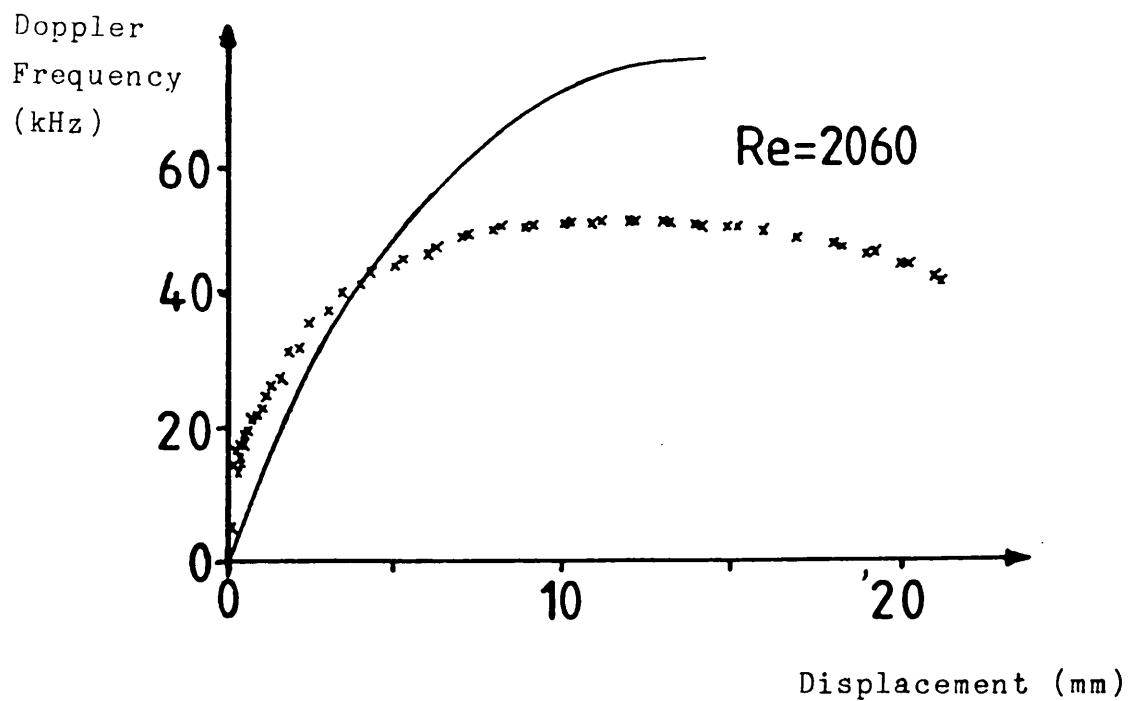


FIGURE 5.15 The Comparison between Lundgen's Model
(solid line) and Experimental Data at
 $Re = 2060$



demonstration of this is to take the example of laminar flow in a pipe, where

$$\frac{u_{\max.}}{\bar{u}} = 2 \quad (5.5)$$

For the square channel at $Re = 1510$, the following relations were computed

$$\frac{u_{\max.}}{\bar{u}} = \begin{cases} 2.00 & \text{Overall channel} \\ 1.45 & \text{Planar Profile given in Fig. 5.14.} \end{cases} \quad (5.6)$$

Therefore, for a square channel, the streamline of velocity equal to $\bar{u}$ is, on average, further from the centreline.

This idea is further explained in the next section.

The errors involved in the velocity profiles are around $\pm 2-3\%$ in velocity. However, the error should be the same for all four curves. It is due to the inaccuracy of measuring the laser beam bisector. These errors are covered in Section 5.3.2

5.2 Water - Impermeable Membrane System.

5.2.1 Effect of Entrance Length on Velocity Profile

Fig. 5.16 gives an interesting and expected relation for the effect of entrance length on the velocity profile in laminar flow. While the flow is still developing, the profile has a uniform velocity at the centre, as shown in the case of the 19 equivalent entrance diameters from the channel entrance. Further downstream, after the effects of wall shear stress have been transmitted through to the centre of the channel, a typical parabolic velocity profile has been obtained.

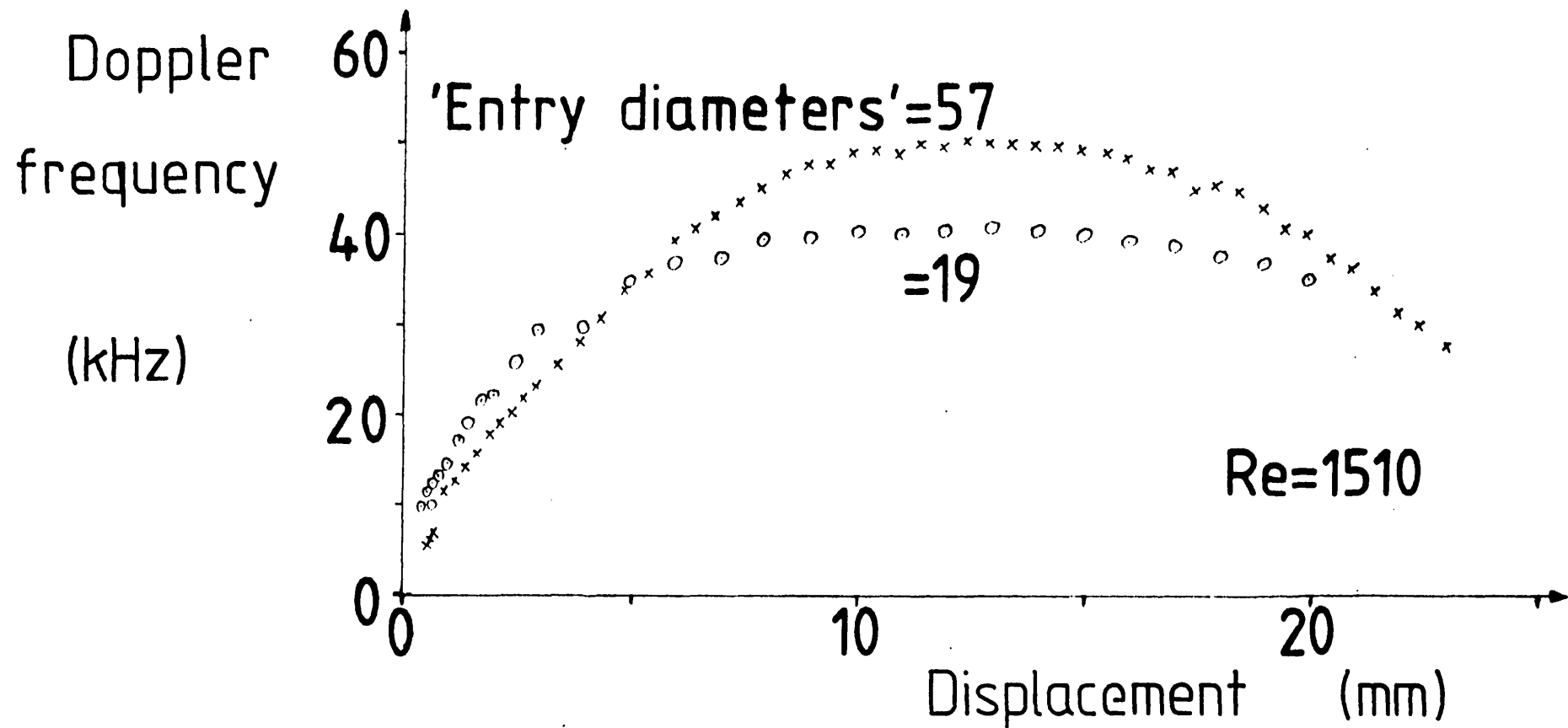


FIGURE 5.16 Effect of Entrance Length on the Velocity Profile.

For similar reasons as those given in the last section, the areas under both curves cannot be identical. They should only be the same for a symmetrical 1D case, i.e. the diameter in a cylindrical pipe. The velocity profiles as a function of entrance length are schematically given in Fig. 5.17. The higher mid-channel velocity of the fully developed flow was compensated by the higher velocity in the narrow but larger cross-sectioned rectangular outer annulus of the developing flow.

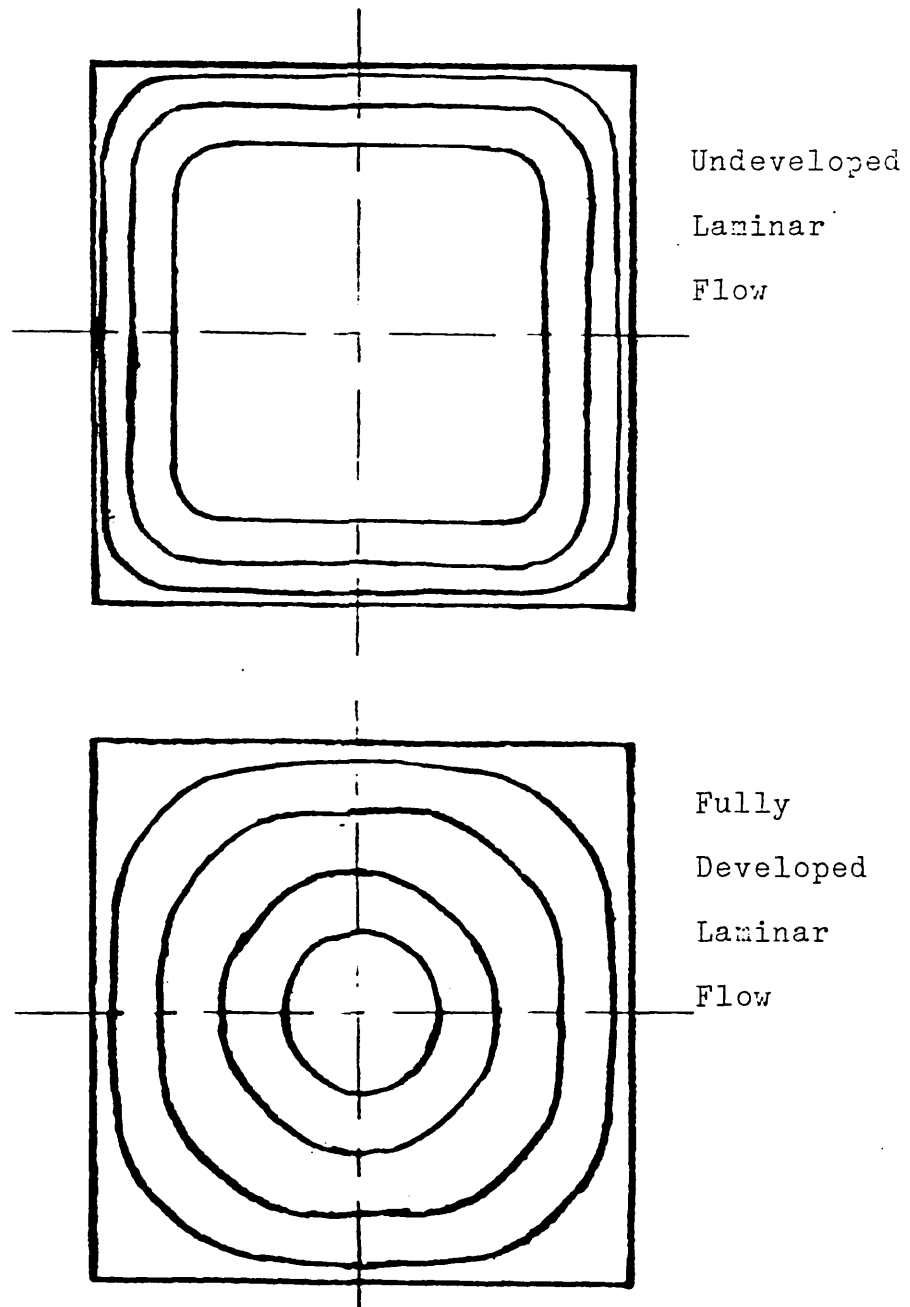
No theory was available to numerically conclude the result.

5.2.2 Effect of Reynolds Number on the Velocity Profile.

As the flowrate and hence Reynolds number increases, the velocities at each point must also increase such that over the whole flow area, mass is conserved.

The velocity profiles were observed to be markedly different for laminar flow. Fig. 5.18 shows an enlargement of the velocity profile close to the impermeable wall, for Reynolds numbers of 1270, 2850 and 7200, corresponding to laminar, transitional and turbulent regimes respectively. As can be seen, the velocity gradient near the wall increased markedly with Reynolds number. The increased velocity gradient can be used to promote better membrane performances as described earlier.

FIGURE 5.17 Schematic Velocity Streamlines as a Function
of Length



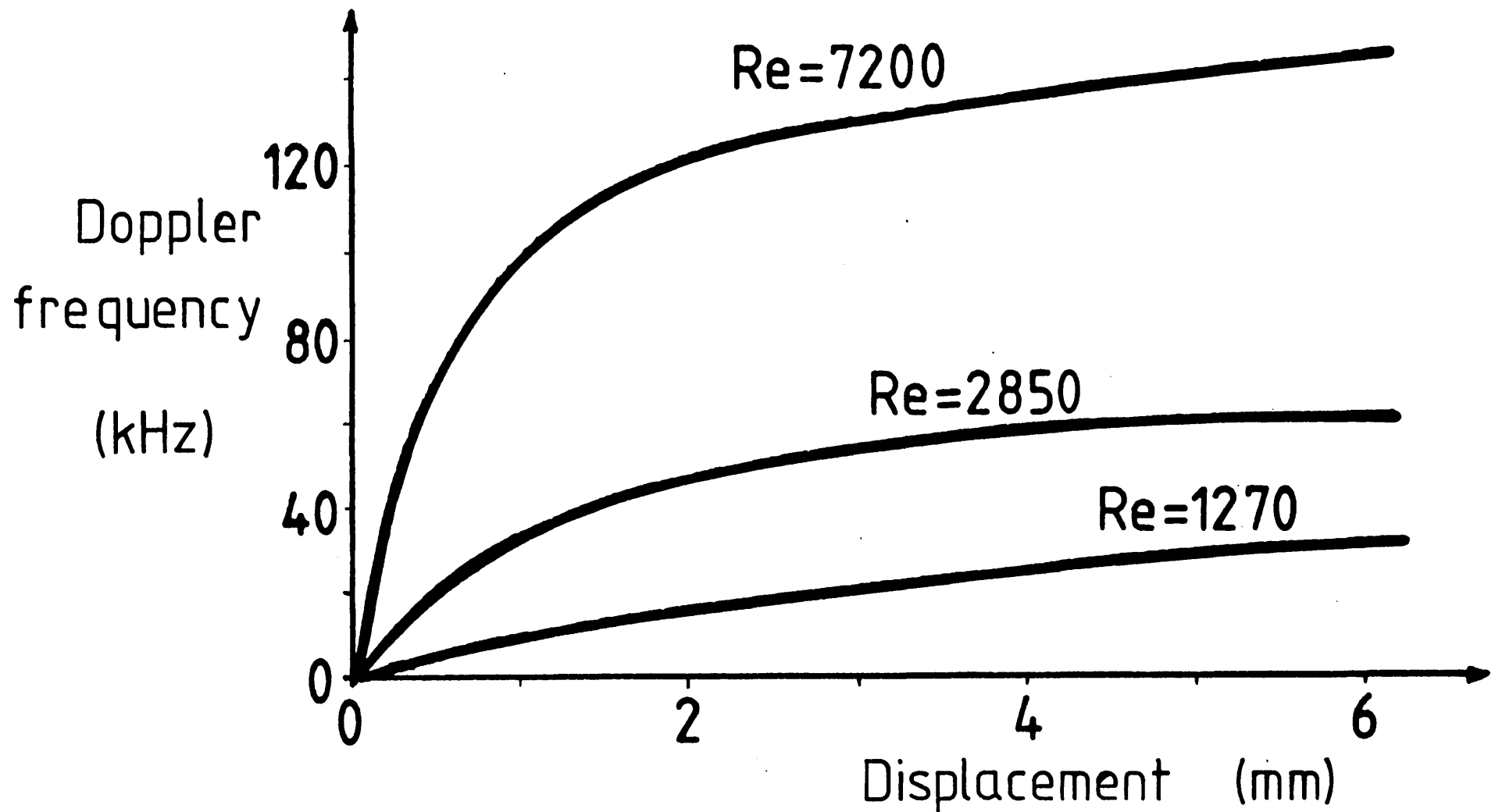


FIGURE 5.18 Effect of Reynolds Number On the Near Wall Velocity Profile of the Impermeable Channel.

5.3 Water-Semipermeable Membrane System

5.3.1 The Effect of Reynolds Number on the Velocity Profile.

Several velocity profiles for the water semipermeable membrane system were obtained. However, the aim of this work is to obtain a universal correlation for turbulent velocity profiles in a rectangular channel. This may be a function of the permeability of the membrane.

Two of these curves may be regarded as examples and typical. The velocity profiles obtained at Reynolds numbers of 6910 and 9200 are plotted on normalised velocity and distance from the wall coordinates with respect to the maximum measured velocity in the profile and the half channel height. Fig.5.19. At this scale, the variables $u/u_{\max}$ and y/h appear to have transformed the velocity profile onto the required universal correlation. However, Fig.5.20 shows the near wall region of the profile. These transformations only work outside this region. This can also be shown on a plot of $u/u_{\max}$ versus $\log(y/h)$ (Fig.5.21). The velocity profile of the core appears linear on this plot. A similar linear relation is found when the profile is plotted on log log axes (Fig 5.22). The linear portion has a slope of 0.160 ± 0.005 or approximately $1/(6.25 \pm 0.20)$. The same was true for the water impermeable membrane system, For turbulent air flow in a pipe, Prandtl's one seventh power law estimated the exponent to be $1/7$. Differences between the two exponents could result from the geometry of the channel, the distinction between the profile and the channel maximum velocity and the measurement technique.

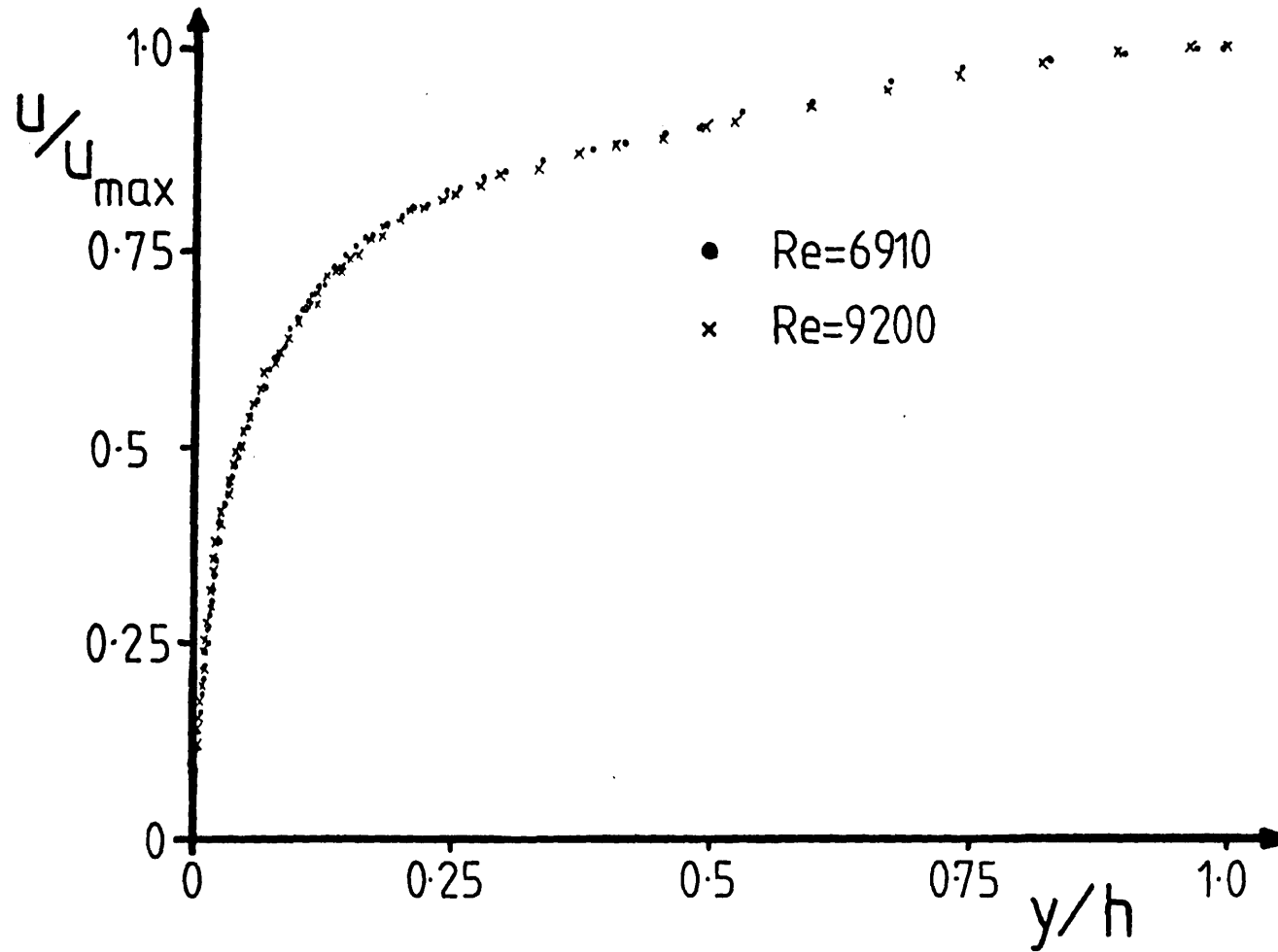


FIGURE 5.19 Two Turbulent Velocity Profiles for the Semi-permeable Membrane System in Maximum Velocity Based Dimensionless Form.

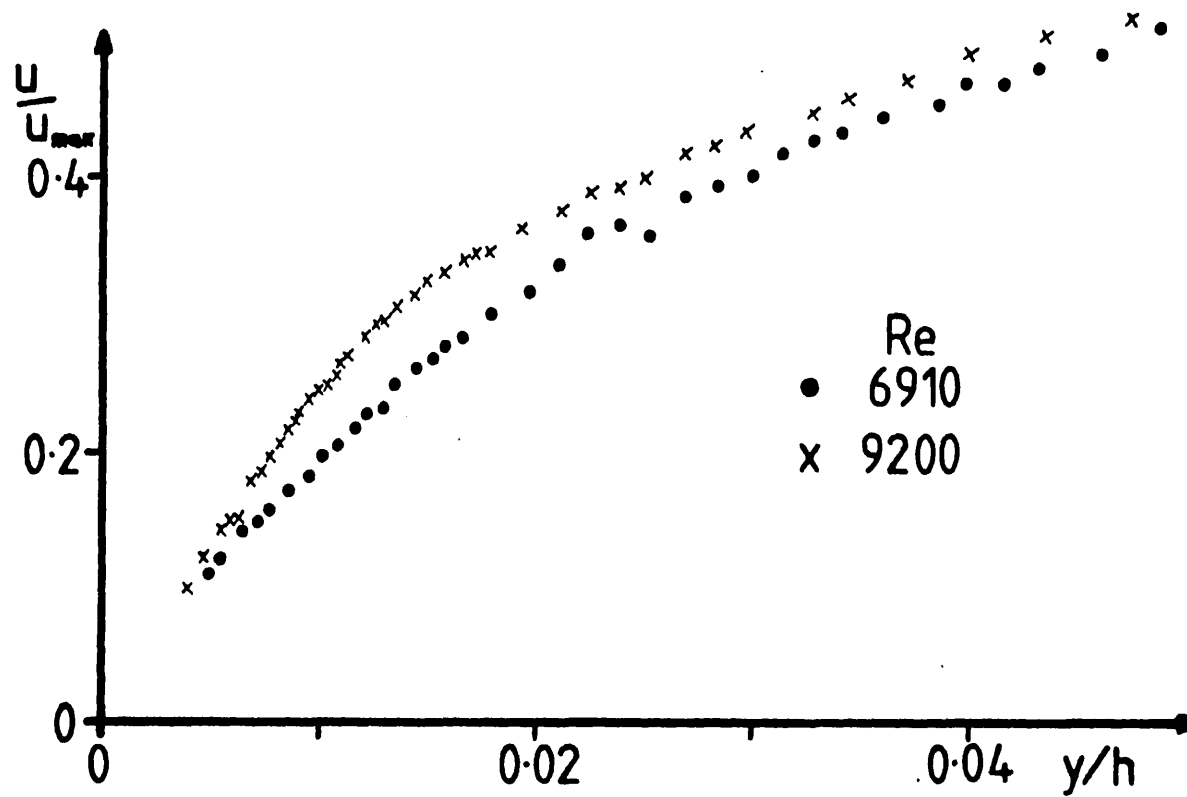
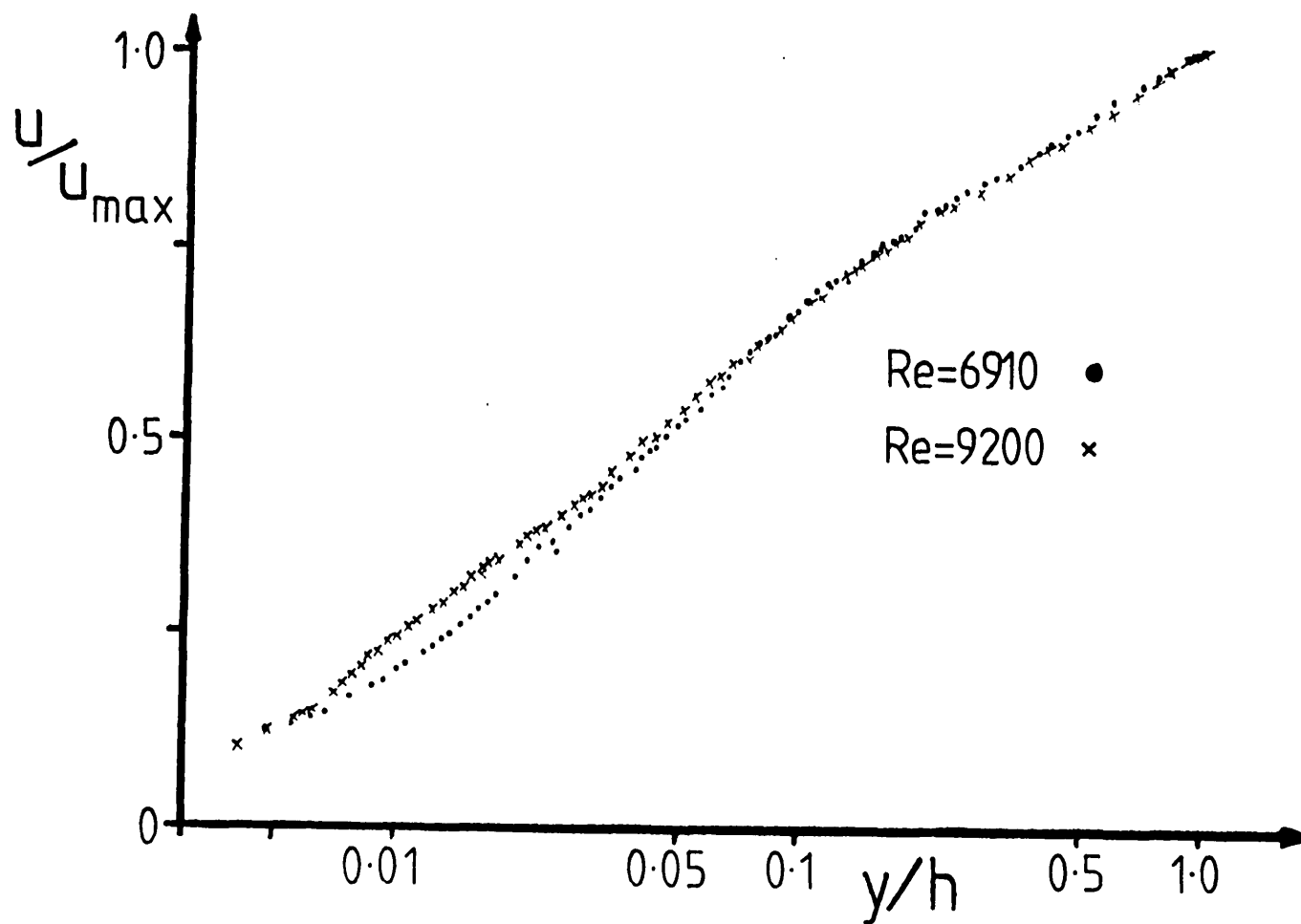


FIGURE 5.20 Maximum Velocity Based Dimensionless Velocity Profiles for the Near Wall
Region at Two Reynolds Numbers

FIGURE 5.21 Semi-log Plot of the Two Reynolds Number Velocity Profiles on Maximum Velocity
Based Dimensionless Coordinates



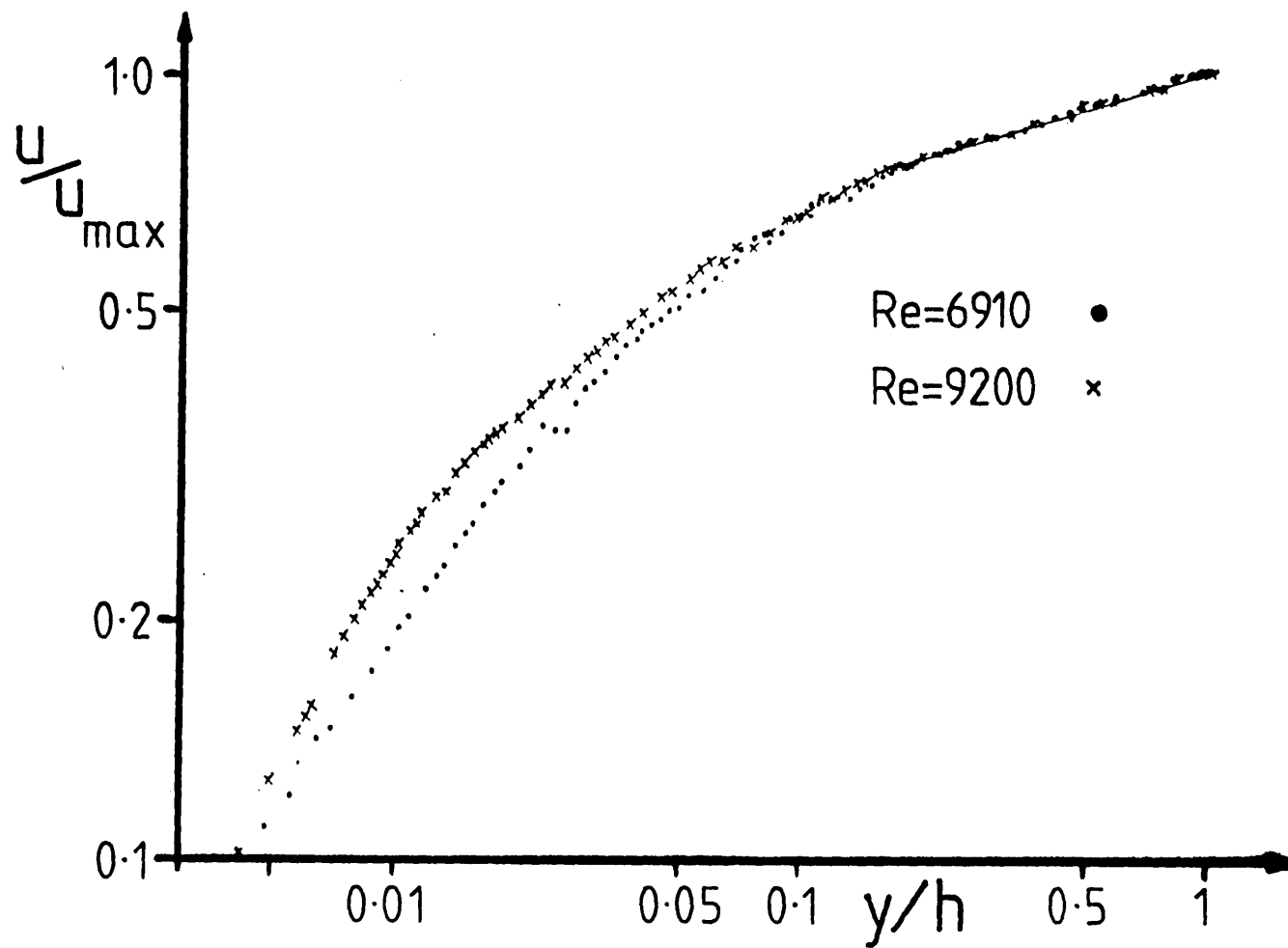


FIGURE 5.22 Log-log Plot of the Two Reynolds Number Velocity Profiles on Maximum Velocity
Based Dimensionless Coordinates

Using the transformations to u^+ and y^+ variables, the two Reynolds number curves become identical over the whole range of measured values. The curves are plotted in Fig. 5.23 on u^+ vs. $\log y^+$ and Fig. 5.24 on u^+ vs. y^+ axes for the region close to the wall, $y^+ < 10$.

As expected, the profile can be split into three distinct regions.

- i) $u^+ \propto y^+$ for $y^+ < 5$, (5.7)
- ii) $u^+ \propto \ln y^+$ for $5 < y^+ < 30$
- iii) $u^+ \propto \ln y^+$ for $y^+ > 30$

From the experimental data given, the best curve fits for the standard Karman Boultner Martinelli ranges are given in Table 5.4. The standard deviation refers to the standard deviation in u^+ between observed data points and the least squares fit of the data. So, in the range $y^+ < 5$, the standard deviation represents 4.6% of the maximum value of u^+ . In the range $y^+ > 30$, the maximum measured value of u^+ was 17.6 and the standard deviation represents only 0.4% of this. This gives a measure of the errors involved in measuring long term average velocities in the near and far wall regions of the channel.

One of the data point sets is plotted with the generalised solutions of the KBM, Deissler, Spalding, Hinze and Thomas equations for turbulent flow over an infinite flat plate, Fig. 5.25. These were covered in Section 2.3. There are discrepancies between the equations and the data presented here. The first three equations were all based on the same experimental data obtained by pitot tubes in a wind tunnel. The later used data gathered by a hot wire

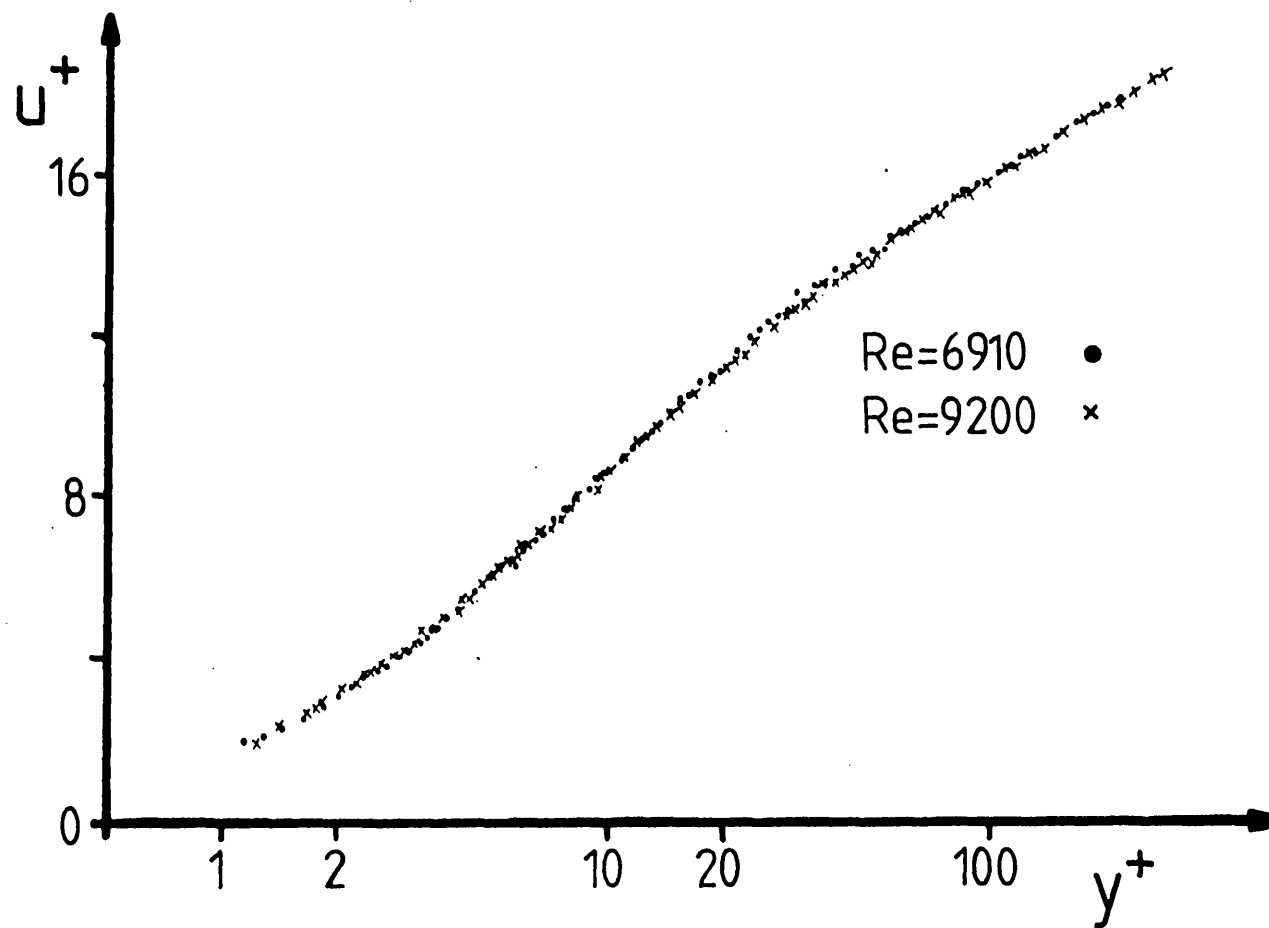


FIGURE 5.23 Two Turbulent Velocity Profiles for the Semi-permeable Membrane System in Wall
Shear Stress Based Dimensionless Form

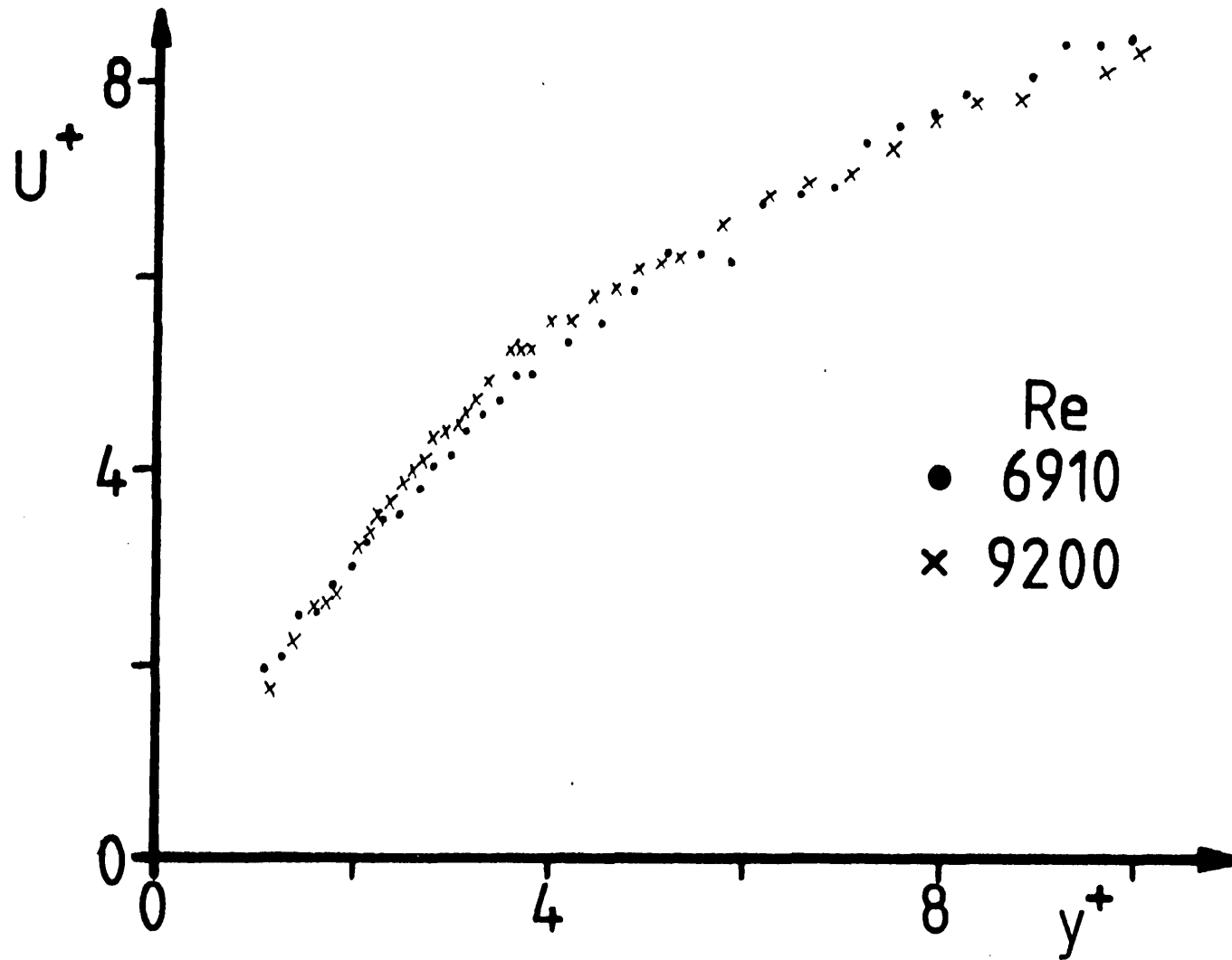


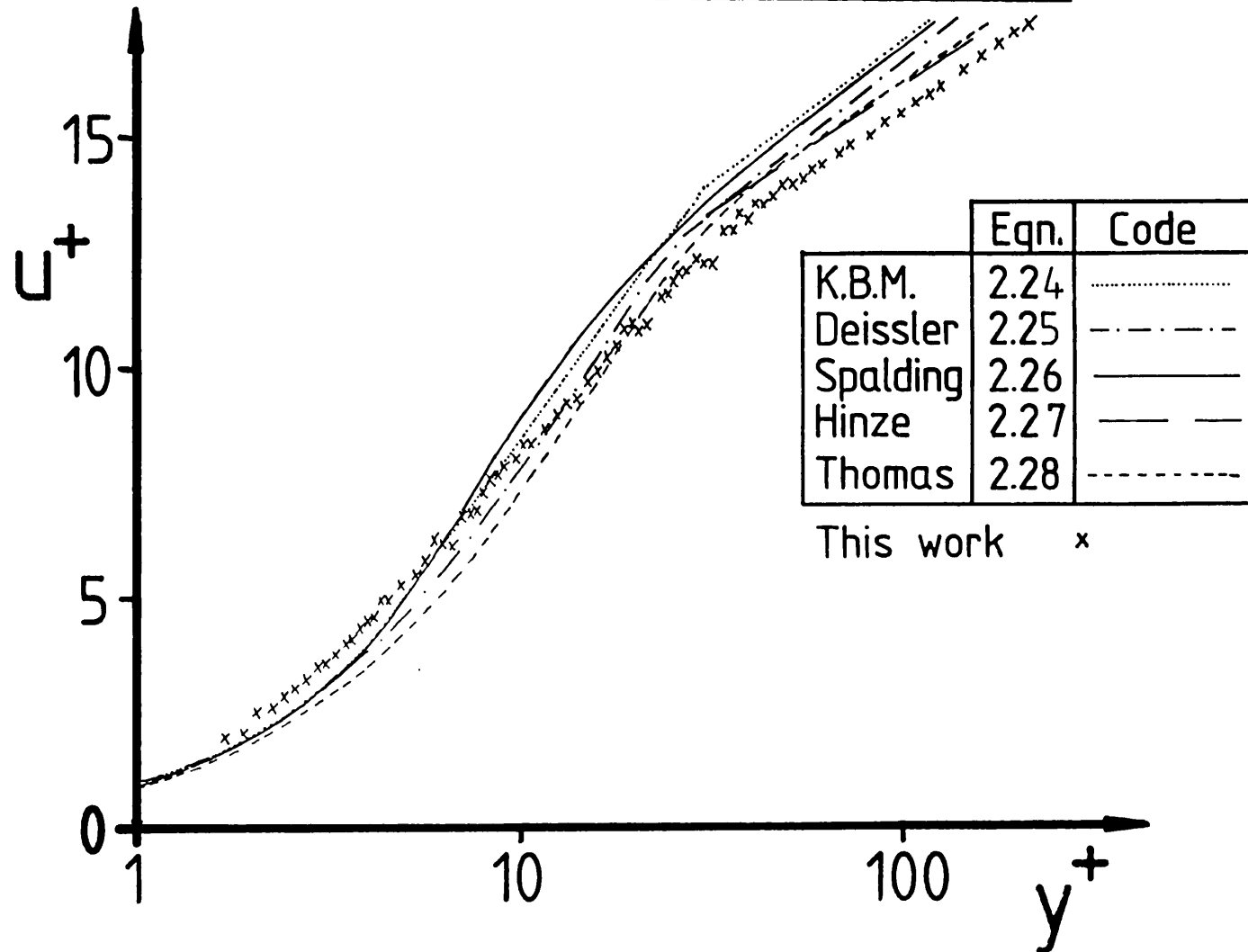
FIGURE 5.24 Wall Shear Based Dimensionless Velocity Profiles for the Near Wall
Region at Two Reynolds Numbers.

TABLE 5.4 Comparison of the Experimental Correlations
with Karmen Boulter Martinelli and Hinze (102).

KBM			
$y^+ < 5$	$u^+ = y^+$		(2.24)
$5 < y^+ < 30$	$u^+ = -3.05 + 5 \ln y^+$		
$y^+ > 30$	$u^+ = 5.5 + 2.5 \ln y^+$		
Hinze			(2.27)
$y^+ > 30$	$u^+ = 4.90 + 2.44 \ln y^+$		
Re = 6910			(5.8)
$y^+ < 5$	$u^+ = 0.55 + 1.18 y^+$	s.d.	0.23
$5 < y^+ < 30$	$u^+ = -0.32 + 3.77 \ln y^+$		0.16
$y^+ > 30$	$u^+ = 4.16 + 2.48 \ln y^+$		0.072

s.d. = standard deviation

FIGURE 5.25 A Graphical Comparison between one of the Experimental Velocity Profiles of
Fig. 5.23 and the Correlations Reviewed in Section 2.3



anemometer again in a wind tunnel. (108)

5.3.2 Error Analysis

Although the variations between the models and the data presented here is comparable to the variations between models, it is important to evaluate as many errors as possible.

- a) Zero error. The computer curve fitting routine estimated the zero error for the profile in Fig. 5.25 to be $66\mu\text{m}$. However, by a linear least squares fit rather than a fifth order polynomial, and limiting the section of the profile to $y < 250\mu\text{m}$ rather than $y < 400\mu\text{m}$, a better zero error would be $98\mu\text{m}$ for this particular profile. This is a distance error of $32\mu\text{m}$ and corresponds to an error in y^+ of 0.54, Fig. 5.26. Fig. 5.25 used the corrected zero error and it is important to realise that such an error only effects the near wall region.

One other effect of the reduced region considered is that the curve fit equation then reduces to

$$\begin{aligned} u^+ &= 1.15 y^+ & y^+ &< 4 & (5.9) \\ u^+ &= -1.31 + 4.12 \ln y^+ & 4 &< y^+ < 33 \\ u^+ &= 4.46 + 2.42 \ln y^+ & y^+ &> 33 \end{aligned}$$

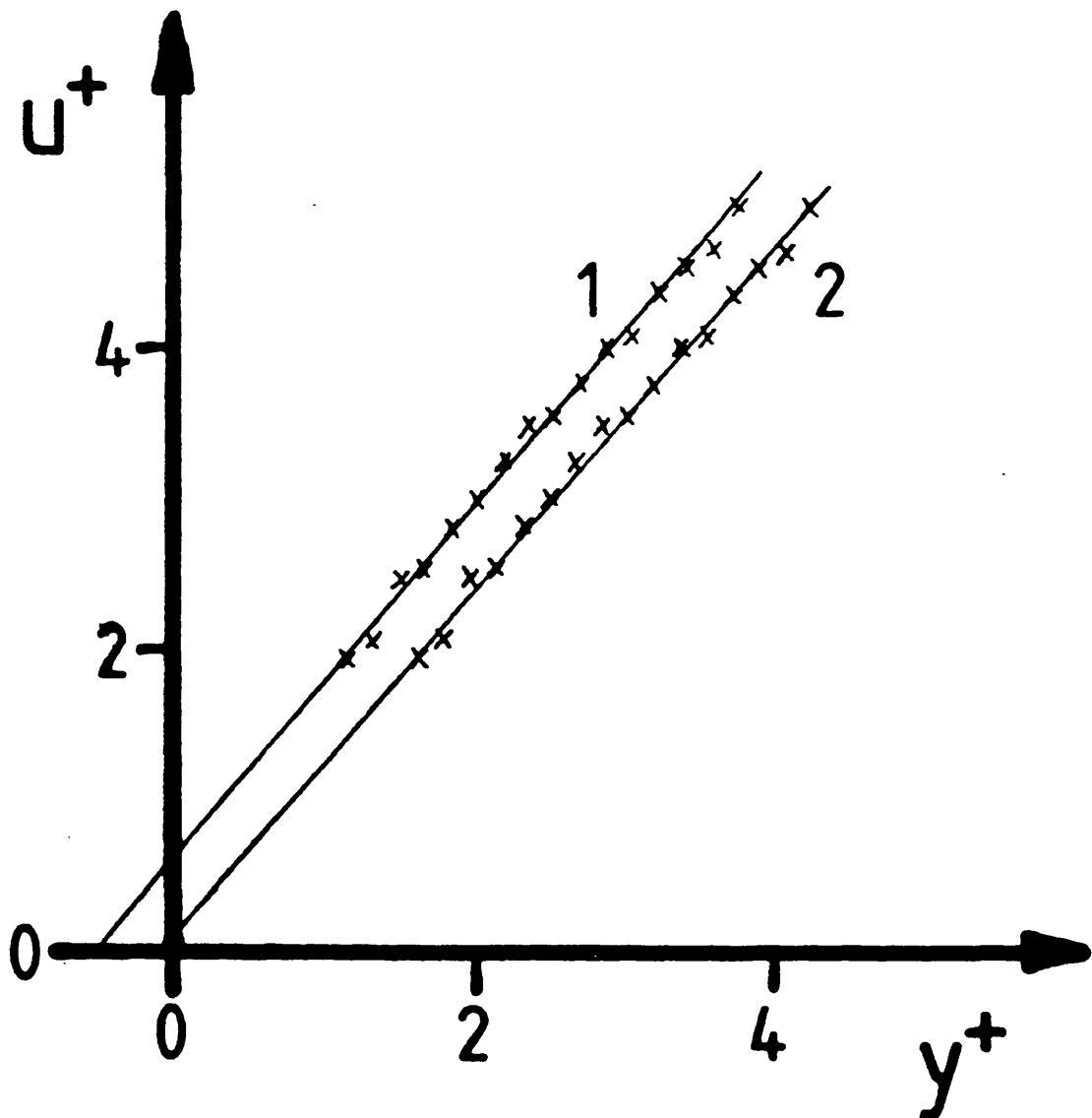
- b) Laser beam bisector angle. During the L.D.A. alignment, the beams separation distance and focal length could be measured to within $\pm 0.5\text{mm}$ in 80mm and $\pm 2\text{mm}$ in 280mm. This corresponds to a maximum uncertainty in the bisector half angle of $\pm 0.16^\circ$ or $\pm 2.0\%$. In

FIGURE 5.26 Near Wall Velocity Profile Showing the Evaluation of the Zero Error.

1. Computer polynomial fit $u^+ = 0.62 + 1.15y^+$
Zero error = $+66\mu\text{m}$

2. $u^+ = 0.11 + 1.15y^+$
Zero error = $93\mu\text{m}$

$$\text{Zero Error} = 66 + (93-66) \times \frac{0.62}{(0.62-0.11)} = 98\mu\text{m}$$



addition, when the L.D.A. equipment was placed on the rig, lack of space prevented the bisector angle being measured daily, so an error of $\pm 4.0\%$ is just plausible in the bisector half angle. Since the angle is small, this directly gives the maximum possible error in the fringe spacing and hence the Doppler frequency as $\pm 4.0\%$.

- c) Wall slip velocity. For the curve shown, The Blasius equation was used to estimate the drag coefficient. The experimental data on which it was based was obtained for smooth pipe flow and gave a scatter of the drag coefficient of $\pm 5\%$. (150) The drag coefficient is defined by equation 5.13. The wall shear velocity is proportional to the square root of the drag coefficient with a consequential error of 2.2%. The membrane may have a different roughness from the delrin walls but let us assume that both are smooth. However, although the data was gathered from pipe flow, this case involved rectangular flow with a larger wall perimeter per unit area of flow so a possible error range on the wall slip velocity may be $\pm 3\%$.
- d) Other errors. Errors in the viscosity of the water and relative distances should be much smaller than the above. Errors in the L.D.A. processing and alignment other than the bisector angle should also be smaller. The exception could be velocity gradient broadening in the region very close to the wall. (Section 2.6) Substituting experimental details into equation 2.85, the optical volume for this case is $95\mu\text{m}$ diameter. However, only about one third of this is observed by the

photomultiplier so the observed optical diameter is roughly one third of the closest observed point of $98\mu\text{m}$ from the membranes. Intuitively, velocity gradient broadening should become more pronounced with decreasing distance from the wall. The linear relationship shown between u^+ and y^+ in the near wall region could be taken as an indication that velocity gradient broadening is not significant over the experimental range observed. In any case, there is currently no theoretical way of analysing velocity gradient broadening errors for turbulent flow. Finally, any other velocity measuring technique of around $30\mu\text{m}$ diameter would suffer the same consequences.

Fig. 5.27 shows the plot of the data given in Fig. 5.26 using the maximum possible errors in the wall slip velocity and bisector angle of ± 3 and $\pm 4\%$ respectively.

The correlations compared in Fig. 5.26 all fall very close to, if not within, the error band. Any discrepancies occur for $y^+ < 10$, where both this data and the data on which other correlations were based are the most sensitive. All of the latter were obtained using obtrusive velocity probes which will clearly be the most erroneous near the wall i.e. low y^+ values.

Whatever the errors involved in the data of Fig. 5.26, the error values will be the same throughout the velocity profile i.e. the errors in the Blasius equation data to give the wall slip velocity and the bisector angle will be fixed for a particular day's experiments. Indeed, only the latter

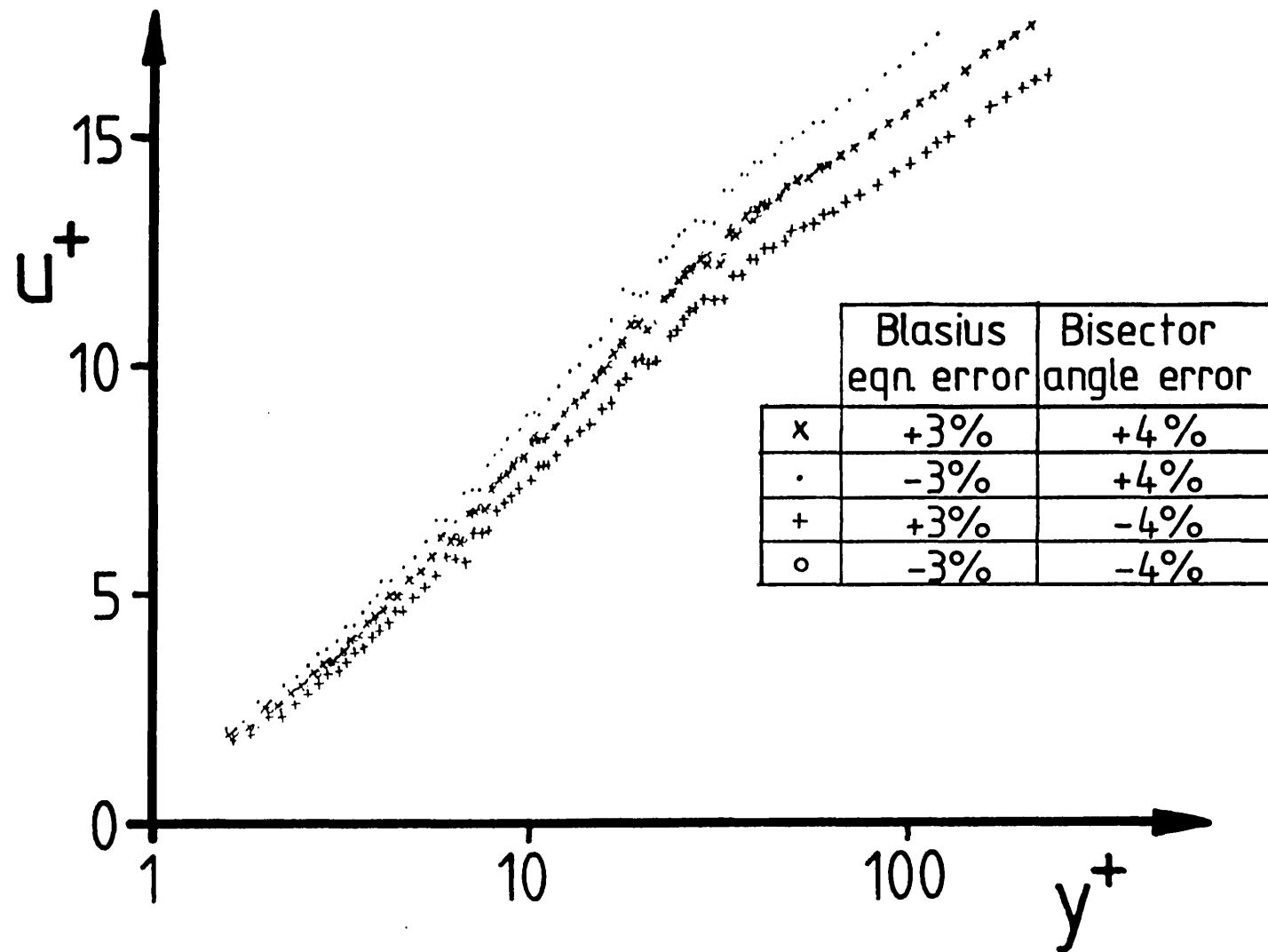


FIGURE 5.27 The Effect of the Plausible Errors in the Bisector Angle and the Blasius Equation on the Experimental Profile Shown in Fig. 5.25

can be effected by this experimental technique. The later work showing no effect on the velocity profile by a series of ultrafiltration parameters shows that the error in bisector angle is constant for at least a period of weeks.

In order to force the experimental data to fit

$$u^+ = y^+ \quad \text{for } y^+ < 5, \quad (5.10)$$

the following error analysis can be deduced. For errors ϵ_1 and ϵ_2 in the bisector angle and the wall slip velocity, it has been shown that if $u^+ = 1.15 y^+$ (5.9)

$$\frac{u(1 + \epsilon_1)}{u\tau(1 + \epsilon_2)} = 1.15 \frac{y u\tau(1 + \epsilon_2)}{y} \quad (5.11)$$

By rearrangement,

$$\epsilon_2 = -1 \pm 0.93\sqrt{1 + \epsilon_1} \quad (5.12)$$

This line does not intercept the possible error window given earlier (See Fig. 5.28). The most likely explanation is the use of the Blasius equation for this rectangular flow. From the earlier observation that the dimensionless velocity profile is Reynolds number independent, the Blasius equation appears to have the right exponent and the wrong coefficient for this flow. The difference, however, is small. One possible solution would be a modification of the Blasius relation $C_f/2 = 0.079 \text{ Re}^{-1/4}$ (5.13)

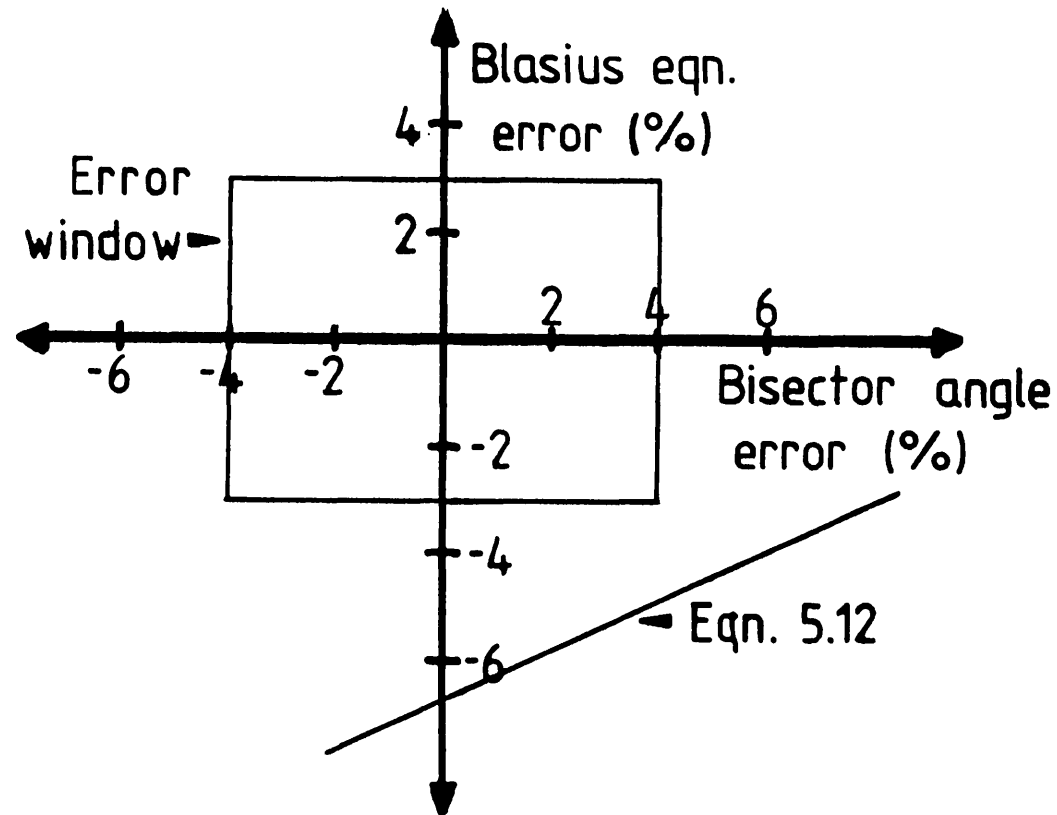
If there were no errors in the bisector angle, the error in the Blasius equation would have to be 6.9%, implying a modified Blasius equation of

$$C_f / 2 = 0.79 \times \sqrt{1 - 0.069} \text{ Re}^{-1/4} = 0.076 \text{ Re}^{-1/4} \quad (5.14)$$

The Reynolds number used in the Blasius equation was based on the channel height. If the hydraulic diameter of the channel has been used instead, the wall shear velocity would have decreased by 1.0%.

FIGURE 5.28

The Plausible Error Window Considered and the Locus of the Curve Forcing the Experimental Data to fit Equation 5.10.



In summary, the velocity profile data presented here has good accuracy and is reproducible. Discrepancies between this work and others are small and have been explained.

5.3.3 The Effect of Membrane Use on the Velocity Profile.

Fig. 5.29 shows the u^+ versus $\ln y^+$ result for velocity profiles obtained on the same membrane at different times over its first 100 hours of use. There is no detectable effect of membrane use on the velocity profile, as might be expected.

5.3.4 The Effect of Membrane Permeability on the Velocity Profile.

Fig. 5.29 referred to the effect of membrane use, however, each velocity profile was obtained at a different membrane flux as tabulated in the insert. Fig. 5.30 gives a further set of curves showing the effect of ultrafiltration membrane permeability on the velocity profile. One set of points refer to an impermeable film while the other refers to one of the curves given in Fig. 5.29. The curves are almost identical and the explanation has been given previously.

Similar conclusions can be drawn from Fig. 5.31 where two different permeable membranes are used. The agreement is partially hampered by the fact that one of the curves was obtained prior to the realisation of the significance of

FIGURE 5.29

The Effect of Membrane Use on the Observed Turbulent Velocity Profile

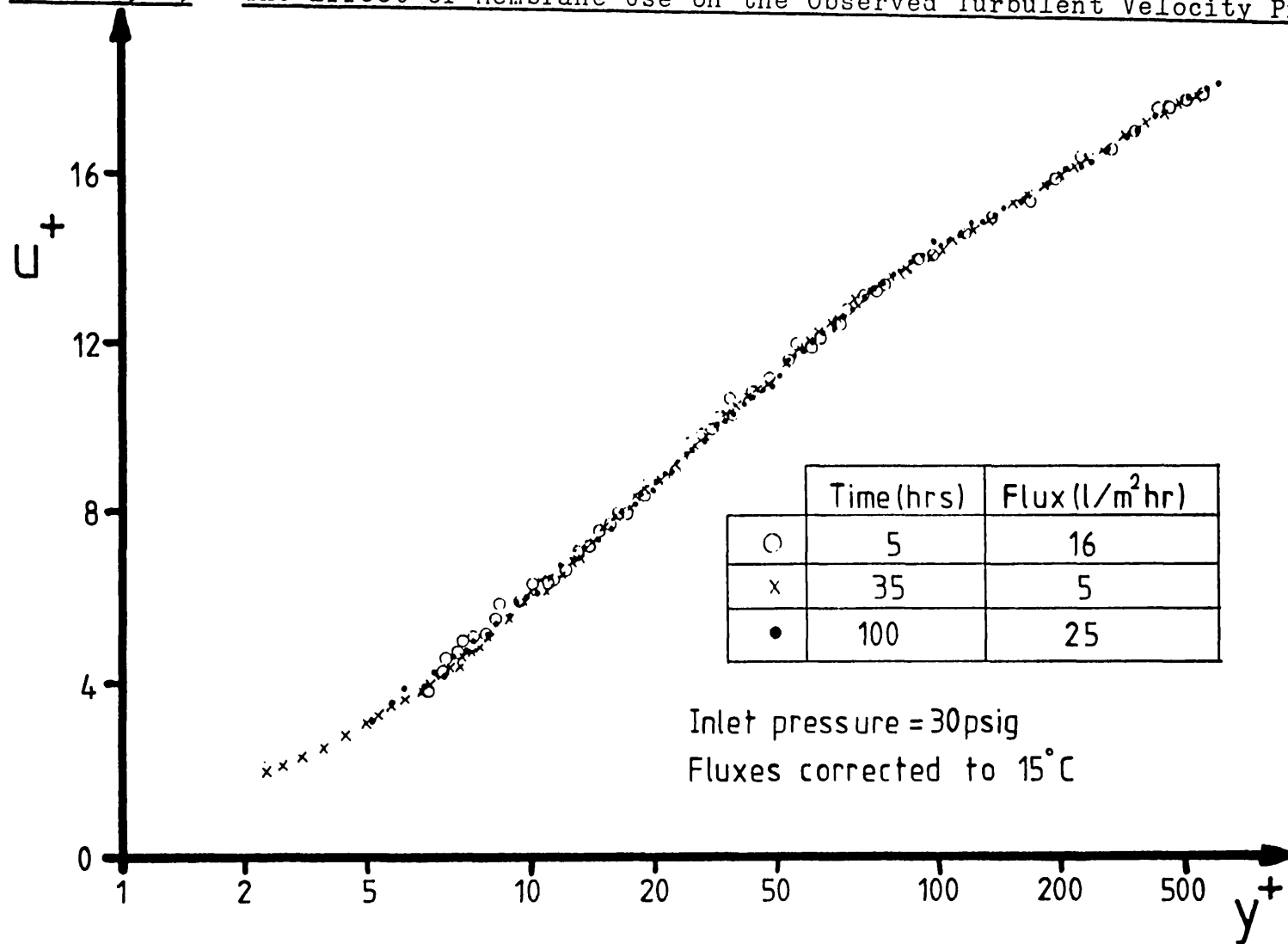


FIGURE 5.30 The Effect of Permeability on the Observed Turbulent Velocity Profile

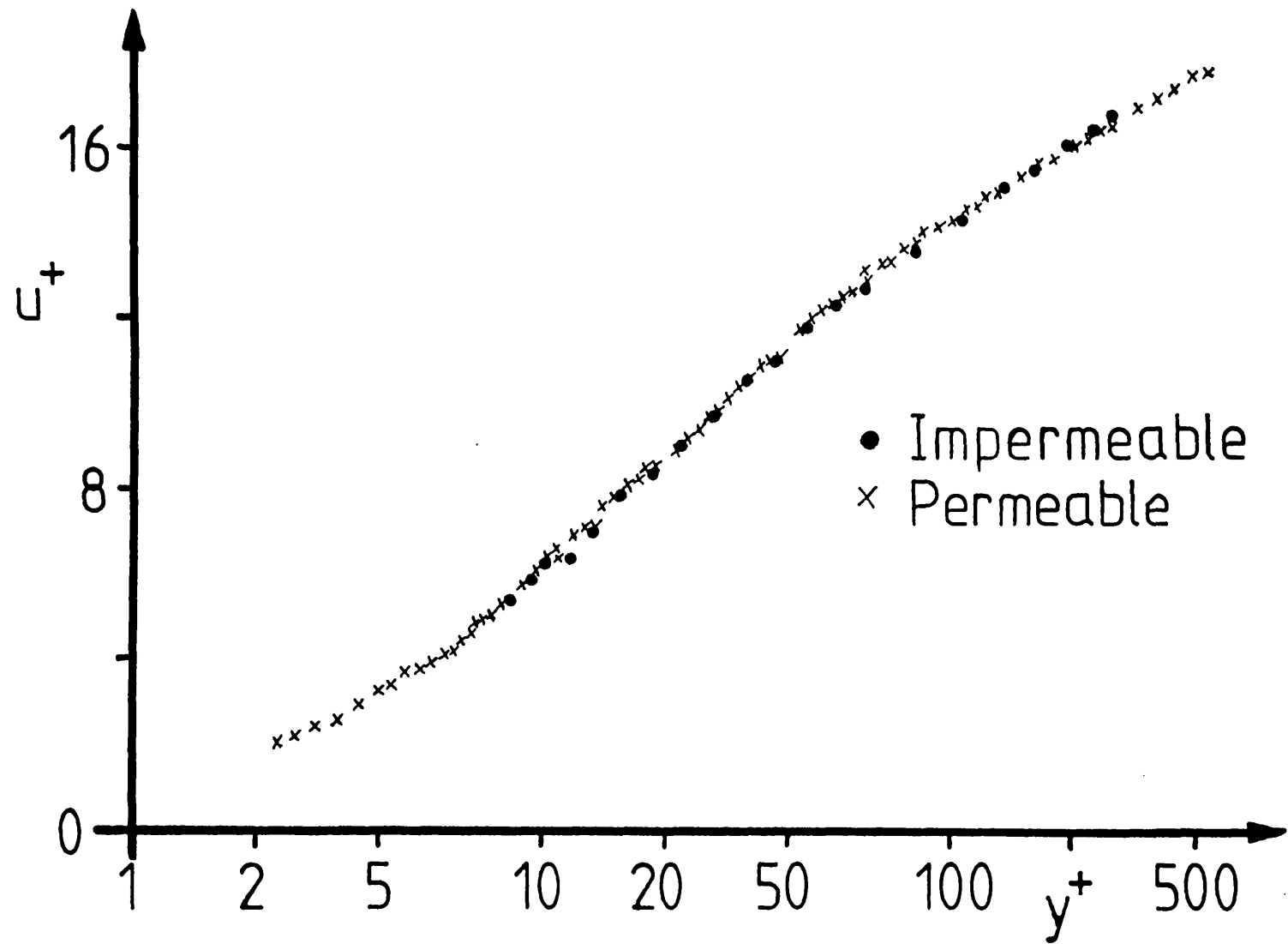
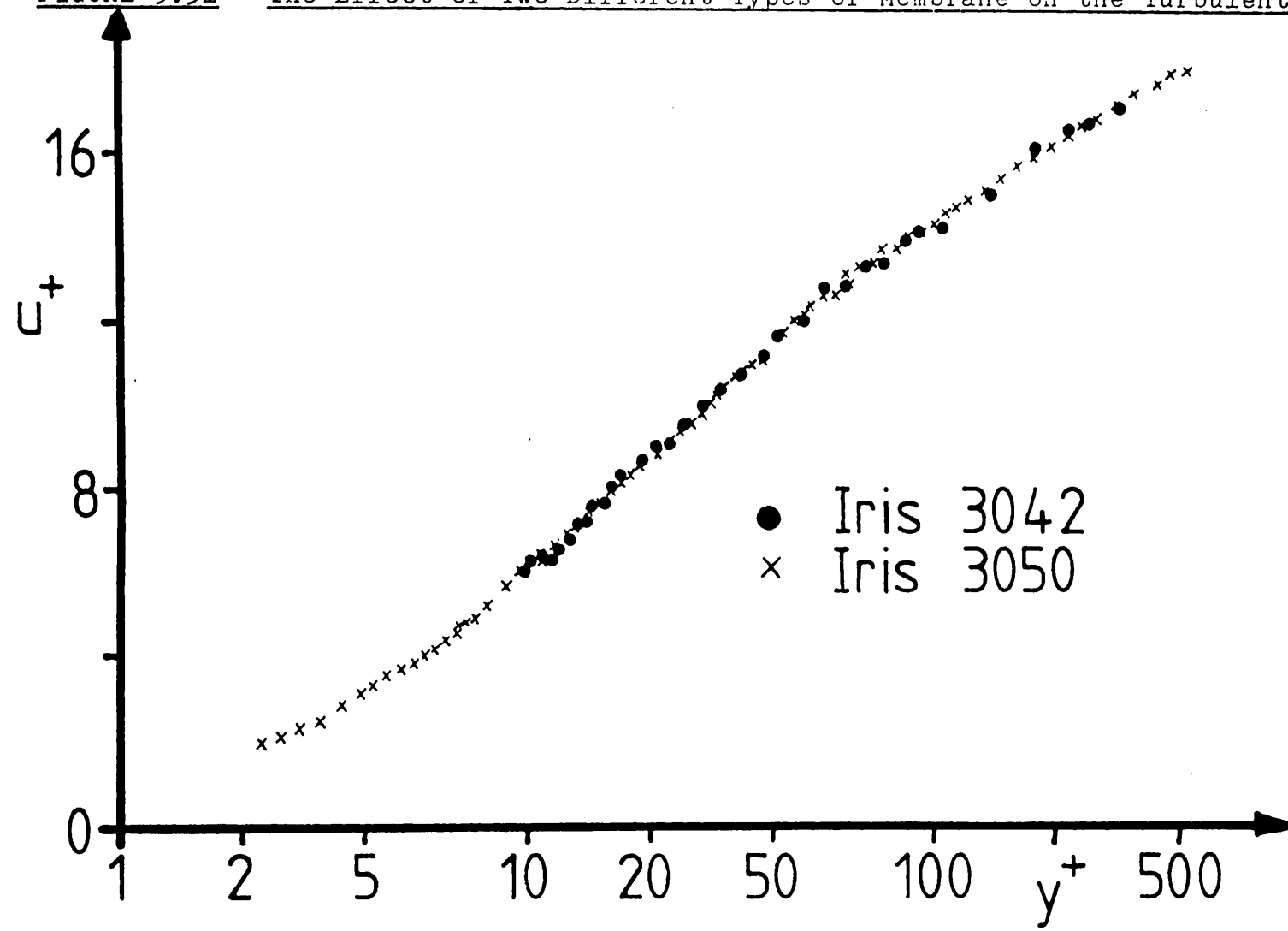


FIGURE 5.31 The Effect of Two Different Types of Membrane on the Turbulent Velocity Profile



allowing the channel time to adjust to the internal pressure. Hence, there are no data points for $y^+ < 10$.

5.3.5 The Effect of Pressure on the Velocity Profile

Similarly, Fig. 5.32 shows that the velocity profile was independent of applied pressure, again an expected result.

5.4 Solute-Water-Semipermeable Membrane System.

5.4.1 The Effect of a Solute and Reynolds Number on the Turbulent Velocity Profile.

A solute which would be totally rejected by the membrane was required to give the extreme case of concentration polarisation. A 0.1 % w/w egg albumen suspension was chosen. The egg albumen was difficult to mix with water because it tended to float. To overcome this problem, the pH was reduced by the addition of 10cm³ concentrated sulphuric acid to 40 l of solution. Secondly, the suspension was left recirculating for the one to two hours required to allow the channel to obtain a steady position.

Results were obtained on two occasions. The most comprehensive set of data is given in dimensionless boundary layer coordinates in Fig. 5.33. The crosses represent the no solute case treated earlier by a thorough error analysis. Clearly, at a given dimensionless distance, the solute case

FIGURE 5.32

The Effect of Pressure on the Observed Turbulent Velocity Profile

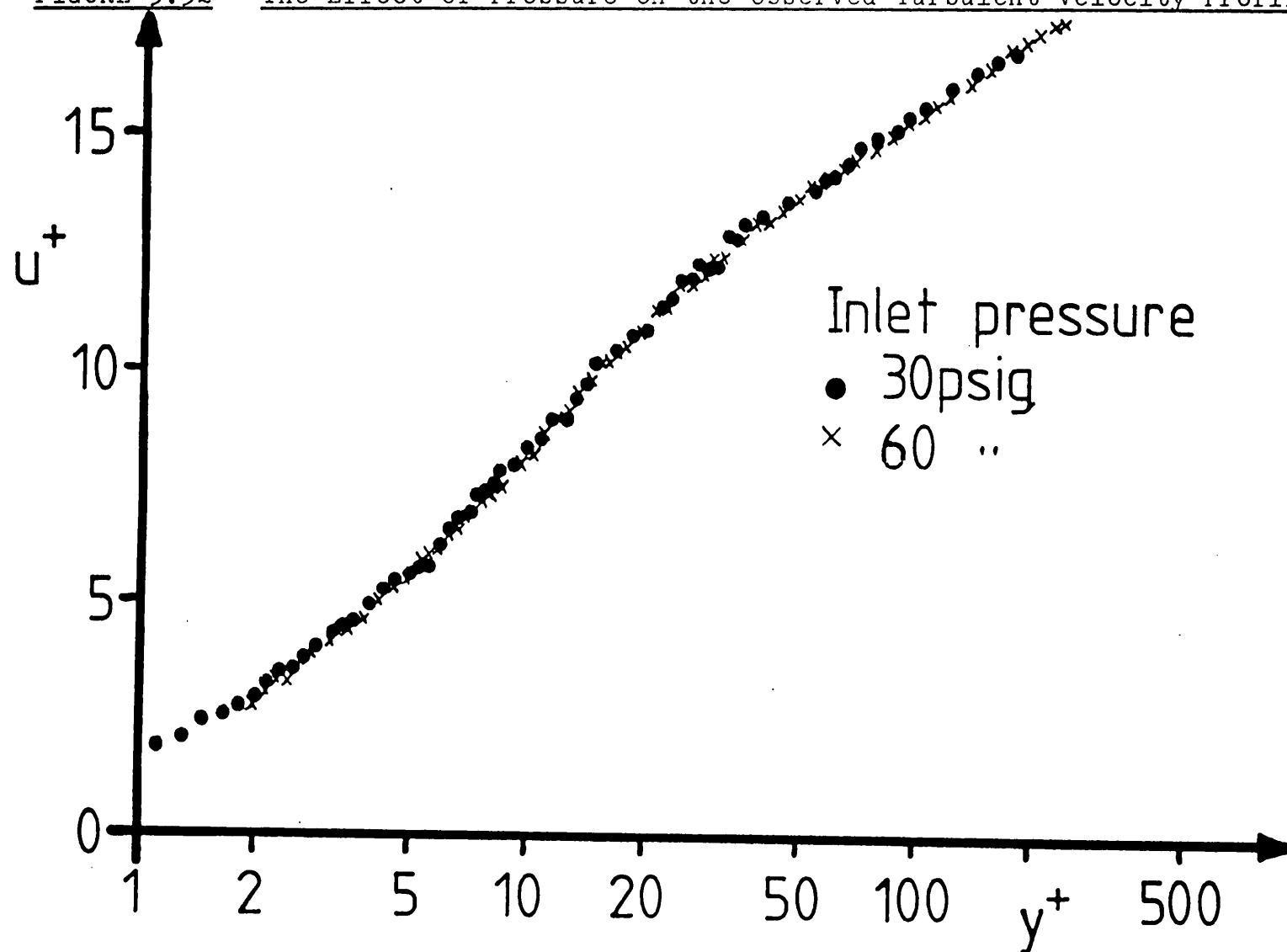
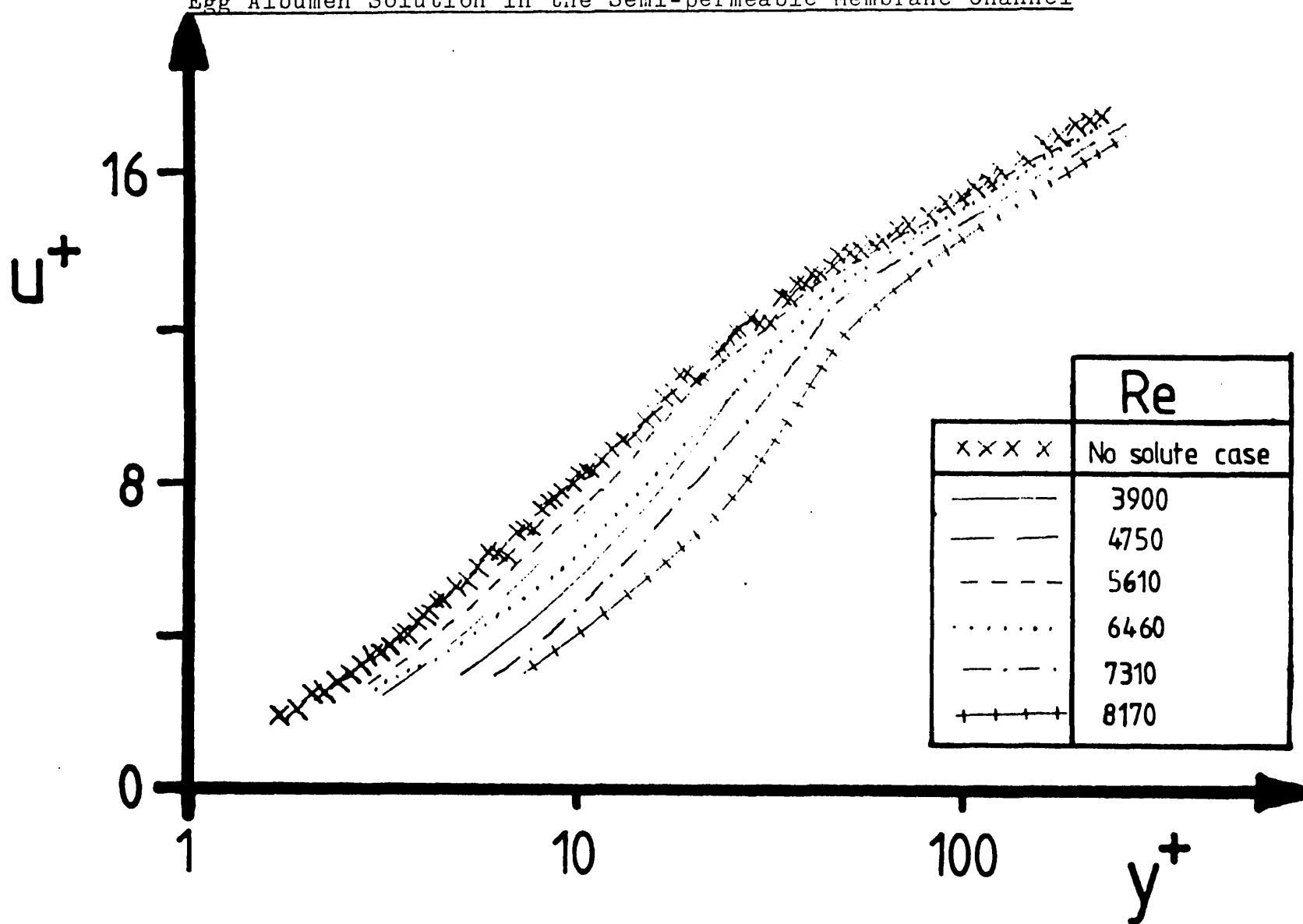


FIGURE 5.33 The Effect of Reynolds Number on the Turbulent Velocity Profiles of a 0.1% w/w Egg Albumen Solution in the Semi-permeable Membrane Channel



has the same or a lower dimensionless velocity as measured by the L.D.A. system. The velocity profile still breaks down onto the three usual zones, i.e. laminar, buffer and core. As the Reynolds number increases from 3900 towards 8170, the deviation from the single solute case close to the membrane appears to decrease and then increase again. This experimental observation could have significant effects on membrane technology since the data indicates that there could well be an optimum turbulent Reynolds number for a given system at which the ratio of the scour velocity to the wall shear velocity is maximised (See Table 5.5). The table contains data for the dimensionless distance of $y^+ = 10$. There is no significance in the choice of this distance. At a Reynolds number of 8170, the dimensionless velocity for the solute case was half that for the no solute case at $y^+ = 10$, whereas at $Re. = 5610$, it was 7/8ths of the no solute case, a potentially very significant observation. A confirmatory piece of evidence is that the slope of the velocity profile is increasing with increasing Reynolds number, (see Table 5.6). A lower velocity at the wall must be compensated by an increased velocity elsewhere for conservation of mass.

It must be pointed out that currently there is only limited data. The first set of data (three velocity profiles one of which was repeated) showed the same points. No further work was done due to lack of time.

It is important to observe the errors that exist in this analysis. The introduction of a new variable into the dimensional analysis, namely the solute concentration,

TABLE 5.5 - Data Points Read from Fig.5.33 to Demonstrate a Maximum Reynolds Number Concept.

Reynolds No.	u^+ at $y^+ = 10$
3900	5.9
4750	6.7
5610	7.3
6460	6.4
7310	5.0
8170	4.2
No solute case	8.2

TABLE 5.6 - Slope of the Velocity Profile in the Core Region.

Reynolds No.	Angle $\pm 0.5^\circ$
3900	22.0
4750	26.0
5610	27.5
6460	29.0
7310	31.0
8170	33.0
No solute case	28.5

TABLE 5.7 - Experimental Data Showing the Asymmetric Velocity Profile.

Reynolds number	Sum of three Doppler frequency readings		
	Before mid-channel	After mid-channel	Difference
3900	236.6	236.3	-0.3
4750	288.2	288.8	+0.6
5610	336.4	338.8	+2.4
6460	388.9	390.5	+1.6
7310	435.5	439.4	+3.9
8170	488.6	498.3	+9.7

renders the dimensionless groups technically invalid. The solute concentration will affect the viscosity and possibly the wall shear stress and will be increased at the wall by the membrane separation. There is little that could be done in the time available to evaluate the effect except for the following. Firstly, intuition suggests that the effect is real and not a figment of the the dimensionless analysis. Secondly, a Pouiseulle flow viscometer was constructed. No detectable difference in viscosity was found, in fact, the 100 ml of egg albumen suspension taken from the L.D.A. rig took 2-3s less in around 8 minutes to flow through the capilliary than the equivalent volume of water. The temperatures were controlled by immersing the containers in a thermostatically controlled bath at the room temperature of 18°C before carrying out the test. Solute concentrations at the membrane surface have been theoretically predicted to be of the order of ten times that of the bulk by many authors. However, at the dilute concentrations used here it is unlikely that the local viscosity will be orders of magnitude greater than water, even at these increased concentrations.

Finally, at least for the core region, the velocity profiles are very similar to the no solute case, indicating that any solute concentration effect is limited to the near membrane regions, (laminar and buffer layers). This implies that there cannot be a great change in the wall shear stress due to the solute.

The flowrate through the membrane channel was measured using the water calibrated rotameter. It may be just

possible that the presence of the solute could give an erroneous reading greater than the experimental accuracy to which it could be read, $\pm 0.5\%$ on flowrate. However, this would only affect the conservation of mass over the channel not specifically the near wall velocity profile. It is quite likely that the velocity profile is asymmetric i.e. a slightly higher velocity in the half channel furthest away from the membrane. Evidence for this is given in Table 5.7. The channel half height occurs at 13.4mm. By summing the experimental data points for 11, 12 and 13 mm from the membrane and comparing them with the sum of the points obtained at 14, 15 and 16 mm, evidence for the asymmetry is shown. It should be noted that the mid-channel point is slightly towards the membrane wall, even after multiplying by the tangent of the channel's elevation compared to the L.D.A. plane of $2^{\circ}00'$. It is unlikely that the difference is random scatter. Each value in Table 5.7 represents the average of about 60,000 particles passing through the optical volume. The increasing difference between the two sums is linked with increasing core region dimensionless velocity slope with Reynolds number mentioned earlier.

One error that can be ruled out is any transient effect (membrane movement, protein hydrolysis etc.). In both sets of experiments, one velocity profile was repeated with at least two velocity profiles being measured in between. These repeated velocity profiles were identical.

The plots shown in Fig. 5.33 have had the zero distance errors corrected manually. The computer corrected curves have similar trends. Whatever the mode of correction, zero

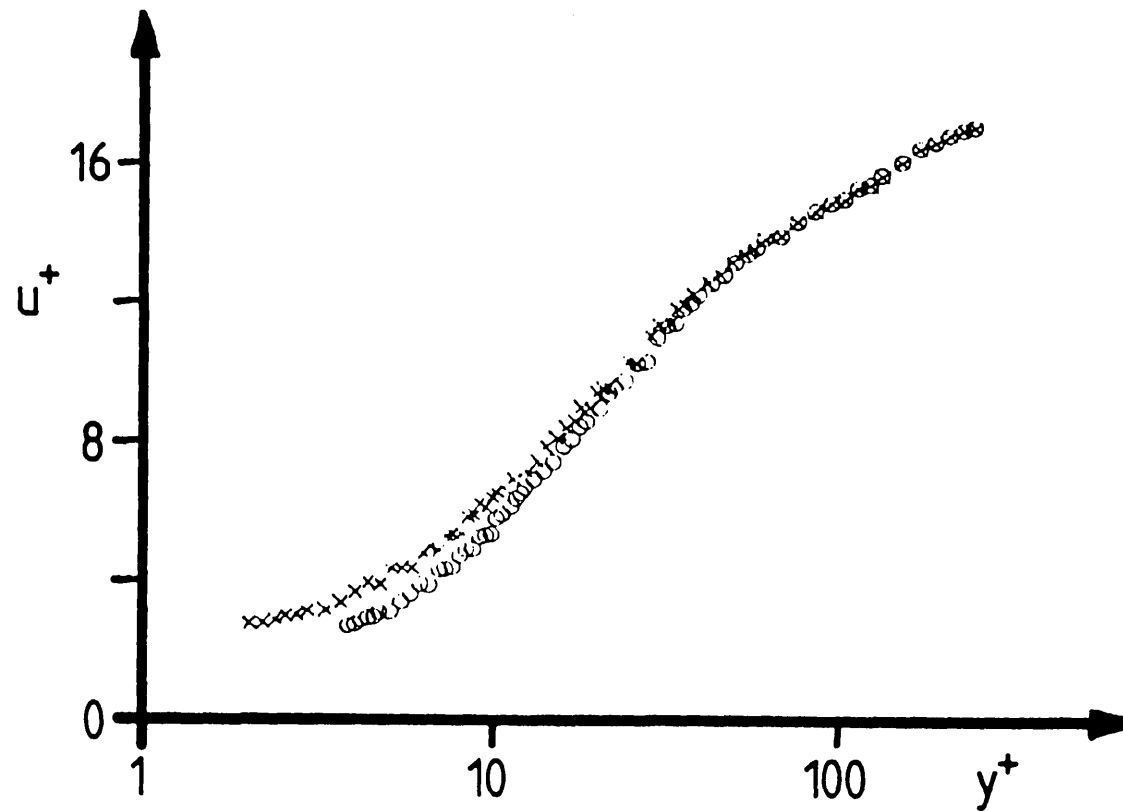
errors only effect the near wall region in a manner demonstrated by Fig. 5.34. Zero error is not the explanation for large differences in u^+ , particularly in the buffer region of the velocity profile for the solute - no solute cases.

In summary, the effects of solute on the velocity profile in membrane channels are significant, and they are measurable. At the start of the work, it was not known whether a sensitive instrument could be devised but this has been done. After much more qualitative work, the results from this equipment should be very beneficial.

5.4.2 Transient Effects of a Solute on the Turbulent Velocity Profile.

Having established the effect of a solute on the velocity profile, two attempts were made to see whether these effects take a reasonable time to build up. The egg albumen was mixed separately in 10 l of acidified water using an electric mixer. Meanwhile, the rig was commissioned using 20 l of water. Having recorded one velocity profile at a Reynolds number of 5610, the L.D.A. optical volume was positioned at one spot, as close to the wall as possible. The velocity at this point was measured using the middle averaging time to check that there was no channel movement and establish a base line. An assistant quickly poured the albumen into the head tank and the tracker readings were observed. The Doppler readings were occurring about every two secs. upto the albumen addition.

FIGURE 5.34 The $Re = 6460$ Curve from Fig. 5.33 Showing the Effect of a $\pm 50\mu m$ Discrepancy
in the Zero Error



Within 20 s, the Doppler reading frequency had decreased to zero and far fewer discernible Doppler signals could be seen on the oscilloscope. No attempt was made to find the explanation for this system failure. It was thought not to be laser alignment, since the system was set up on the screens just inside the window and this was independent of whether solute was present or not. One possibility is that when the slightly opaque egg albumen suspension reached the optical volume, there was a lot of 'noise' which distracted the electronics. This is an experiment worth repeating since it would give confirmatory evidence of the effect of solutes, i.e. a decrease in velocity at a given distance from the wall. How long does the velocity decay take? It could well be in the 10-100s region which would be detectible, particularly with the lowest averaging time setting on this apparatus.

5.5 Point Velocity Distributions

The L.D.A. optical volume could be fixed at one spot and the average frequencies monitored. This gave an idea of the local variation in axial velocity. By repeating this at different points in the velocity profile, one can deduce the variation as a function of distance from the wall.

Figs. 5.35 and 5.36 show these distributions for channel Reynolds numbers of 6910 and 9200 at the same positions in the channel. The actual position in the channel was deduced from back calculation using the turbulent dimensionless profile of Fig. 5.23. Even though

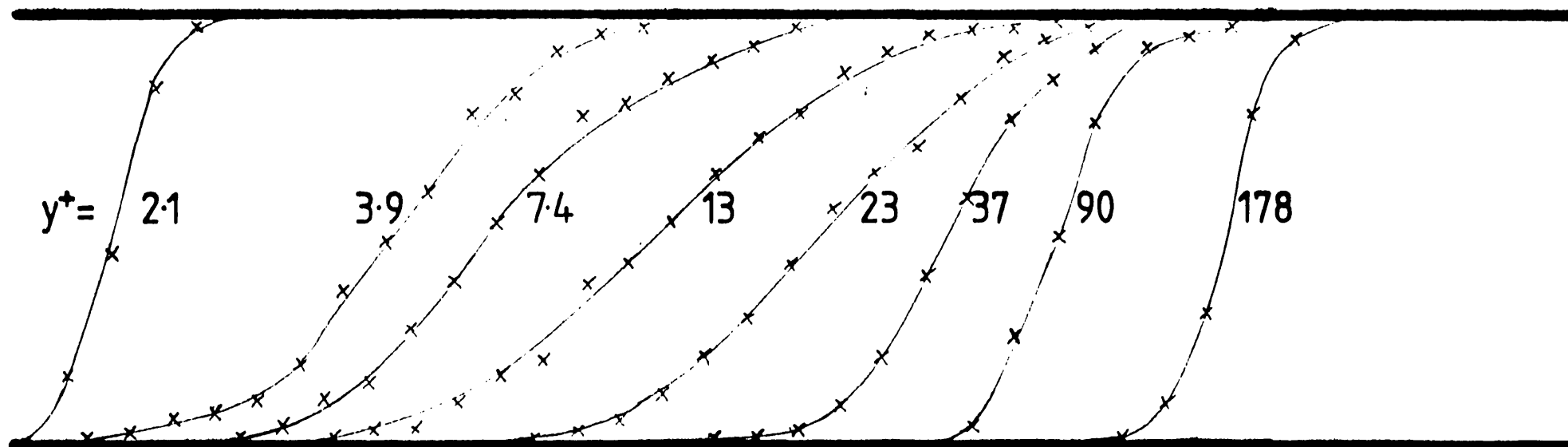


FIGURE 5.35 Doppler Frequency Distributions for $Re = 6910$ in the Single Solvent
Semi-permeable Membrane Channel

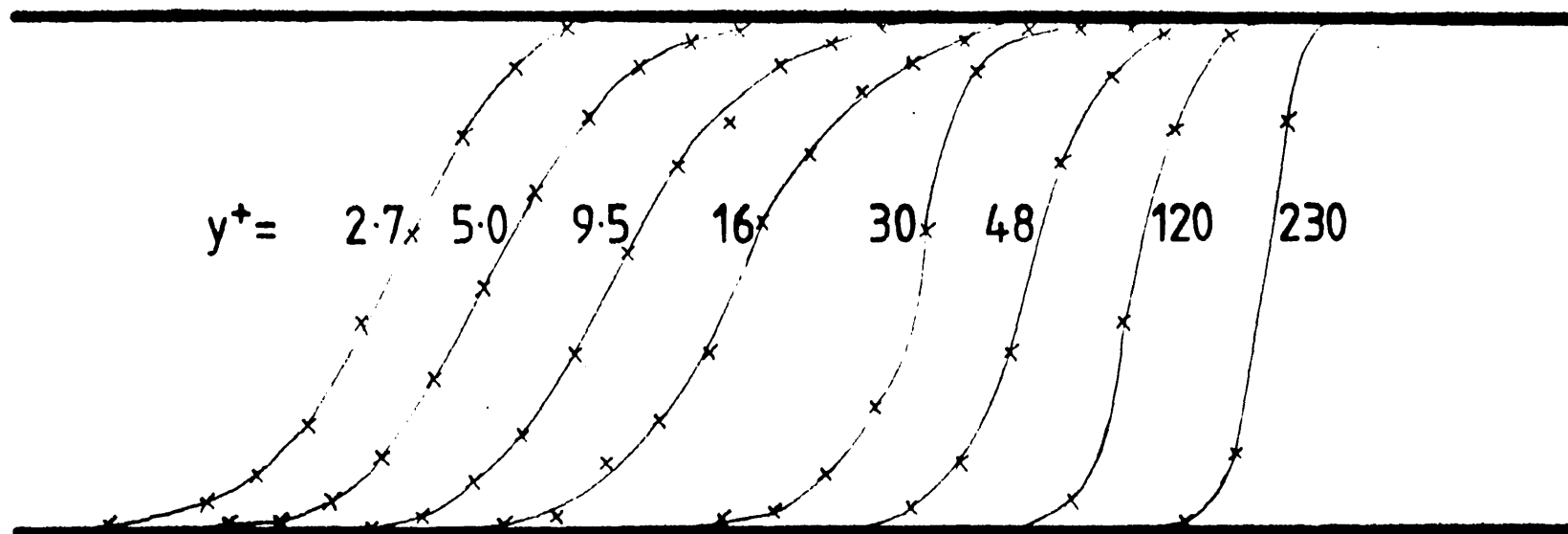


FIGURE 5.36 Doppler Frequency Distributions for $Re = 9200$ in the Single Solvent
Semi-permeable Membrane Channel

the actual distances were the same, the dimensionless distances are different because of the different wall slip velocity. Figs. 5.35 and 5.36 are presented in the best, but not the obvious, manner. For the curve labelled $y^+ = 2.1$ in Fig. 5.35, the data is given in Table 5.8. The graphs of Doppler frequency range versus cumulative frequency were then plotted, (Fig. 5.37), and these were then traced onto a composite plot, (Fig. 5.35). In this composite plot, the coordinates only have a meaning to the local curve. Any other form would not have been compact or clear. The dimensionless y^+ distance is given above the curve at the 50% cumulative frequency point. The number of average Doppler frequencies recorded at a given position ranged from 60 as in the above case, to 80.

Figs. 5.35 and 5.36 show that the Doppler frequency at distances $y^+ \leq 2.5$ and $y^+ \geq 100$ is relatively uniform. At intervening distances, there is much more of a spread. A numerical way of showing this is given in Table 5.9.

There are two competing phenomena. Close to the membrane, inside the traditional laminar boundary layer, one should expect no variation in axial velocity. The fact that one does, is the result of velocity gradient broadening i.e. a finite optical volume pretending to measure the velocity at a point, and secondly turbulent bursts. The latter can be observed by using a storage oscilloscope on the photomultiplier signal. Most of the Doppler bursts have a very similar frequency. Occasionally, a signal would be spotted whose frequency may be 2 to say 6 times larger than the usual frequency. Such frequencies had a clear, well

TABLE 5.8Velocity Distribution Data at $y^+ = 2.1$ $Re = 6910$

Doppler frequency range (kHz)	Number of occurrences	Cumulative number of occurrences	Cumulative frequency of a Doppler frequency less than and including the range
26 - 26.99	0	0	0.000
27 - 27.99	9	9	0.150
28 - 28.99	17	26	0.433
29 - 29.99	23	49	0.817
30 - 30.99	9	58	0.967
31 - 31.99	1	59	0.983
32 - 32.99	1	60	1.000
	60		

FIGURE 5.37 Doppler Frequency Distributions for $Re = 9200$
in the Single Solvent Semi-permeable Membrane
Channel($\gamma^+ = 2.1$)

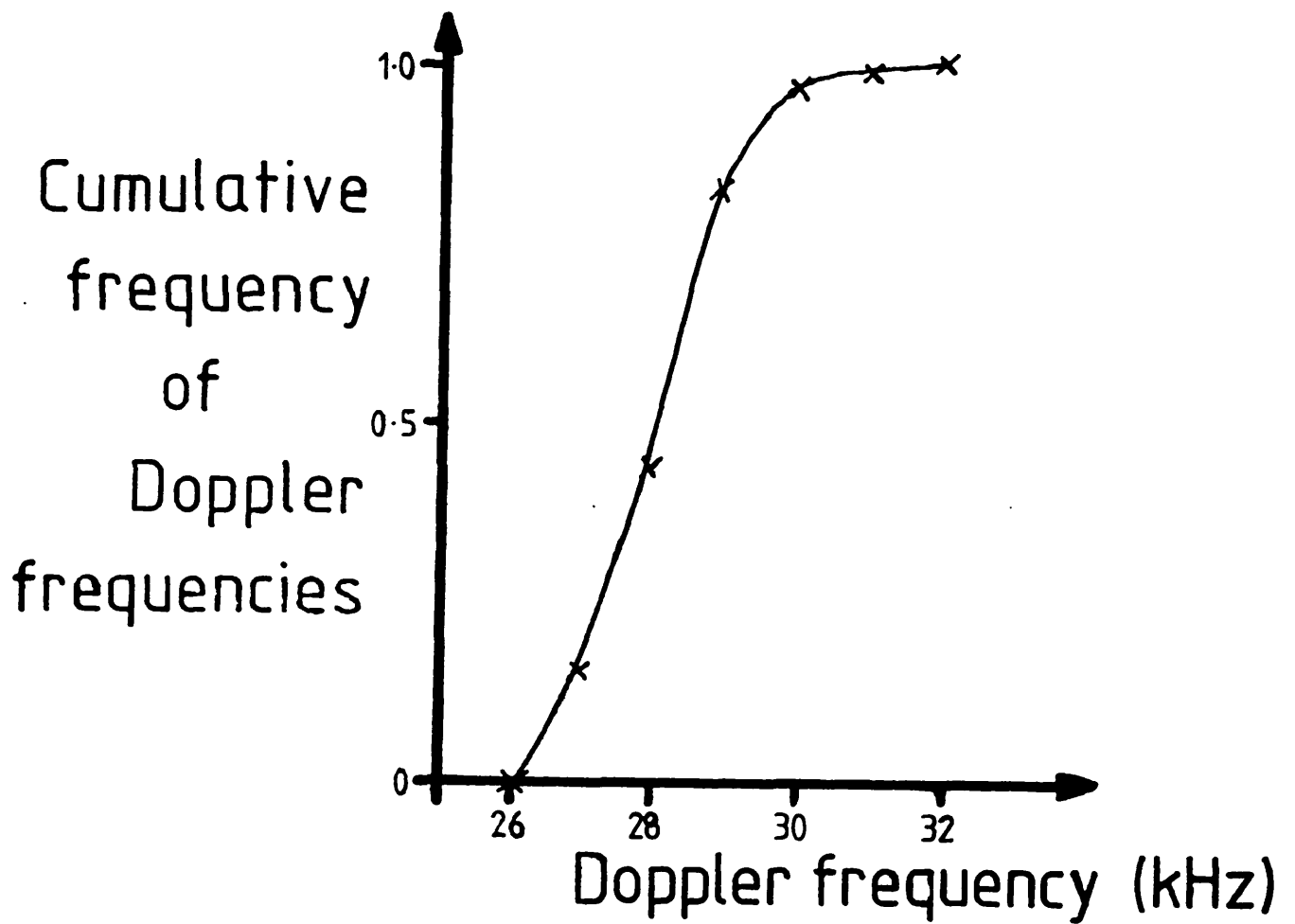


TABLE 5.9 The Spread of Doppler Frequencies Observed as a Function of Distance from the Membrane.

y^+	Difference between the smallest and largest Doppler frequency	Average Doppler frequency	% change in Doppler frequency over the range	Reynolds number
	kHz	kHz	(%)	
1.4	3	22.4	13	9200
1.6	3	18.0	17	6910
2.1	6	29.1	21	6910
2.7	10	37.6	26	9200
3.9	16	37.3	23	6910
5.0	13	53.1	24	9200
7.4	15	49.9	30	6910
13	19	67.0	28	6910
23	15	84.8	18	6910
37	11	96.7	11	6910
90	8	111.0	7	6910
178	6	125.5	5	6910
230	4	164.6	2	9200

TABLE 5.10 An Approximate Sample Size of Individual Doppler Signals used in Table 5.9.

Distance y^+	Average Doppler frequency / kHz	Number of signals per Doppler frequency reading
1.6	18.0	1800
2.7	37.6	3760
7.4	49.9	4990
37.	96.7	9670
178.	125.5	12550

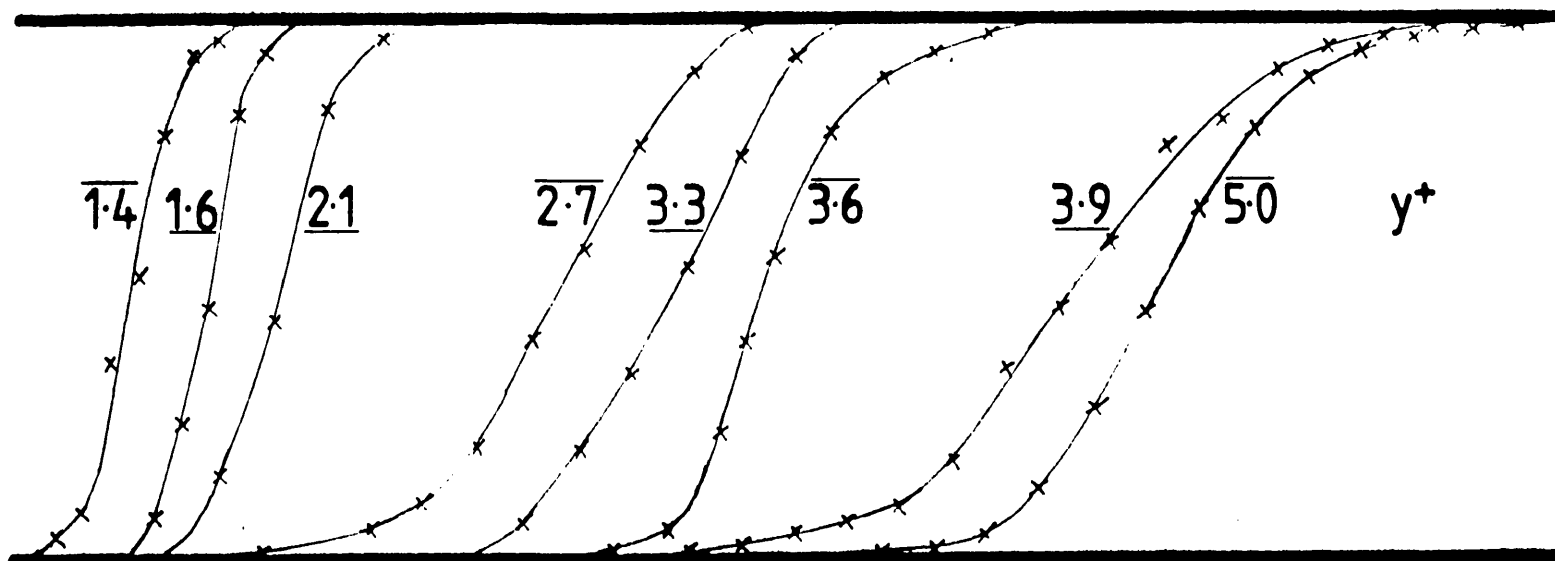
Basis: 10 waveforms before signal is validated
Averaging time = 1.000 s.

defined waveform and could not be regarded as noise. Therefore, during such a burst, the tracker observed a particle travelling at between two and six times the usual velocity. As the beams moved further from the wall, the random frequencies occurred more often than the steady laminar frequency. At further distances from the wall, the higher Doppler frequency leads to more particles contributing to the Doppler frequency reading on the tracker, (Table 5.10). The extreme readings become less significant and hence a steady frequency is again observed.

In order to improve the understanding of membrane technology, the turbulent burst phenomena in the near wall region is again crucial. Fig. 5.38 gives the results of the closest velocity distribution data obtained using water and a semipermeable membrane. It is obvious that the velocity in the near wall region is not laminar. If the flow were laminar, only one frequency would be observed which would be represented by a vertical line on Fig. 5.38 rather than the S shaped curve. Velocity gradient broadening is a small factor in that its effects should be reproducible on a sample size of 1800 + particles.

The second point is that at a distance of about $y^+ = 2.5$, there is a more significant variation in velocity in the dimensionless distance optical volume. At the Reynolds numbers of 6910 and 9200, this dimensionless distance corresponds to actual distances from the membrane of 140 and 110 μm . This dimensionless distance represents the boundary of the momentum boundary layer that would exist in this water membrane system. Above this distance,

FIGURE 5.38 Doppler Frequency Distributions in the Near Wall Region for a Single Solvent
Semi-permeable Membrane System



y^+ values underlined were obtained at $Re=6910$. Those overlined were evaluated at $Re=9200$.

turbulent bursts should be more significant in mixing than back diffusion. Below this distance, turbulent bursts still exist and it remains to be shown whether turbulent bursts or back diffusion is the limiting phenomenon in both concentration polarised and fouling situations.

Thirdly, from Fig. 5.38, the distributions do not clearly show an effect of Reynolds number on the frequency of turbulent bursts. Far more experiments and statistical analysis would be required to show this conclusively.

CHAPTER 6CONCLUSIONS

The L.D.A. system has the demonstrated potential of measuring down to $65\mu\text{m}$ from the membrane with an optical volume whose observed diameter was about $30\mu\text{m}$ centred on the above distance. This performance was better than expected, mainly because the optical construction was done in house. In wall shear stress dimensionless terms, velocities were measured down to $y^+ = 1.1$, well inside the laminar boundary layer. The results of the system have been validated by comparing laminar velocity profiles with a Navier Stokes series solution to laminar flow in a rectangular channel.

The membrane channel, which in itself took a great deal of engineering effort, has proved satisfactory. Problems of sealing the rig have been solved and movement of the membrane support bar relative to the base bar have been characterised and eliminated as potential errors to the velocity profile measurement. This characterisation has been useful, since it showed that the L.D.A. could be used to follow significant buildup of material at the membrane surface (of order $10\mu\text{m}$ thick) with time by measuring the velocity as a function of time and then back calculating the distance from the wall.

The technique has been used to show the effect of entry length and Reynolds number on the velocity profile using impermeable films. The Reynolds number work was then compared with similar work using a semi-permeable membrane. It has been shown that pressure, membrane use and permeability have no effect on the velocity profile since

the trans-membrane velocity is so small compared to the crossflow velocity during turbulent flow.

For the case of turbulent water flow, the velocity profile has been plotted on various coordinates and in different dimensionless groups. The dimensionless groups based on wall shear stress have been shown to be the best. The turbulent profile may be described by

$$\begin{aligned} u^+ &= 1.15 y^+ & y^+ < 4 & (5.9) \\ u^+ &= -1.31 + 4.12 \ln y^+ & 4 < y^+ < 33 \\ u^+ &= 4.46 + 2.42 \ln y^+ & y^+ > 33 \end{aligned}$$

These profiles were compared with those of other authors whose data came from wind tunnel measurements using physical probes. The data reported here is similar to the work of Hinze (103) for the core region. A thorough error analysis has been carried out for this work, and the above correlations have error bars which currently span most of the other literature work. The error bars in the literature data were almost certainly larger than those encountered here, although they were not recorded as such.

The addition of a solute changed the predictability of the above results. In the near wall region there was a significant drop in the turbulent wall shear stress dimensionless velocity at a given distance from the membrane. There was a Reynolds number effect and an optimum Reynolds number for the given system was evident. Optimum refers to the dimensionless velocity profile being as close to the profile obtained with no solute, particularly in the near wall region. There was also evidence of an increased core region velocity gradient and slight asymmetry over the whole

channel to compensate for the lower velocities in the near wall region with increasing Reynolds number. These results require much more work before the full significance of these observations may be assessed.

The other effect observed by the system was the presence of turbulent bursts, even at a distance of $y^+ = 1.4$, i.e. well within the laminar boundary layer. The bursts are most prominent in the region $2 < y^+ < 30$. Observations were made using a no solute, semipermeable membrane system and two turbulent Reynolds numbers. As with all of the above, virtually every curve was checked for reproducibility.

Having demonstrated the equipment's ability, many more experiments are required to obtain definitive guidelines on membrane system design based on the understanding of the velocity profile and turbulent bursts. Other work reported in Appendices I and II have the following conclusions. On one brand of tubular membranes, the ends are more permeable than the centres. To determine which end is more permeable, (top or bottom) would require many experiments to obtain a statistically significant result - and only for one brand!

Scanning electron micrographs revealed the structure of the active surface to be made of polymer granules of order 10nm. These granules form into aggregates of order $0.1\mu\text{m}$ and become larger with increasing distance from the top surface. By deduction, the pores are actually the interstices between the granules or nodules. Since the nodules are fairly uniform in size at a given depth, the interstices are reasonably even. The supposition has been

put forward that the boundary of aggregates is clearly a weak spot and hence may have larger interstices. This would clearly reduce the specificity of the membranes. These comments have been recorded elsewhere albeit in a divided and unforceful way. However, it does give a fundamental and factual understanding to membrane structure that most membrane literature papers overlook or do not realise.

CHAPTER 7 SUGGESTIONS FOR FURTHER WORK

- 1) All of the velocity profiles obtained in this work were obtained on a plane 12mm in from the transmission window. It would be useful to record velocity profiles at various planes in the channel at two velocities to have a totally experimental measure of continuity by evaluating the channel average velocity and comparing this with the rotameter reading. This could be the ultimate L.D.A. system validity check.
- 2) Many more systematic experiments are required to evaluate the effect of solutes on the turbulent velocity profile in order to write membrane system design guidelines. The concentration and type of solute should be varied and velocity profiles measured for a series of Reynolds numbers to evaluate optimum Reynolds numbers. This could be checked by operating a parallel U.F. system at three different Reynolds numbers, the mid-number being the predicted optimum, to check for fouling/concentration polarisation control on long term performance testing. The choice of solutes should take into account viscosity ranges, solute membrane interactions and permeability of the membranes. Solute rejections and membrane materials are interlinked with the solute membrane interactions.
- 3) The work so far carried out proved the existence of turbulent bursts and noted some of their characteristics on a no-solute system. What is the effect of solutes on their frequency and size?

The equipment has not been pushed to the limit. The

averaging time may be decreased by an order of magnitude in order to increase the sensitivity, and facilities exist to be able to interface the tracker output so that every individual Doppler burst frequency that was tracked could be recorded, allowing more sophisticated statistical analysis. A lot of work could be done in this area. What are the factors besides Reynolds number and viscosity that promote turbulent bursts? How effective are turbulence promoters used by some membrane manufacturers? What about rough membranes? The L.D.A. technique would be a method of characterising the overall membrane performance with measurements of the key parameters, - a scientific approach.

In both (2) and (3), the work has concentrated on turbulent flow. There are several membrane applications using laminar flow on relatively non fouling feeds so the work could be repeated for laminar flow. Turbulent bursts in laminar flow, surely not? However, this work has shown that they exist inside the 'laminar boundary layer of turbulent flow'. The answer to this question would indicate the origin of turbulent bursts, whether they come from core eddies of large momentum, or some form of fluid wall stickiness which creates vorticity.

- 4) The lens used in all of the work had a 280mm focal length. Two other lenses of 90 and 70mm focal length were constructed. The 90mm lens has been shown to produce parallel fringes with a calculated optical volume diameter of $61\mu\text{m}$. The 70mm lens should have a

volume of $54\mu\text{m}$ $\emptyset$. Their purpose was to be able to measure closer to the wall. How close?

The laser alignment was very critical for the 90mm lens case. This could well limit their use to just near wall velocity profiles because of the time involved in setting up the system compared to the current system.

- 5) The photomultiplier pinhole has a diameter of $50\mu\text{m}$. Since the P.M.T. amplifier was used on a low setting it would be possible to have a laser cut, smaller diameter, pinhole installed. This would further reduce the observed optical volume.

One of the benefits of (4) and (5), i.e. changing the optical volume size would be to evaluate the currently unknown L.D.A. system errors, particularly velocity gradient broadening. For the same position near the wall and the same flowrate, a plot of Doppler frequency versus observed optical volume size would evaluate these errors' true magnitude.

- 6) The largest error associated with the wall shear stress dimensionless approach was the error associated with the data used to derive the Blasius equation for wall shear stress. It should be possible to put pressure tappings in the membrane channel so that the wall shear stress may be experimentally defined.

One problem is that static pressure is isotropic. If the channel walls do not have the same roughness, the measured 'channel' shear stress will not necessarily be the shear stress associated with the membrane.

Clearly, there is a case for a few roughness

experiments or cladding the other bars with the same membrane material.

- 7) The velocity profiles in whatever system, are, at least over finite distances, a function of entry length. Preceding work could be repeated to derive a scientifically experimental method for evaluating the optimum channel length, if one exists. The channel has been constructed to give eight different measurement positions by using either of the four windows with flow in either direction.
- 8) The channel can also be orientated in any plane. What effect does orientation have on the solute containing velocity profile? Some theoretical papers have suggested that density gradients are an extremely important mechanism in the control of concentration polarisation. (Section 2.2.4) Is this borne out experimentally?
- 9) The equipment has shown itself capable of following physical buildup/movement of the wall by calculating the displacement of the wall from the measured velocity. The limitation that the buildup/movement must be of the order of $10\mu\text{m}$ and that the foulant to be used must not effect the L.D.A. system, does limit its use. However, experiments could be conceived whereby for example, polystyrene latex was used as a fouling medium or the flows could be switched from any fouling medium to an optically clear fluid to obtain measurements. Another variation would be to foul the surface and then using a clear washing solution, follow the foulant layer's thickness decay.

- 10) One of the reasons for the purchase of the tracker was its ability to measure low Doppler frequencies. Using the smallest focal length lens on the lowest tracker frequency band, the system can measure down to a velocity of $1.6 \times 10^{-4} \text{ m/s}$. In transverse velocity terms, this is equivalent to a flux of $560 \text{ l/m}^2 \text{ hr}$. Using highly permeable membranes, the equipment has the potential of measuring local fluxes. If there is not too much noise created by the reflection of the laser beams off the membrane, this would be a potential tool for characterising membranes and the points mentioned above, e.g. turbulence bursts, orientation, foulants etc., could all be re-evaluated in the light of more data in the transverse direction.

NOMENCLATURE

a	Half channel width	m
a'	Distance from the optical volume to the receiving lens.(Fig.2.7)	m
A	Constant used in equation 2.49	m^3/s
b	Flux decline exponent	---
b'	Distance from the receiving lens to the pinhole.(Fig.2.7)	m
B	Constant used in equation 2.49	m^3/s
c^+	Coefficient defined by equation 2.57 and used to model curved pipe flow	---
c_b	Concentration of solute in the bulk of the liquid	kg/m^3
c_f	Drag coefficient for fluid flow	---
c_{fi}	Concentration of solute i in the feed	kg/m^3
c_g	Gelling concentration of solute	kg/m^3
c_{pi}	Concentration of solute i in the permeate	kg/m^3
c_w	Concentration of solute at the porous wall surface	kg/m^3
c_w^*	Dimensionless solute concentration at the wall used in equation 2.41	---
$C(x,y)$	Local concentration at the point (x,y)	kg/m^3
d	Parallel beam spacing half distance defined by Fig.2.7	m
d_B	Diameter of the transmission parallel beams (Fig.2.7)	m
d_p	Particle diameter	m
d_{pH}	Diameter of the photomultiplier hole (Fig.2.7)	m

d_r	Diameter of the observed optical volume (Fig.2.7)	m
d_t	Diameter of the transmission optical volume (Fig.2.7)	m
D	Diffusion coefficient	---
D'	Variable for curved pipe flow defined by equation 2.54	---
E	Constant used in equation 2.26 = 10.0	---
f	Fanning friction factor	---
f_i	i^{th} term in the series	---
f_n	n^{th} term in the series	---
f_r	Receiving lens focal length	m
f_t	Transmission lens focal length	m
$f(x^*,y^*)$	Unspecified stream function used in equation 2.37	---
$f(q)$	Unspecified function used in equation 2.49	---
g	Dimensionless distance from the wall of a curved pipe defined by equation 2.58	---
h	Half channel height	m
i	Exponent used in equation 2.21	---
I	Intensity of a laser beam	W/m^2
I_{max}	Maximum intensity of a laser beam	W/m^2
j	Exponent used in equation 2.21	---
J_v	Membrane flux	m^3/m^2s
J_v^*	Dimensionless membrane flux used in equation 2.37-2.41 = hJ_v/ν	---
J_{vlim}	Limiting membrane flux with a fully developed concentration boundary layer	m^3/m^2s
J_{vo}	Membrane flux at time t_o	m^3/m^2s

$J_v(0)$	Membrane flux at the start of the channel	m^3/m^2s
$J_v(t)$	Membrane flux at time t	m^3/m^2s
k	Constant used in equation 2.26 = 0.407	---
k'	Constant used in equation 2.25	---
K	Dean no. for curved pipe flow defined by equation 2.53	---
l	Prandtl mixing length for turbulent flow	m
l_t	Length of the optical volume formed by two laser beams defined in Fig.2.7	m
L	Channel/pipe length	m
m	Constant used in equation 2.68 = 0.0154	---
n	Constant used in equation 2.67 n=0 for flat plate, n=1/3 for infinite width flat channel	---
n'	Constant used in equation 2.25 = 0.109	---
N	Number of particles	---
N_n	Coefficient defined by equation 5.2	---
p	Probability of an event	---
P	Pressure	N/m^2
q	Dimensionless distance from the centre of tube $= (r/R)$	---
Q	Volumetric flowrate through the channel	m^3/s
r	Radius coordinate in a pipe from the centre	m
r_d	Rate of foulant deposition	m/s
R	Radius of pipe	m
R_i	Rejection of solute i (usually expressed as %)	
s	Exponent used in equation 2.8	---

$S(x)$	Integral function of membrane flux defined by equation 2.45 and used in equation 2.43	---
t	Time	s
t_o	Initial time	s
u	Local axial velocity	m/s
u'	Fluctuational velocity for turbulent flow defined by equation 2.78	m/s
$\bar{u}$	Average axial velocity in channel	m/s
u^*	Dimensionless axial velocity used in equations 2.37-2.41 = $u/\bar{u}$	---
u^+	Wall shear stress based dimensionless velocity defined by equation 2.69	---
u_1^+	Wall shear stress evaluated at $y^+=26$ by equation 2.74. Defined by equation 2.76	---
$u_{\max}$	Channel maximum velocity	m/s
u_t	Threshold average axial velocity in channel (Section 2.2.1)	m/s
u_τ	Wall slip velocity defined by equation 2.69	m/s
$\bar{u}(0)$	Average axial velocity entering the channel	m/s
U	Velocity of a particle	m/s
U_{act}	Actual velocity (equation 2.92)	m/s
U_{obs}	Observed velocity (equation 2.91)	m/s
v	Local transverse velocity	m/s
v^*	Dimensionless transverse velocity used in equation 2.37 to 2.41	---
v_ϕ^+	Dimensionless velocity for the tangential transverse velocity in a curved pipe	---

defined in equation 2.51 on a coordinate system shown in Fig.2.5

v_{θ}^{+}	Dimensionless velocity for the tangential axial velocity in a curved pipe defined in equation 2.52 on a coordinate system shown in Fig.2.5	---
$v_{\theta\delta}^{+}$	Dimensionless velocity used in the calculation of the velocity profile in a curved tube defined by equation 2.56	---
x	Coordinate distance in the axial direction	
x'	Characteristic flow dimension e.g. diameter of a pipe	m
x^{*}	Dimensionless axial distance used in equation 2.37-2.41 = x/hRe	---
Δx	Fringe spacing within the optical volume	m
y	Distance from the wall	m
y'	Coordinate distance from the channel mid point towards the wall	m
y''	Radial distance from the external surface of a porous tube	m
y^{+}	Wall shear stress based dimensionless distance = $u y/\nu$	---
y^{*}	Dimensionless distance from the wall used in equation 2.37-2.41 = y/h	---
y_1, y_2	Specific distances away from the wall	m
$Y_n(\lambda)$	nth coefficient used in equations 2.30 - 2.32	---
z	Coordinate dimension in the plane of the wall perpendicular to the axial coordinate	m

Fig.5.11

Dimensionless Numbers

Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number

Greek Symbols

α	Constant used in equation 2.2	s/m
α'	Constant used in equation 2.67 = 0.4696...	---
β_1	Constant used in equation 2.41	---
β_2	Constant used in equation 2.1	---
β_n	nth coefficient used in equation 2.30-2.32	---
δ	Fouling layer thickness	m
δ''	Diffusion boundary layer thickness for the externals of a porous tube	m
δ^+	Dimensionless coefficient defined by equation 2.55 for curved pipe flow	---
δ_c	Concentration boundary layer thickness	m
δ_m	Momentum boundary layer thickness	m
ϵ	Eddy viscosity	m ² /s
ϵ'	= x/h. Used in equation 2.30.	---
	Dimensionless axial distance	
ϵ_1	Fractional error in the bisector angle	---
ϵ_2	Fractional error in the wall slip velocity	---
ρ	Density	kg/m ³
ρ_b	Density of salt water (bulk phase)	kg/m ³
ρ_i	Density of solute i	kg/m ³
ρ_w	Density of salt water at the membrane surface	kg/m ³
θ	Angle used to define a spiral coordinate	---

system shown in Fig.2.5 for curved
pipe flow

θ_t	Transmission laser beam bisector angle defined in Fig.2.7	---
θ_r	Receiving laser beam bisector angle (Fig.2.7)	---
λ	Wavelength of light	m
$\bar{\lambda}$	$= y'/h$ Used in equation 2.29 & 2.30 Dimensionless transverse distance	---
μ	Absolute viscosity	N/sm ²
$\mu^*(x^*, y^*)$	Dimensionless viscosity used in equation 2.38 as a function of position	---
ν	Kinematic viscosity	m ² /s
$\bar{\nu}$	Average profile Doppler frequency	Hz
ν_D	Doppler frequency	Hz
ν_τ	Wall slip equivalent Doppler frequency defined by equation A7.1	Hz
ξ	$= J_v/\bar{u}$. Used in equation 2.30. Dimensionless flux	---
$\xi(0)$	$= J_v(0)/\bar{u}(0)$. Used in equation 2.33 Dimensionless flux at start of channel	---
τ_w	Wall shear stress	N/m ²
ϕ	Angle used to define a spiral coordinate system shown in Fig.2.5 for curved pipe flow	---
Ψ	Stream function defined by equation 2.49 and used in equation 2.48	m ³ /s
w	$= hJ_v/\nu$. Used in equation 2.29	---
$P(x)$	An unspecified velocity function used in the calculation of the diffusion boundary	m/s

layer thickness for the externals of a
porous tube

κ Dimensionless radius of curvature defined ---
by equation 2.58 for curved pipe flow

$\bar{r}$ Radius of curvature shown in the m
coordinate system given in Fig.2.5 for
curved pipe flow

n Rejection parameter defined by equation ---
2.73

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APPENDIX 1 Tubular Membrane Permeability as a Function of Length.

Introduction

From the patent literature, (36) it is found that tubular membranes are made by either bob casting or spraying the polymer dope onto the porous backing material. The membrane is then cured by a suitable combination of air drying and water and ice bath leaching to obtain the required porosity. Whichever process is used, the polymer solvent has to be removed from the polymer into the carrier fluid, air or water, along the tube and into the bulk of the bath. The large length to diameter ratio means that there will be significant solvent concentration gradients in the tube which could be translated into significant differences in membrane porosity along the tube length.

If this supposition is correct, there could be an economic incentive to arrange the tubes in a specific way. For example, if it were observed that the bottoms of the tubular membranes were more permeable than the tops of vertically cured membranes, and maximum permeability were required, the optimum system would consist of tubes arranged with the bottoms, the most permeable end upstream. The developing entrance region should keep the membrane less fouled and concentration polarisation restricted than the downstream section.

This section attempts to deduce any permeability differences between sections of tubular membranes.

Experimental

The equipment was of a similar construction to that outlined in Section 3.1, the major difference being that the membrane test channel was replaced by six stainless steel 3' long membrane support tubes connected in series. The tubes had 0.5mm diameter permeate outlet holes drilled on a $\frac{3}{4}$ " square pitch. (Standard Paterson Candy International design). The membranes tested were PCI T6/B type. They were delivered in nominal 12' lengths with the manufacture's date stamped on the 'top' of the membrane. (26 and 27 July 1986)

Three lengths of 3' were cut from each 12' length representing the top, middle and bottom portions, and each was labelled with the same number. This ensured that the membranes were installed in the six support tubes in the same order in every sense, when 'tops', 'middles' or 'bottoms' were fitted. The membrane fitting procedure is given in P.C.I. literature (151). The membranes were pre-pressurised according to the same instructions.

Fluids used include water and dextran solutions. (Grade C, BDH, 70 000 nominal molecular weight) The concentrations of dextran across the membranes was determined by sulphuric acid addition, a fixed time delay and a spectrophotometer measurement at 490 nm. The fine details are not given because the variation in concentration due to membrane separation was less than the reproducibility variations in making the measurements.

Results

Sample experimental data summaries are given in Table A1.1. The results are corrected for temperature using data from P.C.I. literature (151). The data given was gathered in this order though with many other experiments and cleaning sessions between trials. Each flux is the mean of three measured values.

It can be seen that there is a difference between the different portions of membrane. On the whole for this set of membranes and after pre-pressurisation, the permeability order was tops > centres > bottoms.

In order to rule out time variations, the second batch of membranes were paired so that two tops and bottoms from different whole tubes were tested simultaneously and the experiment repeated in a similar fashion for the remaining tops and bottoms. A sample set of data is given in Table A1.2. This batch of membranes has a larger individual variation and a greater permeability for the bottoms of the membranes than the tops.

At this point it became clear that, whilst there were differences along the tube length, there were no consistent differences. Many tubes would have to be tested to get a statistically significant result, and, after all this work, any conclusion would only be justified for one of a particular commercial manufacturer's membranes.

The experiments were not pursued.

TABLE A1.1

		Flux $\text{m}^3/\text{m}^2\text{hr}$ @ 15°C		
		Top	Centre	Bottom
Prepressurisation	1	0.152	0.190	0.185
10 barg	2	0.170	0.191	0.175
Water	3	0.149	0.200	0.180
	4	0.159	0.180	0.165
	5	0.179	0.200	0.170
	6	0.177	0.195	0.162
	Mean	0.164	0.193	0.173
Water	1	0.0361	0.0361	0.0347
42 psig	2	0.0382	0.0357	0.0303
	3	0.0298	0.0348	0.0295
	4	0.0329	0.0304	0.0275
	5	0.0331	0.0287	0.0258
	6	0.0299	0.0253	0.0228
	Mean	0.0333	0.0318	0.0284
Water	1	0.120	0.118	0.122
100 psig	2	0.125	0.118	0.113
	3	0.109	0.120	0.116
	4	0.118	0.114	0.108
	5	0.128	0.118	0.111
	6	0.121	0.114	0.105
	Mean	0.120	0.117	0.113
Dextran	1	0.0396	0.0348	0.0371
42 psig	2	0.0426	0.0353	0.0341
	3	0.0333	0.0341	0.0324
	4	0.0356	0.0315	0.0290
	5	0.0350	0.0304	0.0277
	6	0.0333	0.0272	0.0232
	Mean	0.0366	0.0322	0.0306

TABLE A1.2

		Flux $\text{m}^3/\text{m}^2\text{hr}$ @ 15°C	
		Top	Bottom
Prepressurisation	1	0.254	0.259
Water	2	0.135	0.244
10 barg	3	0.125	0.201
	4	0.110	0.138
	Mean	0.156	0.211
Water	1	0.0622	0.0760
42 psig	2	0.0590	0.0702
	3	0.0603	0.0699
	4	0.0257	0.0257
	5	0.0384	0.0415
	6	0.0273	0.0475
	Mean	0.0455	0.0551
Water	1	0.177	0.176
100 psig	2	0.167	0.187
	3	0.175	0.180
	4	0.070	0.072
	5	0.107	0.124
	6	0.082	0.153
	Mean	0.130	0.149
Dextran	1	0.0585	0.0629
42 psig	2	0.0556	0.0634
	3	0.0564	0.0594
	4	0.0244	0.0216
	5	0.0361	0.0429
	6	0.0238	0.0469
	Mean	0.0425	0.0495

APPENDIX 2 Scanning Electron Microscopy of Membranes.

Introduction

In 1980 Imperial College purchased a new Jeol 120 CX Temscan scanning electron microscope. The machine was claimed to have a resolution of 25 Å and was certainly one of the most advanced commercially available at that time. To take advantage of this, eight half day sessions were hired to examine the microscopic details of commercial membranes.

Method

The samples of membrane were either cut by a microtome or scalpel or freeze fractured. Ideally, the specimen was just under a millimetre wide and about 5mm long. It was stuck to the copper holding plate by silver drag. A Technics Hiemmer metal scatterer was used to scatter a conducting layer of gold onto the specimen. A typical set of conditions consisted of an ionisation current of 5.0 mA at 1100 V for 2.0 mins. This gave a calibrated coating of 110 Å uniform thickness. Other settings were used to give thicknesses of between 80-150 Å. However, the condition given above represents a compromise between the need for the thinnest coating and a coating that would not overheat while the microscope was being focussed at high resolutions prior to photography.

The microscope could magnify upto 200 000 times and by photographing and enlarging the region, a further

magnification could be achieved upto a factor of about 10.

Results

A set of six photographs have been selected for this thesis out of about 120 possible shots. These are given in plates A2.1-6.

An oblique, low magnification view of a reverse osmosis membrane is given in plate A2.1. The characteristic fingers forming a porous backing structure are clearly visible. Prior to examination, the membrane was used on citric acid and a line of protazoa can be seen clearly on the centre left of the picture. A similar magnification picture is given in plate A2.2. On this occasion, an ultrafiltration membrane was viewed from above. The wrinkled structure of the surface has an estimated roughness of between 1-2 μ m and occasionally holes appear black. In this picture, the most intensely dark area is in the centre of the picture.

Plates A2.3 and A2.4 show higher magnification shots of the top surface of two different membranes. There is a granular appearance to the surface of characteristic size 10-20nm. A similar structure was observed on side views of a membrane shown in plate A2.5. However, the granules appear larger and are formed into aggregates of granules rather than a continuum.

Plate A2.6 gives a 200 000 times magnification shot of the active top surface of a membrane. One stereo-scan pair of pictures was achieved which showed the granules to be 3 dimensional, and, from pictures like this, the granule size

for the top surface was measured to be in the region of 14-16nm on a sample size of around 50. It must be emphasised that the boundary between granules is subjective.

Discussion

Many other authors have taken low magnification shots. One of the first papers to be published was that of Gittens (152). The pictures lack clarity but reveal similar porous structures for most of the membrane thickness with an apparently continuous thin active top surface.

Three very interesting papers at this level of detail are by Frommer et al.(153) and Strathmann et al.(154) and (155). These contain many micrographs showing the morphological effects of various casting techniques and parameters. References 153 and 154 concentrate on cellulose acetate and polyamide membranes respectively, while reference 155 proposes a mechanism for the formation of membranes.

Plate A2.1 contains an unexpected degree of surface fouling. The membrane had been used once on citric acid and the foulant was identified as a species of protazoa. From a membrane technology point of view, the intriguing question is why the protazoa have laid down almost in the form of a line. Could it be that there is a linear defect of high permeability in which the protazoa were drawn and became lodged?. Advice from the Department of Zoology at Imperial College suggests that there is no biological reason. The protazoa in plate A2.1 are about $2\mu\text{m}$ in diameter.

One paper has been found in the literature in which polystyrene latex was used as an artificial foulant. Belfort et al.(42) took scanning electron micrographs of the fouled membranes showing some of the latex particles had penetrated the membrane surface. However, the fouling of the membrane surface was usually in the form of a continuous layer of upto $12\mu\text{m}$ thick.

As stated earlier, plates A2.3-6 contain micrographs with a granular appearance, where the measured granule size is 14-16nm average diameter for the active surface and about 50nm for the cross-section. The surface of the specimen was covered by about 10nm of gold, so anything larger than this should be a reasonable representation of the morphology. In addition, a stereo-scan of one of these pictures showed that the surface was indeed granular in three dimensions. With such reasoning, the active surface of a membrane is made up of polymer granules of increasing size with distance from the surface. These granules can be lumped into larger aggregates of characteristic dimensions of $1\mu\text{m}$. The pores are actually the free space between the granules with larger passages between aggregates. However, other authors have observed the same morphology and used different descriptive language. In alphabetical order, Alegranti et al.(156) includes micrographs showing 7-10nm granules on the surface and $\sim 30\text{nm}$ granules in the crosssection of polyamide membranes. Broens et al.(157) however, produced just one micrograph with the conclusion that it consisted of nodules of 20-200nm diameter.

Kesting (158) and (159) wrote of microcrystalline or

paracrystalline "micelles". The former paper showed pictures of 'Dry Reverse Osmosis' membranes with surface granules of around 150nm. The latter paper studying cellulose acetate membranes, described the micelles as having a diameter of 20nm and hence minimum interstices of about 4nm. Membrane surface granules of around 50nm were observed by Jiayan et al.(160) and membrane morphology was characterised by four types of substructure, sponge, finger, needle and psuedo poreless. The latter was a description of the closed packed polymer granules noted earlier. The micellular morphology was limited to only certain classes of membranes by Panar et al.(161). The micelles are described as deformed spheres of diameter 40-80nm leaving interstices of the order of 7.5-10nm. The largest published micrographs on the granular nature of the active surface were published by Sanderson et al.(162). Aggregates of around $2\mu\text{m}$ are shown in the cross-section of polysulphone membranes with the constituent nodules appearing to have a diameter around 50nm. Whilst there is a large spread of actual sizes in the literature, the general morphology is demonstrated.

Improved, more specific membranes must be possible if the size and shape of the large aggregates can be influenced. The spaces between aggregates probably represent larger interstices than between their many constituent nodules. The nodules themselves, and hence the interstitial gaps, appear to be reasonably uniform at a given level in a cast membrane. Therefore, if it were not for the aggregates they would provide a very selective filter which becomes more porous through the active surface. The range of nodule sizes is very fortunate in that membranes of different

separating abilities can be made. There is potentially a continuous spectrum of nodule sizes over the range of say 5-100nm. Consider the enormous potential of membranes that could be made with properties approaching the selectivity of zeolites.

APPENDIX 3 Assembly of the Membrane Channel

This section records the technique for assembling the membrane channel. It is laid out in instruction form for brevity.

Materials

In addition to the delrin bars and channel frame, the following are required.

- a) Membrane or impermeable film (3m x 15cm) rolled up with the active surface inside. (Vinyl gloves should be worn whenever the membrane could potentially be fouled.) Membranes should be immersed in distilled water to prevent them drying out.
- b) 3" double sided welding tape
- c) Windows (8) and correct gaskets, each individually identified with its corresponding window.
- d) Longitudinal gaskets (6) rolled up and labelled to speed their fitting.
- e) End blocks, gaskets and end plates (2 each)
- f) Silicone rubber sealant.
- g) 86 sets of 6mm studding, two washers and two nuts.
- h) 14 1/2" Ø bolts.
- i) Hide mallet.
- j) Scribe
- k) Razor.
- l) 4" paint brush and beaker full of distilled water.
- m) Distilled water spray gun.
- n) 8 Carver or G clamps.

- o) Sockets and wrenches for 6mm nuts and 1/2" bolts.
- p) 18 x 12mm Allen screws, membrane bar jig and an Allen key.
- q) 3 planed wooden batons at least 1ft long.
- r) 2mm diameter copper wire.

Method

- 1) Ensure all materials are clean;
 - a) Clean delrin bars thoroughly in detergent solution. Sterilise in sodium hypochlorite solution and rinse in double distilled water. If any stubborn adhesive or bacterial growth remains, use various organic solvents as necessary.
 - b) Rub glass windows gently with tissues and cotton wool soaked in various organic solvents until clean.
- 2) Lay the side bars outside face down and install the correct windows and gaskets. Check that the windows are slightly proud but parallel to the bars. If they are not $30-50 \times 10^{-3}$ " proud cut new gaskets.
- 3) Make diffuse screens from 1" strips of greaseproof paper and stick on one of the edges of the window to provide a visible focusing point for the laser beams. These strips should be stuck on with copydex, but the strength of the bond is not sufficient to assume the windows are firmly fixed. Gravity is the only sure way of keeping the windows in place, and this must be born in mind during the assembly.
- 4) Clamp the edges of the windows of one of the bars in place with rubber sheathed Carver clamps from the

bevelled side.

- 5) Tilt the channel mounted bar with the mating face to the side bar in step (4) pointing slightly upwards. Lay the joining face gasket on the mounted bar.
- 6) Position the side bar from (4) onto the supporting channel. Using the studding, align the side bar, gasket and the bar at every 8th hole.
- 7) Affix the wooden batons to the metal channel to hold the side bar on, and tilt the channel in the reverse direction. Remove the window restraining clamps and insert all the base studding so that 1/2" to 1" protrudes from the other side.
- 8) Insert the studding to the top holes in the side bars and roll on the top gasket. The studding should protrude sufficiently to hold the gasket in place.
- 9) Roll the narrow gasket on the other side of the base bar over the ends of the studding.
- 10) Fasten the membrane supporting bar onto the jig with Allen screws.
- 11) Stick the welding tape onto one side of the narrow neck of the membrane support bar. Pare the surplus with the razor, roll up and retain. The tape should be without wrinkles and firmed down with hand pressure along its length.
- 12) Peel the backing paper and roll the thin rubber strip onto the tape flush with the base of the neck. Firm the strip down.
- 13) With great caution, stick the retained surplus roll of welding tape to the same side of the bar with its base touching the jig. There must be no wrinkles or

blemishes. Apply hand pressure along the length of the side.

- 14) Repeat stages 11, 12 and 13 on the other side of the membrane support bar.

From henceforth time is very important in order not to let the membrane dry out or the silicone rubber to set before the channel is tightened up.

- 15) At this stage the membrane support bar is flush with one side of the jig. Remove the backing on the welding tape on the opposite side.
- 16) Unroll the beginning of the membrane smoothly onto the exposed tape using the jig as the base edge.
- 17) Dry the next 6" of the membrane with tissues and push this onto the welding tape. Repeat until all the membrane is unrolled. The adhesion can be assisted by hand pressure to the base of the joint provided that it is never exposed to fluids when in use.
- 18) Encourage the membrane neatly over the top surface and down the other side. Rubber lined clamps gripped at the edges of the membranes should be used as weights to assist this process, but removed before proceeding. In between times, use the water spray to keep the membrane active surface moist.
- 19) Remove the backing from the remaining welding strip
- 20) With great care use one hand to hold the membrane away from the exposed tape some 6" to 18" from the other hand which carefully pulls the membrane taut and smoothes it firmly onto the tape. Move the operation slowly along the membrane length. The membrane must fit the support bar snugly.

- 21) Remove the surplus membrane using a razor blade between the bar and the rounded edge of the jig.
- 22) Pierce the bolt holes with the scribe after holding the membrane taut across each hole.
- 23) Liberally apply silicone rubber to the end block sockets in the installed side wall and channel base. Using the hide mallet, tap the end blocks into their position.
- 24) Squeeze more silicone rubber onto the tops of the end blocks.
- 25) Carry out a check of the membrane surface integrity and smoothness. Spray the membrane with water and then lightly dry the end $1\frac{1}{2}$ " with tissue.
- 26) Turn the jig over and place on the end blocks of the channel. Push five lengths of the top studding through the membrane support bar supporting the opposite side of the membrane as the stud comes through.
- 27) Loosen three of the jig Allen screws and remove the others.
- 28) Push the remaining studding through the support bar in a similar manner to (25)
- 29) Remove the remaining Allen screws and hence the jig.
- 30) Impail the remaining gasket onto the studding protruding through the membrane support bar by $1\frac{1}{2}$ "-1"
- 31) Apply silicone rubber to the other side wall end block sockets.
- 32) Check the integrity and smoothness of the membrane and spray all except the ends with water.
- 33) Tilt the channel slightly in the other direction.
- 34) Judiciously, place the remaining side wall on the

channel and ease a few of the studs through the side bar. Having secured the construction with nuts and washers on the exposed studs, tap the remaining studs into the side bar.

- 35) Fit nuts and washers to all the studs.
- 36) Tighten the twelve studs of one end so that there is no gap in the construction.
- 37) Place a Carver clamp over the supporting tube and the channel to firmly mate the membrane-end block interface.
- 38) Repeat (36) and (37) for the other end.
- 39) From the centre to the ends hand tighten all the nuts.
- 40) Repeat the same procedure with the sockets in three waves until the nuts are evenly tight. (The torque used was in the region of 20-25 ft lb)
- 41) Observe the membrane flatness through the window and end tubes.
- 42) Apply the end gaskets and plates using the 1/2" bolts to a similar tightness.
- 42) Turn the channel through 180°.
- 44) Fit the flexible connecting tubes with the jubilee clips and fill the channel with water.
- 45) Deal with any minor trickles by slight further tightening of the relevant fasteners. It is important not to have an uneven torque applied to the studding along the channel length.
- 46) Using copper wire, bend the surplus gaskets to collect any leaking fluid separately from the permeate.
- 47) Sling the permeate collecting tray under the channel with copper wire.
- 48) Pressure test the channel at twice the operating

pressure. (Appendix 5)

Further channel descriptions and drawings are given in
Section 3.2.

APPENDIX 4 Observations made during the membrane channel construction

The aim of this section is to record some of the difficulties experienced during the channel construction, and the solutions devised to solve them. These difficulties all stem from the desire to have a channel in which the laser beams can be projected across and including the surface of the membrane whilst maintaining the integrity of the separation carried out by the membrane. A great deal of lateral thinking was carried out in order to make sure that a simpler solution had not been overlooked.

Delrin Bar Straightening

As recorded in Section 3.2, the four bars making up the channel were delivered severely warped. Before any machining could take place, the bars were straightened on a steel channel base frame by the following method. 8mm diameter holes were drilled in the steel channel on a 9" spacing along two opposite sides of the channel. On one side, the holes were drilled out to accept the heads of 8mm Allen screws. The channel was turned over on a flat surface so that the 8mm holes were facing upwards. Suitably sized blocks were then used to sandwich the delrin bar on the steel channel so that the addition of the two blocks and delrin bar was a few thousandths of an inch greater than the channel. Two wooden batons and a G clamp were used to hold the sandwich in its correct position on the channel. The same procedure was used along the length of the bar until

the bar was firm and straight to the eye. Cigarette paper through to cardboard was used to adjust the position of the bar on the channel by their inclusion in the sandwich. The clamped bar was then left for a few days to deform plastically to a better shape. The clamped assembly was turned over and marking holes were drilled from the other side into the delrin through the 8mm holes. The assembly was unclamped and the marked holes drilled and tapped to take 15mm long screws. At this stage, the delrin bar was screwed onto the steel channel by Allen screws where it remained during all the machining operations. The position of the bar on the channel had to be thought through in advance to maximise machinability.

Machining

Delrin was very easy to machine, to a mill it was akin to cutting butter with a knife. This property though, had its problems. Firstly, if the machining were carried out too quickly machining weals were left which required a great deal of sanding later. Secondly, because the delrin was held on the channel at finite intervals, the bar sometimes twisted or bent during machining, particularly when the delrin faces perpendicular to the top of the channel were being worked. The solution to both of these problems was to take time during machining, to a frustrating degree, with frequent checks on progress. In addition, when large amounts of material were to be cut away, the operation was carried out in two or three attempts, so that mistakes were minimised and potentially correctable unless it was the final cut.

'O' Rings

After the bars and the end blocks had been cut, except for the glass window slots, the delrin channel was constructed and tested for sealability. Initially, the design involved 2mm diameter 'O' rings being sunk into the base and top of the bars, but the channel was far from water tight. Different diameters of 'O' rings from 1/16" to 1/8" and 1.5 to 3mm diameter were tried. Combinations were also tested and the countersunk 'O' rings were sealed in silicone rubber during assembly. No combination was successful. The delrin-silicone rubber bond was very weak.

The gross leaks only occurred at a few points along the channel length. Initially, it was thought that the 'O' rings had come adrift during assembly and this was true in a minority of cases. Also, in about half of the cases the leaks worsened when the studding was tightened. The explanation is given in Fig.A4.1. The increased compression on the studding was not necessarily directly applied to the 'O' ring seal throughout the channel length. Tightening the studding could actually reduce the compression on the 'O' ring locally. At this stage, one solution would have been to have double 'O' rings equispaced about each stud. However, there was still the problem of the 'O' rings becoming dislodged on assembly, and there was the niggling doubt that the mating forces were far from parallel because of the residual warp. Only the base delrin bar was held on a steel channel. The other bars were fixed relative to it, so any twisting in one bar could be compounded on construction. The solution to these problems was to have a

FIGURE A4.1 A Schematic Explanation of the Mode of Leaking
on Overtightening the Studding using O Rings

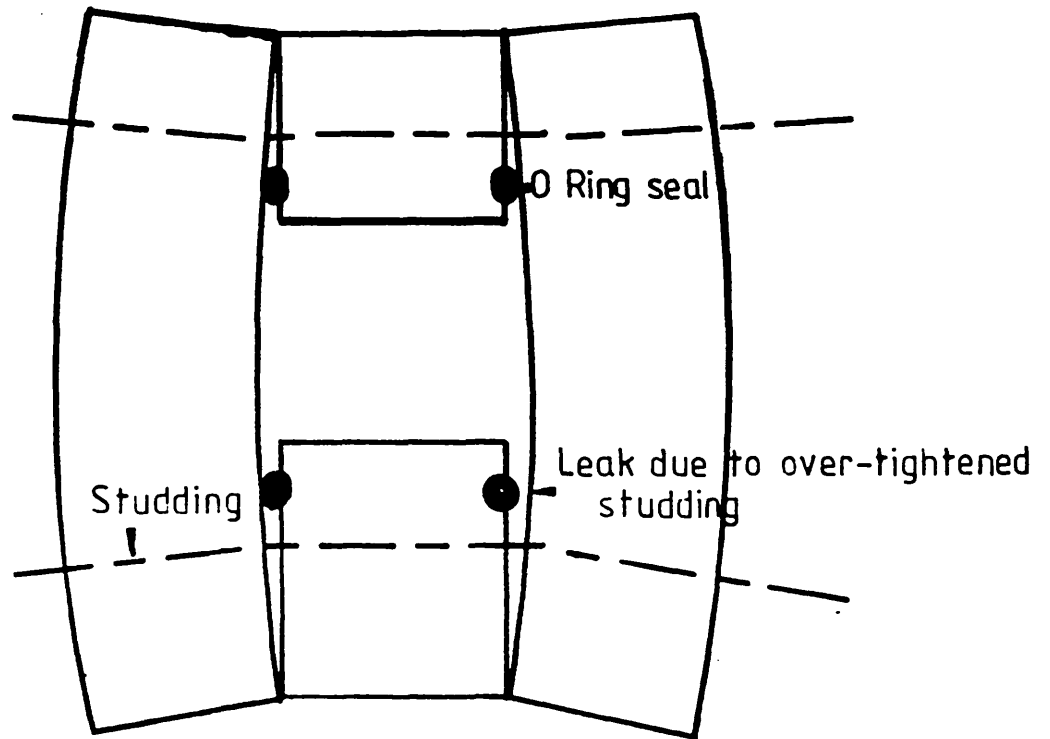
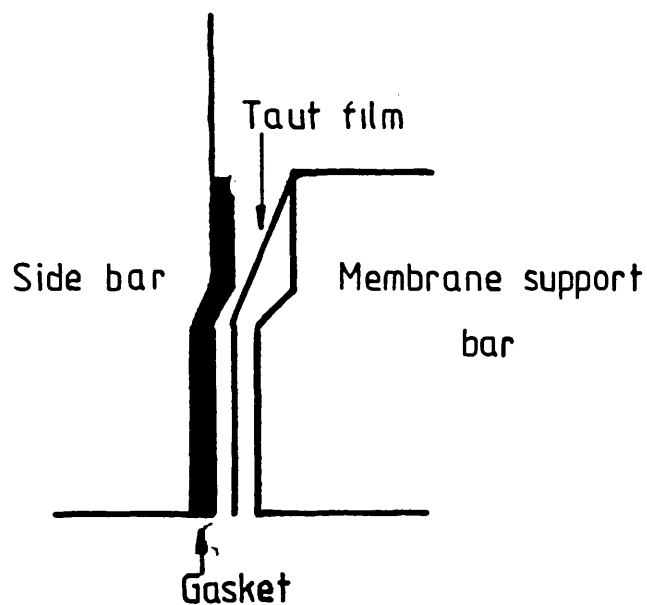


FIGURE A4.2 A Schematic Diagram Showing an Over Taut Film
Over the Channel Base



large sealing surface, a flat strip gasket rather than the point seal of an 'O' ring. Six Imperial sizes from 1/32" to 1/8" of steam quality rubber were tried in combination to obtain a leakproof seal.

Wedge Shape Film Tightening Action

The use of thicker gaskets than the originally designed countersunk 'O' rings led to the channel width being larger than was intended. It was then observed that the impermeable polycarbonate film used for the sealing tests was stretched too tightly across the wedge shape, (see Fig.A4.2). The mating force of the base of the wedge was pulling the film too tight. Any significant internal pressure could tear the film. Ideally, the top of the wedge should pull the film taut marginally faster than the base. The solution lay in obtaining a defective nominal 1/32" steam quality rubber strip whose thickness was actually 26.0-27.0 x 10⁻³" rather than the 31.0 x 10⁻³" it should have been. This was stuck between the neck of the wedge on the membrane support bar and the film. The narrow gasket also had the benefit of reducing the crosssectional area for fluid flow which was already a deviation from the true rectangular channel.

End Plates

The end blocks key into three of the four surrounding bars. The fourth bar, the membrane support bar, has a straight mating face covered with silicone rubber because

the membrane had to be brought outside the internal channel to separate the permeate from the concentrate. As the sealing problems earlier were overcome, the internal pressure increased to the point where the silicone rubber joint failed. Half an inch thick neoprene was cut in the form of a gasket which tightly fitted the membrane support bar and covered the end of the assembly. This was then fastened to the remaining bars by seven 1/2" bolts squeezing the gasket onto and around the membrane support bar. The seal was effective.

Studding Holes and Studs

Delrin absorbs water to an extent that additional warping was induced when the bars were separated after use. For ease of construction, the holes to take the studding between the side bars and the membrane support bar were enlarged. The end six holes of each of the side bars were drilled to 6.5mm diameter and the remaining holes in the side bar were enlarged to 1/4" diameter. All the other holes were left at 6mm diameter. In addition, the last millimetre of each of the studs was rounded off using a brandisher.

Glass Windows

The windows were designed to be sunk into the side bars and sealed with silicone rubber. This was on the advice of Loctite, an adhesive manufacturer. The sealant worked for anything upto an hour when the joints began to weep and

and gradually turn into prolific leaks. After taking the channel apart, it was found that the silicone rubber had failed along the delrin interface in the form of channels running from inside to outside. Loctite suggested pretreatment of the delrin surface with carbon tetrachloride and ethyl acetate to act as degreasing agents. Neither worked. Sanding the delrin and scoring the surface with a scalpel also failed. Between each test, the silicone rubber had to be removed from the glass, to which it firmly bonded. After much advice from Loctite, the only organic solvent found to work was toluene. This softened the silicone so that it could be easily cut with a razor followed by rubbing with a tissue or cotton wool covered PTFE stirrer blade. In practice, the latter operation required about a fortnight of toluene soaking and daily rubbing to obtain a relatively sealant free glass without undue scoring of the glass face. This procedure was first developed in house using ordinary glass rather than the finely polished channel glass windows. A microscope was used to observe the degree of scratching on the surface of the glass. It can be justifiably designated as minimal. A cellulose based glue (Durafix), an epoxy resin (Araldite) and two other Loctite adhesives, a polyester resin and cyanacrylate were also tried. The first two did not even pass a test using scrap materials. The cellulose glue did not give a watertight seal and the epoxy resin was inflexible. The polyester resin was better than the cyanacrylate but neither was as good as the silicone rubber. The polyester resin failed in the same manner as the silicone rubber. Brittle fracture along the delrin-cyanacrylate bond was the main failure for the other. Ethyl

acetate and dichloroethane were used as solvents to remove the polyester resin and cyanacrylate from the glass. Both solvents were far more effective than using toluene to remove silicone rubber.

A radical solution was required. This involved hand cut gaskets made from 10.0×10^{-3} " thick white rubber to be placed between the window and the lip of the delrin side bar. The number of gaskets required per window varied, but the aim was to make the window 30.0 to 50.0×10^{-3} " proud. (The white rubber was very spongy with a Shor value of 50) Provided the gaskets were not wrinkled during construction, they gave a leakproof seal.

APPENDIX 5 Safety

Laser Hazards

Lasers produce highly intense radiation. The 5mW Helium Neon laser used in these experiments is classified as a class 3b because it has a continuous power intensity of greater than 5mW/mm^2 but less than 0.25 W/mm^2 . Such a laser poses a hazard only to the eye because the focusing action of the eye lens produces an even more intense radiation on the sensitive retina. A flowchart for laser classification is given by Tozer (164).

The following points were observed,

- 1) Do not stare at the laser beams.
- 2) Operate the laser in as high a background lighting as possible.
- 3) Block all unused laser beams as close to their source as possible.
- 4) When the laser beams are to be observed, use a rough surface screen to form an indirect diffuse image.

Pressure Vessel Hazards

The product of the gauge pressure and the volume of the fluid of the vessel gives the maximum amount of pressure energy that could be given to fragments of fracturing vessel. For this experiment, a 5 litre pressurised volume at 7 bar contains 3500 J of pressure energy. Napier (165) considered that any vessel containing greater than 100 J of pressure energy should be considered a pressure vessel and treated

accordingly.

To minimise any possibility of fracture,

- 1) All components have been designed to a factor of at least twice the maximum operating stress.
- 2) The constituent parts have been pressure tested to at least 1.5 times the maximum operating pressure.
- 3) A maximum pressure trip was installed to operate at the maximum operating pressure.

(The static head of the pump was 1.6 times the maximum operating pressure.)

- 4) All fastenings were regularly checked.

APPENDIX 6 Polystyrene Latex Manufacture

General

Laser Doppler anemometry depends on the presence of small particles as light scatterers, typically in the size range $\Delta x \leq d_p \leq 2\Delta x$. Δx is the fringe spacing, and, in this case, was in the range 1 - 2 μm . Additionally, the intensity of the scattered light in the direction of the receiving optics will be affected by the particle size and shape. It was, therefore, desirable to have monodisperse spheres as control particles in the channel and polystyrene latex (PSL) was found to be the most suitable. This gave monodisperse spheres in the particles range of 0.4 - 0.8 μm . In fact it was later found that the water filtered by a 2 μm absolute cartridge filter gave the same results as double distilled water and PSL. However, PSL was still added to the filtered water system to give a higher concentration of light scattering sources to speed results, and hence to reduce the available time when the tracker could conceivably evaluate 'noise'. (5 ml per 40 l batch)

The manufacture of PSL was based on a paper by Goodwin et al (163) and much experimental advice by Dr. D.G. Walsh (Dept. of Chemical Engineering, Imperial College).

The key parameter in preparing PSL was the control of the ionic strength of the reactant mixture and to a lesser extent the reaction conditions. Only analytical grade chemicals were used and all glassware, which had to be pyrex, was washed twice in double distilled water and oven dried.

Chemicals per Batch

$K_2S_2O_8$	$0.7448 \pm 0.0020g$
Na Cl	$0.1785 \pm 0.0020g$
Double Distilled water	$700.0 \pm 0.1g$
Styrene	$73.0 \pm 0.1g$

Safety

The reaction was carried out under a nitrogen blanket as the reactants and air form an explosive mixture. All ground glass joints had to be well greased.

Method

1. Set water bath to $70.3 \pm 0.2^{\circ}C$. Wait until the temperature is stable.
2. Add about 670g water to the reactor. Set the stirrer $1cm \pm 0.1cm$ from the base of the reactor and stir at 350 rpm..
3. Connect the condenser and ensure the water filled wash bottle is full.
4. Wait for the reactor to come to temperature.
5. Insert the nitrogen sparger $1cm$ from the stirrer shaft and blade. Bubble oxygen free nitrogen through the reactor for 10 mins. Check that the water wash bottle is working correctly and set the nitrogen supply rate to a lower stable flowrate. (The reactor was a 1 litre 4 necked round bottom flask, with the stirrer in the central port
6. Add the styrene slowly and leave the system for 3 mins.

7. Meanwhile dissolve the initiator ($K_2S_2O_8 + NaCl$) in 30g of water.
8. Add the initiator to the reactor. The reaction time is $9\frac{1}{2}$ hours with stirrer, nitrogen blanket and temperature control applied.
9. Remove the reactor from the bath and transfer the contents to a separating funnel.
10. Allow 8 hours for any remaining monomer to separate out. (Only on one occasion was monomer observed at this stage) Decant off the latex through lead free glass wool.
11. Dialyse the latex using twice boiled visking in double distilled water. Place the visking tubes in beakers of double distilled water with a water to PSL volume ratio of at least 20:1. Change the water daily until the water has an undetectable conductivity relative to fresh double distilled water. Typically, this requires six water changes.
12. Store the product PSL in pyrex containers. Research shows that the PSL is stable for many months provided step 11 is carefully carried out.

Results

Scanning electron micrographs were taken of four batches of PSL. The best set of conditions, given earlier, resulted in a batch of monodisperse spheres of mean diameter $0.46\mu m$ and standard deviation of $0.035\mu m$ on a sample size of 122 spheres. Reproducibility of the same degree of uniformity was checked using the above recipe on two other batches, although photographs and hence sizes were not recorded.

APPENDIX 7 Computer Program and Data File Listings

The master copy of the thesis contains a computer disk with the relevant FORTRAN IV programs and data files stored on it.

Programs

Each program uses a data file containing single point data such as rotameter readings and the viscosity of the fluid. This is followed by data pairs of relative distance and average Doppler frequency. The programs validate the data and arrange the pairs in relative distance from the wall. A specified proportion of the frequency profile is curve fitted and the absolute distances iteratively adjusted until the profile can be extrapolated through the origin. At this point the programs begin to differ. The basic dimensionless program (VEL) evaluates the profile average frequency and uses this and the channel half width to form dimensionless data pairs. These are then plotted on linear, semi-log and log-log axes and various sections of the curve can be curve fitted.

The most commonly used program (DIM) transforms the data pairs into the turbulent boundary layer dimensionless groups of u^+ and y^+ . (See Section 2.3) This is done by evaluating the profile space average frequency and the wall shear velocity from the Blasius equation. The frequency based wall slip velocity is then

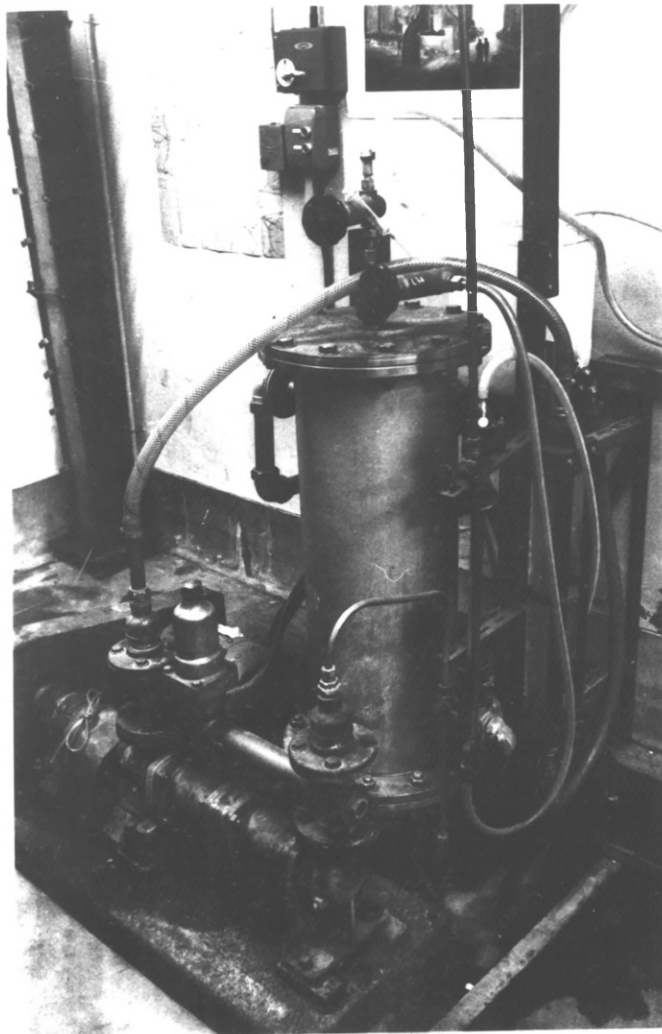
$$v_\tau = \frac{u_\tau}{\bar{u}} \bar{U} \quad (A7.1)$$

ν_z and $\bar{\nu}$ are the wall slip and average frequencies respectively, and u and $\bar{u}$ are the wall slip and average velocities. It also plots the data on several different axes and has the facility to curve fit sections of the curve. Program KBM, DEISS and SPALD are extensions of DIM in that the u^+ values of the data pair values of y^+ are evaluated from the Karmen Boultner Martinelli, the Dessler and the Spalding equations respectively. The experimental and calculated values are then plotted on the same plots. (See Section 2.3)

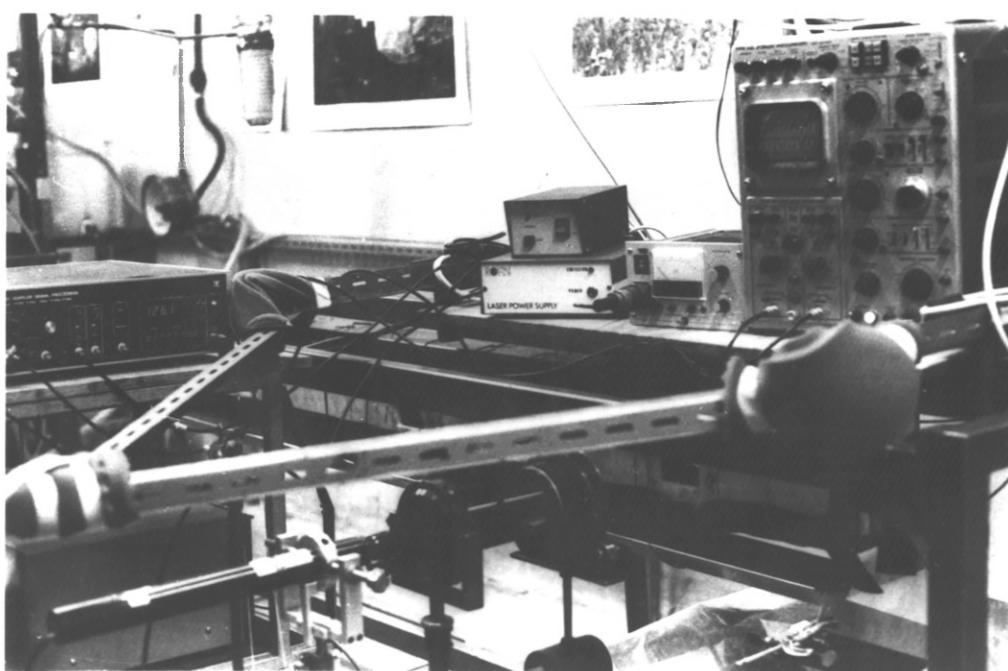
The data files may be identified by the following system.

- a) The first letter refers to the velocity profile recorded on a particular day, A being the first, B the second etc.
- b) The numbers refer to the date, so 35 represents the 3rd of May. Due to the shortness of the experimental period, 3 numbers was the maximum required to avoid ambiguity.
- c) M refers to the modified results, ie. the initial few data points of spurious origin were neglected.
- d) D refers to the data set suitable for the program VEL. Its purpose was to minimise Central Processor Unit (CPU) time.
- e) N refers to a data set suitable for DIM, KBM, DEISS and Spald. Its purpose again was to minimise CPU time.

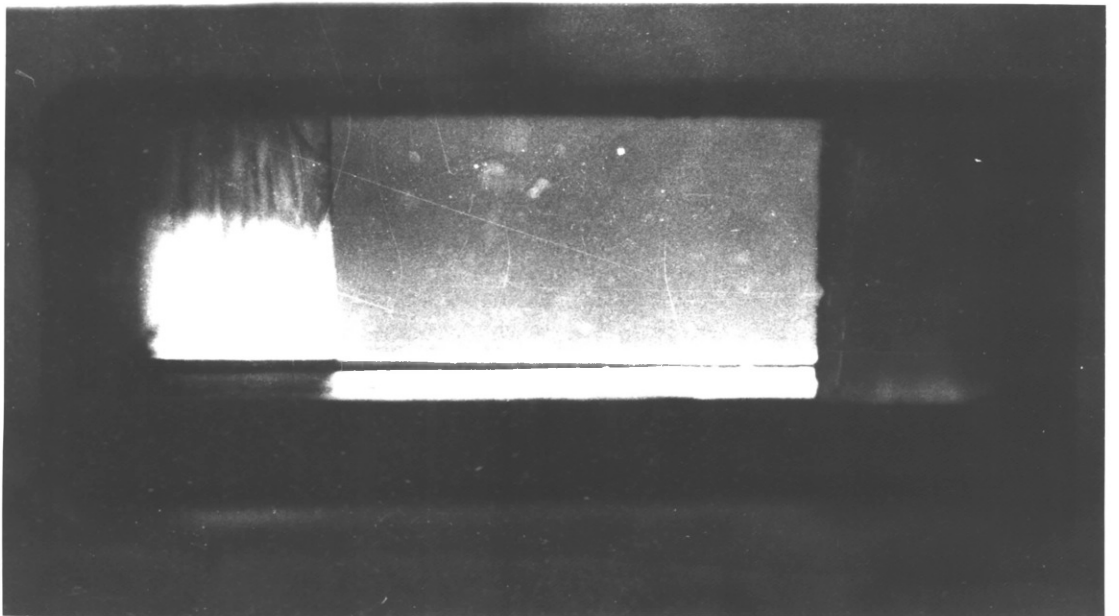
Codes D and N require the knowledge that the raw data does not give spurious answers, so the raw data is first run on Vel or Dim and then items such as the zero error entered to prevent repetition and excess use of DO loops.



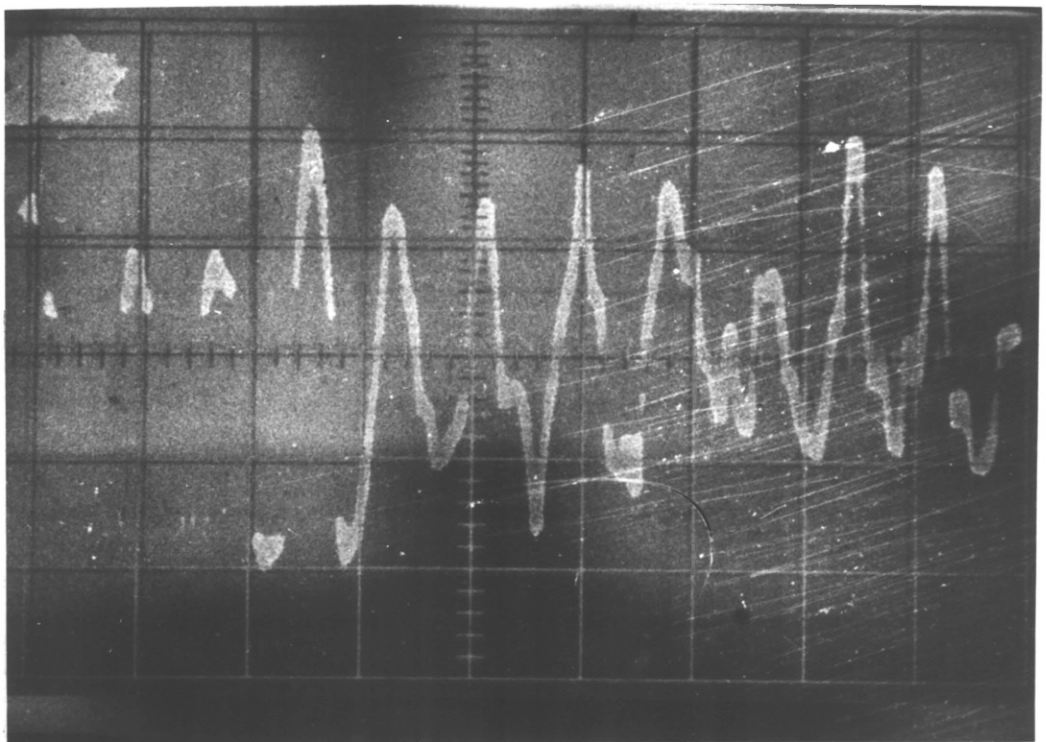
Photograph 1 View of Pumping System.



Photograph 2 View of Membrane Channel.



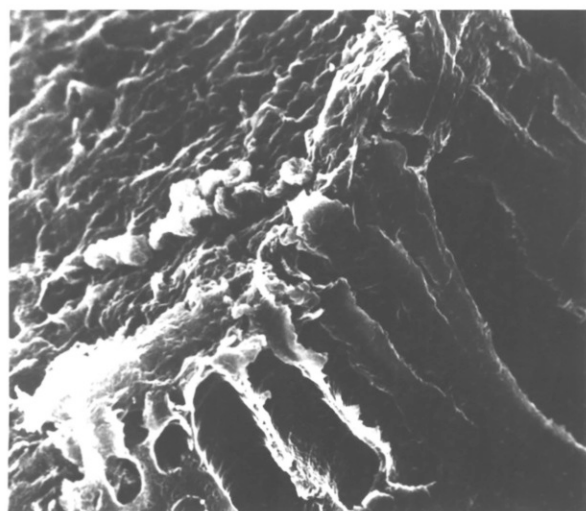
Photograph 3 Membrane Channel Window.



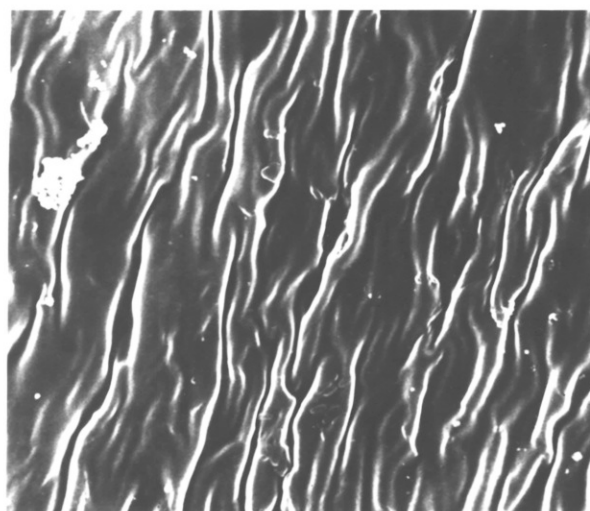
Photograph 4 Oscilloscope Trace of Part of a Doppler Burst.

PLATES A2.1-6

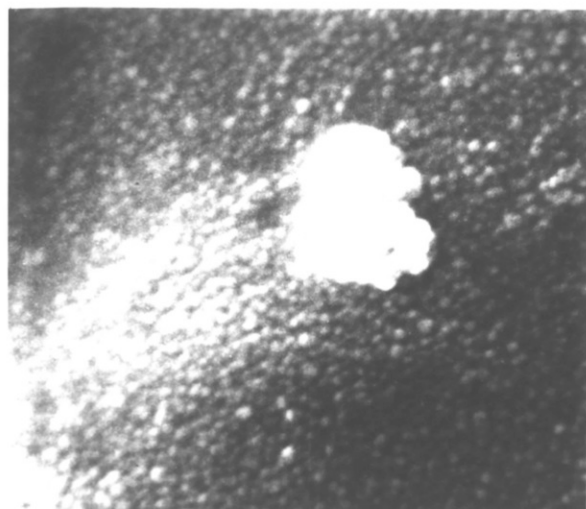
Scanning Electron Micrographs of Membrane



a $5\mu\text{m}$



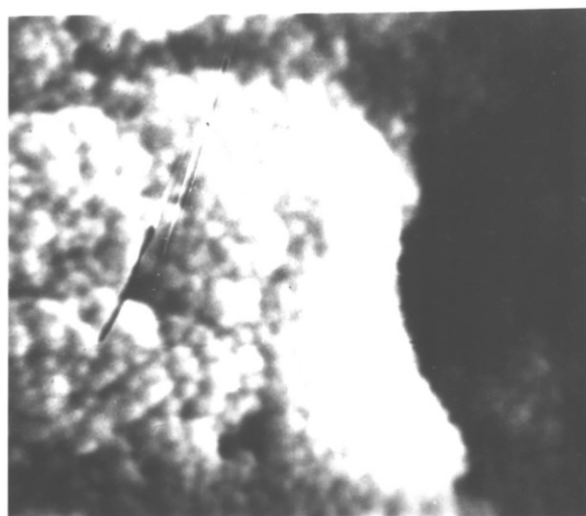
b $5\mu\text{m}$



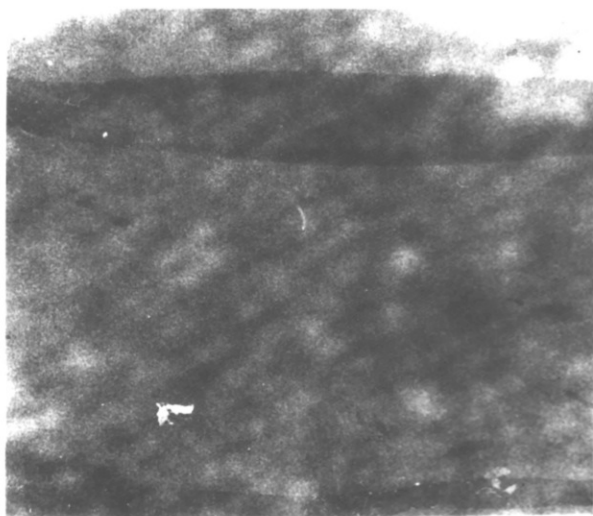
c $0.1\mu\text{m}$



d $0.1\mu\text{m}$



e $0.1\mu\text{m}$



f 50nm