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FILM-COOLING OF A TURBINE NOZZLE GUIDE VANE ENDWALL

by

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**Thesis for the Degree of Master of Philosophy
and for the Diploma of Imperial College.**

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Abstract

The heat transfer to the outer endwall of a high pressure, high temperature turbine nozzle guide vane (NGV) has been studied with and without film-cooling on the endwall. The results indicate that high levels of cooling can be achieved on the endwall with acceptable cooling air flow rates, and verifies the cooling design philosophy.

The secondary flow field within the NGV passage causes the film-cooling air to be deflected towards the suction side of the NGV. Consequently, the coolant does not reach the pressure side of the vane where it intersects with the casing near the trailing edge. This leads to diminished film-cooling at this location. However, measured heat transfer rates indicate that over most of the outer endwall film-cooling reduces the Nusselt number by 50% to 75% except near the pressure side trailing edge where the reduction is around 10% to 20%.

The concept of placing film-cooling holes along a line of constant Mach number has proved an effective method of film-cooling the majority of the endwall.

Simple empirical correlation of these data with two-dimensional correlating parameters has been fairly successful. It is shown that by correcting for the axial pressure gradient it is possible to correlate the present data against two-dimensional flat plate zero pressure gradient data to within $\pm 11\%$. It is considered, therefore, that the data may be utilised in the design of platform cooling configurations.

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NOMENCLATURE

The following is a list of nomenclature in the thesis but excluding the appendix.

*	{	A	constant in the film-cooling superposition model
		B	constant in the film-cooling superposition model
		C	specific heat
		c	electrical capacitance
		c_t	tangential chord
		c_2	blade spacing at leading edge
		D	density ratio
		d	hole diameter
		G	blowing rate
		HP	high pressure
		h_a	heat transfer coefficient when $T_i = T_g$ and there is unit difference between these and T_w
		h_b	heat transfer coefficient when $T_w = T_g$ and there is unit difference between these and T_i
		h_o	datum heat transfer coefficient
		$\bar{h}$	mean heat transfer coefficient
		I	momentum flux ratio
		ILPC	isentropic light piston cascade
		i	electric current
		K_g	freestream gas thermal conductivity
		k	thermal conductivity
		LE	leading edge
		LP	low pressure
		M	Mach number
		M_{air}	molar mass of air
		M_{co2}	molar mass of carbon dioxide
		M_g	freestream gas molar mass
		M_i	injection gas molar mass
		m	mole fraction
		NGV	nozzle guide vane
		Nu	Nusselt number with film-cooling
		Nu_o	Nusselt number without film-cooling

*** A' and B' are constants without correction for boundary layer property variations.**

NOMENCLATURE (continued)

$Nu_{o,cp}$	Nusselt number without film-cooling in a constant property freestream
n	constant property correction factor
n_i	number of moles of the injectant
n_x	number of moles of constituent x
P_{amb}	ambient pressure
P_i	injection gas pressure
P_g	freestream gas pressure
P_x	partial pressure of constituent x
P_{ti}	injection gas total pressure
P_{tg}	freestream gas total pressure
P_1	pump tube pressure before compression
P_2	pump tube pressure after compression
PDE	partial differential equation
PS	pressure side
q	specific heat transfer
$\dot{q}$	specific heat transfer rate
r	electrical resistance
S	slot width
SS	suction side
St	Stanton number
SIP	strong injection parameter
s	distance along a pseudo-streamline
s_2	distance along a transverse-gridline
T	temperature
T_{aw}	adiabatic wall temperature
T_g	freestream gas temperature
T_i	injection gas temperature
T_w	wall temperature
T_{tg}	freestream gas total temperature
T_{ti}	injection gas total temperature
T_1	pump tube temperature before compression
T_2	pump tube temperature after compression
TE	trailing edge
TET	turbine entry temperature

NOMENCLATURE (continued)

t	time
u	velocity in the axial direction
u_g	freestream gas velocity
u_i	injection gas velocity
u_{inlet}	mid-passage gas velocity
$u_{\text{blade-to-blade}}$	mean gas velocity perpendicular to axial direction
V	electric voltage
v	velocity perpendicular to axial direction
WIP	weak injection parameter
x	distance in the axial direction
y	distance perpendicular to axial direction
α	thermal diffusivity
γ	adiabatic index
ε_t	turbulent eddy viscosity
η	adiabatic wall effectiveness
ρ_g	freestream gas density
ρ_i	injection gas density
θ	temperature difference ratio

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1. INTRODUCTION

In the quest for increased efficiency, durability and improved fuel consumption the gas turbine industry is constantly extending the frontiers of technology. For this reason much research is undertaken on all components of a gas turbine in order to ensure that every part is operating at its most efficient. One such area of research that is the focus of much attention is the cooling of high pressure (HP) turbine blades and nozzle guide vanes (NGV). This somewhat reflects the particularly severe environment that these components endure; pressures in the range 10-30 bar and temperatures in excess of 1800K. It also reflects the highly complex 3-dimensional, turbulent nature of the flow in this region of the engine. Thus, studies in this research field are aimed at improving the understanding of the flow and heat transfer in a turbine blade passage thereby leading to designs for future engines which give better aerodynamic efficiency and a longer thermal life.

1.1 Gas Turbine Film-Cooling

Present day gas turbines operate with turbine entry temperatures (TET) which are significantly higher than those sustainable by the stator and rotor blade materials. This is because the thermal efficiency of a gas turbine is a function of the pressure ratio and maximum cycle temperature such that an increase in either of these parameters produces an increase in cycle thermal efficiency^{1.1}. So, one way for the turbine designer to improve engine efficiency is to raise the TET as high as possible. Consequently, the first stage of the HP turbine requires cooling so that it may have an acceptable operational life in a particularly harsh environment.

Various forms of cooling are employed which inevitably involve bleeding relatively cold air from the compressor. However, in removing air from the compressor the power output of the engine is reduced and so the benefits provided by cooling must be optimised against the loss of power due to the reduced core flow. The cooling air itself is passed from the compressor to the turbine where it flows through passages within the aerofoils. These cooling passages are of complex shape and include ribs and pin-fin turbulence/mixing generators to promote internal heat transfer. In some cases inserts are used to direct the flow via small holes onto the internal

surfaces of the passages themselves. This is known as impingement cooling. Once the air has passed through the passages within the aerofoils it is usually vented into the free stream via arrays of small holes across the aerofoils and endwalls. This injection of air forms a cool layer adjacent to the metal surface which acts as a heat sink for the high-temperature mainstream gas providing protection for the blades and endwalls. This mode of cooling is known as film-cooling and together with the other forms of cooling prevents the metal temperature from exceeding a safe limit.

1.2 Previous Film-Cooling Research

Film-cooling has become a major research field in itself and has been studied since the 1960's because of its important contribution in improving gas turbine performance. Original work by Goldstein et al^{1,2} summarised in a review article gives an excellent overview of the film-cooling process.

The work shown in Goldstein's review was based on a temperature distribution that would **be produced by a perfectly insulated (zero heat flux) surface.**

This temperature was termed an adiabatic wall temperature (T_{aw}), and was used to determine an adiabatic wall effectiveness (η) defined as,

$$\eta = (T_{aw} - T_g) / (T_i - T_g) \quad (1.1)$$

where T_{aw} is the adiabatic wall temperature
 T_g is the freestream gas temperature
 T_i is the injectant gas temperature

The research showed the decay in effectiveness downstream of a single hole inclined at 35° to the wall surface, fig. 1.1. It can be seen, however, that even after 40 hole diameters downstream of injection that the injectant is still providing some protection to the surface ($\eta \approx 0.2$). Interestingly, it can also be seen that at this distance downstream there is a slight rise in effectiveness as one moves by one hole diameter perpendicular to the line directly downstream of the hole. This shows the lateral diffusion of the coolant flow with distance from the point of injection. Fig 1.2 shows the variation of effectiveness with blowing rate (G) where blowing rate is defined as,

$$G = (\rho_i u_i) / (\rho_g u_g) \quad (1.2)$$

where ρ_g is the density of the freestream gas
 ρ_i is the density of the injection gas
 u_g is the velocity of the freestream gas
 u_i is the velocity of the injection gas

It is evident that the effectiveness is a maximum at a blowing rate of 0.5 for a given position downstream of the cooling hole. Goldstein suggests that for blowing rates below this value the coolant remains close to the wall providing an insulating film; above this value the penetration of the injectant into the mainstream flow is such that the coolant separates from the wall and allows the freestream gas to circulate adjacent to the wall.

Most of the experiments by Goldstein employed a mass transfer technique usually involving the injection of a small amount of foreign gas along with the coolant. The coolant was then sampled through tappings on the surface of the object being cooled and the quantity of foreign gas in the sample yielded the film-cooling effectiveness at that location. Recent research using a heat-mass transfer analogy has been performed by Ammari et al^{1.3,1.4}. The experimental technique involved measuring the recession of a swollen polymer surface, using laser holography, before and after being subjected to a film-cooled flow field. The injectant was a foreign gas at a higher temperature than the freestream. The work showed that density ratio (coolant to freestream) had little effect on the normalized heat transfer coefficient for a single row of holes at 90° to the surface of the wall, see fig.1.3. However, for the more engine relevant case of a row of 35° holes a significant effect on heat transfer due to density ratio was found, see fig.1.4. Differences of 10%-20% in normalized heat transfer occurred with a change of density ratio from 1.0 to 1.52; the higher heat transfer occurring at lower densities. The effect of density ratio was most pronounced at the highest blowing rate of 2.0, where the difference in heat transfer rate for the two density ratios is 20%.

An alternative to the use of adiabatic wall effectiveness is the use of superposition theory as proposed by Metzger et al^{1.5} and formalised by Choe et al^{1.6}. Superposition theory allows the correlation of cooled to uncooled heat transfer via a simple linear model involving a non-dimensional temperature difference ratio, theta (θ). θ is defined as

$$\theta = (T_g - T_i) / (T_g - T_w) \quad (1.3)$$

where T_i is the injectant temperature

T_w is the wall temperature

T_g is the freestream gas temperature

and is used in superposition theory thus,

$$Nu/Nu_{o,cp} = (Nu/Nu_o)(T_w/T_g)^n = A + B\theta \quad (1.4)$$

where Nu is Nusselt number with film-cooling

Nu_o is Nusselt number without film-cooling

$Nu_{o,cp}$ is Nusselt number without film-cooling
in a constant property freestream

The derivation of equation 1.4 is detailed in section 3.1. The use of superposition theory is now widespread and it enables true heat transfer experiments to be correlated without having to rely on a mass transfer analogy.

Crawford et al^{1.7,1.8} performed some full-coverage film-cooling experiments and adopted the superposition approach. The work examined the effect of blowing rate and upstream initial conditions on the surface heat flux. It was found that there was a minimum in Stanton number (St) which occurred at a blowing rate of 0.4 to 0.5, see fig.1.5. The rise in St above $G=0.5$ was attributed to a region of disturbed flow with high heat transfer coefficient behind the jets. The upstream initial conditions were altered by varying the Reynolds number (based on enthalpy thickness and momentum thickness). It was found that varying Reynolds number only had a second order

effect on the surface heat flux. Three injection geometries were used in their experiments; normal injection, 30° injection and compound angle injection (30° to the surface, 45° to the direction of flow). The 30° injection configuration produced a lower heat flux distribution than normal injection, and the compound angle injection produced lower St values than the 30° injection. These results can also be seen in fig.1.5.

Forth, Loftus and Jones^{1.9} investigated the effect of density ratio on the film-cooling of a flat plate with a single row of 35° holes employing true heat transfer experiments and data analysis using the superposition model. Fig.1.6 shows their experimental data in the form of non-dimensionalised heat transfer against θ at a blowing rate of 0.76 and at four injection-to-freestream temperature ratios. It can be seen that the data validates the superposition model. It can also be seen that the level of cooling is increased as the injection-to-freestream temperature ratio is reduced, i.e. the denser the injectant relative to the freestream gas, the greater the tendency for the coolant to remain close to the wall, thereby providing greater cooling. Fig.1.7 shows the variation of heat transfer (at $\theta=1.3$) with blowing rate and injection-to-freestream temperature ratio at a position of 8 hole diameters away from the point of injection. This figure shows that there is a minimum in heat transfer for a given temperature ratio and that as the injectant-to-freestream density ratio is increased (decreasing injection-to-freestream temperature ratio) the blowing rate at which this minimum heat transfer occurs is also increased.

Loftus and Jones^{1.10} also examined the effects of freestream gas-to-wall temperature ratio on heat transfer with coolant injection and showed that the superposition model was valid for variations of such temperature ratios. Figures 1.8 and 1.9 show this linearity of heat transfer with gas-to-wall temperature at two blowing rates and two injection temperatures.

Further work at Oxford University by Forth and Jones^{1.11} investigated possible parameters for scaling film-cooled data. Their experiments employed three cooling geometries; a 30° slot, a double row of 30° holes and a single row of 30° holes. They identified two injection regimes; a weak injection regime and a strong injection regime, and were able to correlate their data depending on the regime to which it was applicable. The weak injection regime is characterised by low rates of injection where the injected flow emerges attached to the wall due to the coolant being turned in the direction of the mainstream flow whilst within the injection hole. The strong injection regime is characterised by higher injection rates where the coolant no longer remains attached to the wall and is said to "lift off". The slot injection and double row injection data were both characterised by weak injection since there was no gross separation of the coolant from the wall. These heat transfer data permitted a correlation against the parameter $x/S(I)^{-2/3}$ which is based on the momentum flux ratio, I , which is defined as,

$$I = \rho_i u_i^2 / \rho_g u_g^2 \quad (1.5)$$

The correlation of the slot and double row data are shown in figs.1.10 and 1.11 respectively. The single row data exhibited both injection regimes. At blowing rates less than that at which a minimum in heat transfer can be found, fig.1.7, the flow was in the weak injection regime; at higher injection rates the flow was in the strong injection regime. The data in this strong injection regime was found to scale well with the parameter $(x/d)(u_i/u_g)^{-4/3}$ which is based on the velocity ratio (u_i/u_g) . The correlation of the single row data in the strong injection regime is shown in fig.1.12.

The secondary flow in a turbine blade passage is complex and highly three-dimensional (3D) and our current understanding has been summarised by Sieverding^{1.12}. The flow features of importance in considering endwall heat transfer include the passage secondary flow,

fig.1.13, and the horseshoe vortex, fig.1.14, which separates into two, fig.1.14. The suction side component remains close to the suction surface corner, and is sometimes called the corner vortex, while the pressure side component moves across the passage under the influence of the passage secondary flow. The passage vortex arises due to the turning of the flow in the blade passage and has the effect of sweeping flow along the passage and from the pressure surface to the suction surface at both the endwalls. The horseshoe vortex occurs as a consequence of the rolling up of the endwall boundary layer at the blade leading edge. The vortex then wraps itself around the leading edge and forms two arms. The arm on the pressure side of the blade gets driven across the passage due to the blade-to-blade pressure gradient whilst the arm on the suction side of the blade follows the suction surface forming the corner vortex. Naturally, these secondary flow effects will affect the film-cooling process and heat transfer distribution.

Endwall heat transfer in the absence of film-cooling has been studied by many investigators in two-dimensional (2D) linear cascades. York et al^{1.13} employed a combustor and convergent nozzle in order to simulate the thermodynamic conditions in a nozzle guide vane. They found that whilst the endwall static pressure distribution was that to be expected from a strictly 2D analysis, fig.1.15, and therefore suggestive of no strong endwall interaction, the pattern of heat transfer on the endwall was highly 3D. Fig.1.16 shows contours of the endwall adiabatic temperature and gives evidence of one of the 3D effects in the form of the horseshoe vortex as indicated by the curvature of the isotherms around the suction surface leading edge and by the penetration of the isotherms into the passage entrance region.

Harasgama^{1.14} investigated the aerodynamic and heat transfer characteristics of an NGV using an isentropic light piston cascade (ILPC). His work showed an area of high heat transfer on the NGV casing close to the pressure side trailing edge, fig.1.17. He attributed this "hot spot" to the generation of a new boundary layer subsequent to the passage of the horseshoe vortex. However, high heat transfer at the leading edge of the vane, which is usually

associated with the horseshoe vortex, was not present. It was suggested that the absence of the high heat transfer at the leading edge could be caused by the radial pressure gradient driving the horseshoe vortex off the surface of the outer endwall.

Blair^{1.15}, in some early work employing slot film-cooling of a 2D vane endwall showed that secondary flow on the endwall moving from the pressure surface corner toward the suction surface sweeps the slot coolant across the channel. This has the effect that the cooling is reduced in the vicinity of the pressure surface corner region but enhanced on the endwall adjacent to the suction surface. Fig.1.18 shows the film-cooling effectiveness contours for a blowing rate of 0.75 and shows the area of reduced cooling. However, slot cooling is not used in current engine configurations due to stress problems. More recently, Bourguignon^{1.16} studied the distribution of film-cooling effectiveness on the platforms of 2D linear cascades. However, little in the way of quantitative data were published.

It can be seen that research performed to-date on film-cooling has shown the main parameters to be θ , G , ρ_i/ρ_g ; θ permits correlation of true heat transfer results via superposition theory and cooling is increased with increasing θ ; there is an optimum value of G which gives the best cooling for a given ρ_i/ρ_g ; and cooling is increased with increasing ρ_i/ρ_g .

1.3 Objectives of this Research

The aim of this research is to extend the understanding of film-cooling on a NGV platform in the presence of the highly 3D flows characteristic of turbine blades and provide quantitative data on which future designs may be based. This is an important area of heat transfer research due to the problem of platform burning which can occur in actual engines, fig.1.19. Current knowledge of film-cooling is mainly limited to 2D flat plate studies with some investigation of film-cooling in 2D linear cascades. As such, the design of turbine

film-cooling configurations is based on flat plate correlations. It is thought, however, that the film-cooling process is significantly affected by the blade-to-blade pressure gradient, the passage vortex, and the horseshoe vortex within a turbine NGV. Thus, a research programme was initiated in order to obtain qualitative and quantitative data on the film-cooling process in a realistic NGV environment by conducting film-cooling experiments on a fully annular NGV ring. This thesis discusses the experiments and the conclusions of the work; the first film-cooling research on a fully annular endwall.

2. EXPERIMENTAL FACILITY

This section describes the experimental facility and how the film-cooling process is simulated. It also describes the measurement and analysis of the heat transfer data.

2.1 The Isentropic Light Piston Cascade

The ILPC is a short-duration piston tunnel capable of simulating the aerodynamic conditions and heat transfer of a modern HP turbine nozzle guide vane^{2.1}. Test conditions are steady for approximately 0.5 to 1.0 second during which time pressure and heat transfer measurements are taken. Figure 2.1 is a schematic representation of the ILPC. The principle of operation of the ILPC is now described with reference to this diagram.

Air from the HP reservoir is used to drive a light weight piston along the pump tube. This compresses the test gas ahead of it isentropically raising its temperature from T_1 to T_2 thus:-

$$T_2/T_1 = (P_2/P_1)^{\frac{\gamma-1}{\gamma}} \quad (2.1)$$

When the test gas has been compressed to the desired pressure (P_2) a fast-acting plug valve is opened to allow the test gas to flow through the working section and into the dump tank, a vessel of very large volume previously evacuated to a suitably low pressure. The conditions in the working section remain constant whilst the flow through the plug valve aperture is choked; anything up to one second. During this time heat transfer and aerodynamic measurements are recorded. Fig. 2.2 shows the idealised pressure-time history for a test.

It has been shown by Sucec^{2.2} that it is acceptable to model the turbine component temperature ratio in such experiments rather than having to achieve actual temperatures. This is because it is sufficient to reproduce the thermal boundary layer situation since the heat transfer coefficient is proportional to the temperature gradient and not to absolute temperature levels. So, it is possible to simulate a turbine with TET of 1500K and blade temperature of 1000K in the ILPC by a 4:1 compression of the test gas within the

piston tube. Assuming an initial ambient temperature of 288K this implies a modest test gas temperature of 430K. Simulation of the blade Reynolds number and Mach number may be accurately and independently achieved by pre-setting the pressures in the piston tube and dump tank: the final pressure of the test gas (P_2) determines the Reynolds number and the ratio of this pressure (P_2) to that of the dump tank determines the Mach number.

2.2 Simulation of Film-Cooling in the ILPC

Previous authors, as discussed in section 1.2, have shown that coolant-to-gas density ratio has a significant effect on the film-cooling process. Other parameters of importance are the blowing rate and momentum flux ratio of coolant to gas. These latter two parameters are relatively simple to simulate because they merely pertain to the mass flow and velocity of the coolant and the freestream gas.

For the present engine configuration it was required to simulate a coolant to gas density ratio of 2.0. Consequently, the injectant gas must be air at an extremely low temperature in order to achieve the correct density ratio, or the injectant must be a denser foreign gas at a modestly low temperature. Since condensation and freezing problems were envisaged with injection of air at the necessarily low temperature it was decided to use a denser foreign gas to achieve the correct injection to freestream density ratio. The validity of using a foreign gas in these film-cooling experiments was confirmed in research by Teekaram et al^{2,3}. This paper showed that the use of carbon dioxide (CO_2) as a foreign gas injectant had a negligible effect on the thermofluid behaviour of the film-cooling process providing that the other relevant non-dimensional parameters are correctly matched. Figure 2.3 shows the similarity in thermofluid behaviour between air and CO_2 for various density ratios, values of θ , and non-dimensional distance from the point of injection.

The vane under examination in the present film-cooling experiments is representative of current designs of military engines operating with a mid-passage freestream gas-to-wall temperature ratio

of 1.5 and injection gas to freestream gas density ratio of 2.2. Typical freestream gas-to-wall temperatures of military blades lie in the range 1.3 - 1.8 and injection gas to freestream gas density ratios are in the range 1.6 - 2.2. The non-uniformity of the radial temperature profile at exit from the combustor, however, means that the temperature ratios are reduced at the inner and outer endwalls which are the areas of interest in these experiments. The ratio of freestream gas-to-wall temperature for the endwall of this blade is reduced to 1.3 and the injection gas to freestream gas density ratio is reduced to approximately 2.0. Since there is no means of varying the wall temperature from ambient in the ILPC the freestream temperature and injection temperature become fixed, thus:-

$$\begin{aligned}T_w &= 288K \\T_g &= 1.3 T_w = 373K \\T_i &= 0.5 T_g = 188K \quad (\text{with air as coolant})\end{aligned}$$

where subscript w refers to the wall

g refers to the freestream gas

i refers to the injectant

Since such a low injection gas temperature can only be achieved using expensive cryogenic techniques, it is necessary to use air/CO₂ mixtures at modestly low temperatures in order to model correctly the density ratio. Using the value of injection to freestream density ratio of 2.0 for the blade endwall this provides the ratio of air and CO₂ for injection as follows:-

$$(P_g \rho_i) / (P_i \rho_g) = (M_g T_g) / (M_i T_i) \quad (2.2)$$

Now, $P_g \approx P_i$ for injection at low blowing rates, and gas properties, injection temperature, and density ratio, are known thus,

$$M_i = \text{Constant} \quad (2.3)$$

Equation 2.3 may be expressed using a chemical composition equation based on mole fraction (m),

$$m M_{\text{co2}} + (1 - m) M_{\text{air}} = M_i \quad (2.4)$$

$$\begin{aligned} \text{where } M_{\text{co2}} &= 44 \text{ kg/kmol} \\ M_{\text{air}} &= 29 \text{ kg/kmol} \end{aligned}$$

The Gibbs-Dalton law relating partial pressures to mole fraction can be applied,

$$P_x/P_i = n_x/n_i = m \quad (2.5)$$

where subscript x refers to a constituent of the injectant.

Thus, it can be seen that (m) will represent the proportion of CO_2 by pressure in the injectant mixture; air making up the difference.

2.3 Heat Transfer Measurement

The measurement of heat transfer data in the ILPC is achieved using thin film platinum resistance thermometers and an electrical analogue of the heat conduction process as pioneered by Schultz and Jones^{2,4}. The blade is manufactured from a low thermal conductivity machinable glass ceramic, and, for the short duration of the flow, this allows the blade to be considered as semi-infinite and the heat transfer as one-dimensional. Thus, the heat transfer to the blade is governed by the following equations,

$$\partial \dot{q} / \partial x = -\rho C \partial T / \partial t \quad (2.6)$$

$$\dot{q} = -k \partial T / \partial x \quad (2.7)$$

which gives the diffusion equation,

$$\partial^2 T / \partial x^2 = (\rho C / k) \partial T / \partial t = (1/\alpha) \partial T / \partial t \quad (2.8)$$

These may be solved for the heat transfer rate q at the surface of a semi-infinite medium in terms of the surface temperature to give,

$$\bar{q} = (\rho C k)^{\frac{1}{2}} f^{\frac{1}{2}} \bar{T} \quad (2.9)$$

where the symbols with overbars are Laplace transformed variables and f is the Laplace transform variable.

For the semi-infinite electrical analogue the equivalent equations to 2.6-2.9 are

$$\partial i / \partial x = -c \partial V / \partial t \quad (2.10)$$

$$i = -(1/r) \partial V / \partial x \quad (2.11)$$

$$\partial^2 V / \partial x^2 = rc \partial V / \partial t \quad (2.12)$$

$$\bar{i} = (c/r)^{\frac{1}{2}} f^{\frac{1}{2}} \bar{V} \quad (2.13)$$

Thus, it can be seen that current (i) is analogous to heat transfer rate (q) and voltage (V) to temperature (T), thereby allowing the direct measurement of heat transfer rate as a function of time^{2.5*}. While it is possible to compute heat transfer rate from a digitally recorded temperature signal, it has been shown that the quantization error when digitising the film voltage waveform gives rise to spurious noise on the reconstructed heat transfer rate signal hence the use of an electrical analogue. In order to compute heat transfer rate it is essential that the blade is initially isothermal so that the change in temperature of each heat transfer gauge is known.

* The flow of gas over each thin film gauge changes the electrical properties of the gauge; the current being proportional to the heat transfer rate, as shown. Therefore, the current demanded by each thin film gauge is measured giving a reading which is proportional to the heat transfer rate at the gauge location.

3. THEORY

This section describes the superposition theory, the correction of data for constant properties, the injection parameters used, and how the ILPC data are scaled.

3.1 Superposition Theory

A review of the superposition model^{1.5,1.6,3.1} is now given.

The enthalpy equation for a two-dimensional boundary layer may be written as

$$\bar{u}\partial\bar{T}/\partial x + \bar{v}\partial\bar{T}/\partial y = \partial/\partial y(\alpha\partial\bar{T}/\partial y - \overline{T'v'}) \quad (3.1)$$

where overbars represent time-averaged values and ' represents instantaneous values.

The eddy viscosity/diffusivity concept is,

$$\overline{T'v'} = \epsilon_T \partial\bar{T}/\partial y \quad (3.2)$$

and can be combined with the enthalpy equation to give,

$$\bar{u}\partial\bar{T}/\partial x + \bar{v}\partial\bar{T}/\partial y = \partial/\partial y ((\alpha + \epsilon_T)\partial\bar{T}/\partial y) \quad (3.3)$$

Equation 3.3 is a homogeneous, linear, second order partial differential equation (PDE) in $\bar{T}$ and as such a solution to it may be formed by summing other solutions, ie superposition may be used. One may pose a solution to equation 3.3 in the **case of injection with zero temperature difference between injectant and mainstream and**

a further one with film-cooling; the final solution will be a linear combination of the two independent solutions. A typical experimentally derived solution would be,

$$\dot{q} = h_a(T_g - T_w) + h_b(T_g - T_i) \quad (3.4)$$

where $\dot{q}$ = heat transfer rate
 T_w = wall temperature

and h_a is the heat transfer coefficient when $T_i = T_g$ and there is unit difference between these and the wall temperature; whilst h_b is the heat transfer coefficient when $T_w = T_g$ and there is unit difference between these and the injection temperature.

Reworking 3.4 to give Nusselt number Nu yields,

$$Nu = \dot{q} / (K_g(T_g - T_w)) = A' + B'(T_g - T_i) / (T_g - T_w) = A' + B\theta \quad (3.5)$$

where K_g = mainstream gas conductivity

A' and B' are constants for given fluids and cooling geometry.

Jones et al^{1,9,2.3} have shown that if the coolant-to-gas density ratio is fixed, then the superposition model of equation 3.5 is valid for both air and CO₂.

Thus, by experimentally measuring values of Nu for given values of θ the correlating parameters A' and B' of equation 3.5 may be determined. This is the analytical basis of the present research.

3.2 Constant Property Correction

The values of A' and B' in equation 3.5 are determined by holding the freestream and coolant conditions constant and varying θ by altering the wall temperature. In doing so the gas-to-wall temperature ratio is changed, which also has an effect on the Nusselt number because of property variations through the compressible thermal boundary layer. The effect of property variations due to changes in T_g/T_w have been quantified^{3,3,3.4} and can be represented by,

$$Nu_o / Nu_{o,cp} = (T_w/T_g)^n \quad (3.6)$$

where Nu_o = Nusselt number without film-cooling
 $Nu_{o,cp}$ = Nu_o in a constant property freestream
 n = -0.07 for a laminar boundary layer
 n = -0.25 for a turbulent boundary layer

It is therefore possible to simulate the engine density ratio and correct any property variations using,

$$Nu/Nu_{o,cp} = Nu/Nu_o (T_w/T_g)^n = A + B\theta \quad (3.7)$$

and this equation is used as a correction to equation to 3.5. The ratio of film-cooled heat transfer to uncooled heat transfer also serves as a measure of cooling effectiveness.

3.3 Injection Parameters

The main parameters and equations that describe the film-cooling process have already been introduced in section 1.2. However, for completeness the various parameters and equations are now defined in one section.

Temperature difference ratio, $\theta = (T_g - T_i) / (T_g - T_w)$ (3.8)

Blowing rate, $G = (\rho_i u_i) / (\rho_g u_g)$ (3.9)

Momentum flux ratio, $I = (\rho_i u_i^2) / (\rho_g u_g^2)$ (3.10)

Density ratio, $D = \rho_i / \rho_g$ (3.11)

Weak injection parameter, $WIP = (P_{ti} - P_g) / (P_{tg} - P_g)$ (3.12)

Strong injection parameter,

$$SIP = ((P_{ti} - P_g) / (P_{tg} - P_g)) / ((P_{ti} T_{tg}) / (P_{tg} T_{ti})) \quad (3.13)$$

Adiabatic wall effectiveness, $\eta = (T_{aw} - T_g) / (T_i - T_g)$ (3.14)

For low Mach number flows Jones et al^{1.10, 1.11} have shown that $\eta = -B/A$ where $-B/A$ is evaluated from equation 3.7.

4. FILM-COOLING DESIGN

The design of the endwall film-cooling geometry was based on the current practice in 2D blade film-cooling configurations. An attempt was made to develop a technique for obtaining full coverage cooling in the 3D flow within the NGV passage based on maintaining uniform cooling in the blade-to-blade plane by placing cooling holes **along** an iso-Mach line.

Endwall film-cooling is used on many current engines to prolong the life of the NGVs. It is thought to be advantageous to maintain a constant blowing rate and momentum flux ratio through the film-cooling holes across the entire passage in order to obtain uniform cooling. However, current designs tend to place the cooling holes in a straight line (constant axial plane) across the passage, fig 4.1. This is due to the absence of any 3-dimensional design methods for the positioning of cooling holes. Since the static pressure distribution across the passage varies from the vane suction to pressure side, such a design practice results in non-uniform blowing rates which can lead to jet lift-off and ineffective cooling.

The present cooling hole distribution was designed^{4.1} such that all holes would be placed along a line of constant static pressure. This would generate a constant momentum flux ratio which, for any given density ratio, will result in a constant blowing rate across the platform. A three-dimensional inviscid flow code was used to compute the pressure distribution within the NGV passage and the cooling holes were placed along a predicted iso-Mach (constant static pressure) line. This three-dimensional code has been used before to calculate endwall Mach numbers and comparisons with experiment show it to be very accurate in predicting the NGV aerodynamics^{1.14}. The outer platform Mach number distribution is shown in fig 4.2. Circular sectioned film-cooling holes were placed along the 0.25 iso-Mach number line. Fig 4.3 shows the film-cooled outer endwall as manufactured. The holes are inclined at 30° to the local surface profile and aligned such that the jet exit lies on an

axis normal to the local iso-Mach Line. The present cooling design philosophy was intended to result in improved cooling across the entire passage compared with a straight line of cooling holes. However, it was expected that the viscous nature of the flow giving rise to secondary flows within the passage would modify the cooling distribution.

The cooling hole diameters were sized in order that cooling would be achieved along the length of the NGV passage. The correlation^{1.11} shown on fig 4.4 indicates the variation of normalised cooled to uncooled Nusselt number with distance downstream of the cooling holes. The coolant to gas density ratio for the NGV is 2.0. Using this density ratio and a modest blowing rate of 0.5 shows that the coolant effectiveness will persist^{*} for approximately 20 coolant hole diameters downstream of the injection plane when the coolant hole diameter is fixed at 1.0 mm. The outer platform geometry enabled 19 film-cooling holes to be placed across it which gave a distance between hole centres of 1.75 mm.

This cooling design was incorporated into an existing military NGV typical of current highly loaded designs. The vane was designed to operate at an exit Mach number of 0.93 and Reynolds number based on chord of 2.55×10^6 .

* at a value of $Nu/Nu_0 = 1.0$ i.e. the limit of cooling benefits.

5. INJECTION SYSTEM

Film-cooling was performed on the outer endwalls of a pair of vanes and the injection mass flow was determined using pre-calibrated orifice meters. The temperature of the injected gas was achieved using either an electric heater for 'hot' runs ($\theta < 1$) or a cold air heat exchanger for 'cold' runs ($\theta > 1$). The system is now discussed in more detail.

5.1 Calibration of Injection Orifices

In order to determine the injection mass flow it was necessary to calibrate four orifices of different diameters (1.0, 1.5, 2.0, 2.5 mm). This provided orifices suitable for measuring the injection mass flow over the range of proposed blowing rates (BS orifice plates were too large to use in the injection system). The calibration system is shown schematically in fig 5.1 and comprised a reservoir connected via a 26 mm diameter pipe to the calibration section containing the injection orifice and from there to a British Standard (BS1042) orifice plate which was used as the reference flowmeter. The measurements made were reservoir pressure, static temperature immediately upstream of the BS orifice plate, static pressure drop across the BS orifice plate, static pressure downstream of the BS orifice plate near to the exit to atmosphere and ambient pressure. Using these measurements and by calibrating each of the orifices firstly with air and then with carbon dioxide over a range of reservoir pressures it was possible to arrive at the calibration constants described in the Appendix. Table 5.1 gives a tabulation of the calibration constants for air and CO₂ for each of the injection orifices and figs 5.2 and 5.3 show the calibration curves for the two gases.

5.2 HP and LP System

The injection system is shown in fig 5.4. Two chambers are used to contain the gas mixture to be injected; a low pressure (LP) chamber connected to a small reservoir and a high pressure (HP) chamber connected to a large driver reservoir. The LP chamber is used as a preliminary purge of the plenum feeding the film-cooling holes so that

gas at the required temperature and composition is introduced in readiness for the constant blowing rate injection when the short duration run takes place. It is important not to change the temperature of the endwall before the run commences since this would upset the initial isothermal condition hence the purging gas is kept at low pressure. The HP chamber contains the gas that performs the cooling of the endwalls and this gas is released immediately prior to the introduction of freestream air through the blade working section.

A driver reservoir ensures that the flow from the HP chamber is maintained at a constant blowing rate. Both chambers are enclosed with an insulated jacket through which hot or cold air is blown to heat or cool the gases to be injected.

The release of the coolant gas from the two chambers is controlled using two fast-acting shutter valves. Initially they are in a position such that both chambers are sealed. The LP shutter is fired first, approximately 50 ms before the run starts allowing LP gas to purge the system. This is followed by the firing of the HP shutter which closes off the LP chamber and opens the HP chamber releasing the test coolant simultaneously with the establishment of mainstream flow.

A system of valves controls the supply of air and carbon dioxide to both chambers. There is also a vacuum line connected to the injection system which is used to evacuate both chambers prior to filling with the required composition of test gas (CO_2 and air mixture).

5.3 Injection Gas Heating and Cooling

In order to achieve values of θ other than unity it is necessary to either heat the test gas ($\theta < 1$) or cool the test gas ($\theta > 1$). In both cases heat was supplied to or removed from the test gas using air as the heat source or sink. In the case of heating the test gas the air was preheated using two electrical heaters with a rheostat control. For cooling, the air was passed through a helical copper heat exchanger immersed in liquid nitrogen contained in an insulated vessel. The two arrangements are shown in figs 5.5 and 5.6.

5.4 Bladed Cassette for Injection

The blade ring was manufactured with the facility to take cassettes of four blades which could be withdrawn from the main blade annulus. Two separate cassettes were prepared for the film-cooling experiments. One of these cassettes contained blades manufactured from a low thermal conductivity machineable glass ceramic (Macor)* and was used to provide heat transfer data. The second cassette contained blades manufactured from an aluminium alloy and was used to obtain aerodynamic data.

In each cassette, the two centre endwalls were configured for film-cooling each with one line of 19 cooling holes along a predicted isomach line of 0.25. The holes were of 1.0 mm diameter and pitched at 1.75 mm intervals, and were drilled at an angle of 30° to the surface and normal to the isomach line. Fig 4.3 shows the layout of a cassette with film-cooling holes.

5.5 Measurements

The two endwalls of the Macor (heat transfer) cassette were instrumented with thin film platinum resistance gauges to determine the heat transfer distribution. 32 thin film gauges were arranged on the first endwall and 36 on the second endwall such that the superposition of the two sets of gauges produced a single set of interspaced gauges. However, the presence of the plenum feeding the holes prevented thin film gauges being situated any closer than approximately 8 mm to the cooling holes. This was for two reasons: the plenum had to be as close to the holes as possible to prevent a significant change in temperature of the injectant in passing from the plenum to the cooling holes, and, holes were required to be drilled in the back of the vane to accomodate the leads from the thin film gauges. The arrangement of the two sets of gauges, superimposed, is shown in fig 5.7.

*Macor - trademark of Corning Glass, Corning, USA.

The aluminium cassette was instrumented with static pressure tapings on both of its film-cooled endwalls. The positions of the tapings were chosen to coincide with those of the thin film gauges to give an identical distribution of instrumentation.

The temperature of the coolant gas was measured during a run by four thermocouples; two in each of the plenums feeding the cooling tiles. A pressure tapping in each of the two plenums was used to record the plenum injection gas pressure.

The LP and HP injection chambers were instrumented with three thermocouples each to determine the temperature of the coolant gas prior to injection. Another thermocouple was situated downstream of the LP and HP shutters.

The composition (partial pressures) and pressure in the two chambers was determined using a Wallace and Tiernan 15 bar absolute pressure gauge, with an accuracy of 0.07% over the measurement range.

6. TEST PROGRAMME

The experiments were performed at a nominal design exit Mach number and Reynolds number for the blade ring of 0.93 and 2.55×10^6 respectively. The freestream gas-to-wall temperature ratio was nominally set to 1.30 and the injection-to-freestream density ratio was set to 1.80.

For the heat transfer cassette an investigation was performed at five blowing rates: 0.21, 0.37, 0.52, 0.83, 1.11.

The complete tabulation of runs is given in table 6.1 together with the main calculated parameters.

At a blowing rate of 0.21 three values of θ were explored: 0.87, 1.22, 1.44. For each of these values of θ two runs were required in order to obtain data from both sets of heat transfer gauges. Table 6.1 shows how the runs were paired to produce a full coverage of heat transfer data. In addition, each condition was repeated, to provide further confidence in the data, making a total of four runs per θ value. The highest θ of 1.44 was a limiting value imposed by severe icing problems in the coolant injection mechanism. This was due to the low mass flow of the coolant, at this low blowing rate, requiring a colder pre-injection temperature in order to compensate for heat gain in its path from the HP and LP chambers to the injection plenums.

The same values of θ were tested for a blowing rate of 0.37 as were tested for $G = 0.21$ although no repeats were performed. Again, a limit of θ of 1.44 was imposed due to icing difficulties.

For $G = 0.52$ four values of θ were tested: 0.87, 1.22, 1.44, 1.62. A full set of repeat runs were also performed for all θ .

At a blowing rate of 0.83 the same four values of θ were explored as for $G = 0.52$. Repeats were performed for all values of θ apart from $\theta = 1.22$.

For $G = 1.11$ the same four values of θ were examined as for $G = 0.52$. Repeats were performed for all values of θ apart from $\theta = 1.22$.

On completion of these experiments the film-cooling holes in the heat transfer cassette were filled with super-epoxy resin and uncooled tests were performed to establish a heat transfer datum. It was subsequently found, though, that a hole on each platform was partially unblocked thereby allowing a small amount of air to flow from the gas stream into the injection plenum during the datum tests. However, in comparing these uncooled results with previous uncooled data it could be seen that the effect of the leaks on the heat transfer distribution was minimal.

Finally, the aluminium cassette was installed in order to provide data on the static pressure distribution on the endwall under the influence of film cooling. Two runs at each of the blowing rates of 0.52, 0.83 and 1.11 were performed. θ was maintained at 1.0 for all blowing rates.

A tabulation of the tests performed is given in table 6.1.

7. EXPERIMENTAL RESULTS

The results presented in this section are principally values of θ and Nusselt number measured over the initial part of each of the run time histories. The wall thermal boundary condition is slightly non-isothermal in practice. The mean wall temperature was found to be 302K with a maximum excursion of $\pm 3.5\%$. The inlet turbulence level, generated by an upstream bar grid, was found to be around 6.5%, as measured with a hot-wire anemometer^{7.1}. Uncertainties in the various measurements can be quantified as $\pm 7\%$ in Nu on a 95% confidence level and $\pm 0.5\%$ in pressure readings. . **A tabulation**

of calculated parameters can be found in Table 6.1.

7.1 Film cooling plenum traces

Fig 7.1 shows a typical plenum injection pressure versus time plot for the film-cooling experiments, the particular values of θ and G for this case being 0.87 and 0.83 respectively. The opening of the LP chamber at $t = 30$ ms is clearly seen by the initial pressure rise. As the LP gas purges the system so the pressure falls to a level where the mass flows into and out of the plenum are matched. It is important to note that this level is above the pressure in the working section, indicating that injection and not ingestion is taking place. Approximately 50 ms after the LP gas has been introduced, the HP shutter fires allowing HP test gas to initiate the film-cooling process. This occurs marginally before the tunnel air flows into the working section. For the blowing rates of 0.37 and 0.21 the pressure level in the plenum dropped to that of the working section prior to HP injection, see fig 7.2. It is likely, therefore, that a small amount of ingestion occurred before injection could take place. For this reason the results for the blowing rates of 0.37 and 0.21 are not treated as fully as the three higher blowing rates.

Fig 7.3 shows a typical plenum injection temperature versus time plot (for the case $\theta = 0.87$, $G = 1.11$). Initially, LP coolant gas only is flowing, followed by HP coolant gas at approximately $t=0.05$ seconds which causes the sudden peak in the trace by compression heating in the plenum. After the peak, the HP injection conditions remain steady for approximately 400 ms of the run before starting to decay as the gas in the HP reservoir is depleted. Within each plenum there is a difference between the two thermocouple readings of approximately 10°C . This temperature variation within the plenum is caused by heat transfer taking place between the injectant and the plenum walls. In the data analysis an average of all four thermocouples is used to evaluate the film coolant properties.

7.2 Interpolation of experimental data

Contouring of the measured data enabled information to be obtained at any position of the endwall rather than just at the 68 thin-film gauge/pressure tapping locations. This was achieved by applying a bi-quadratic fit to the data and computing values at the nodes of a fine grid; the same grid used to compute the three-dimensional inviscid Mach number distribution, see fig 4.2. A comparison between the bi-quadratic fit and the raw data showed the acceptability of the interpolated contoured data, see fig 7.4, which shows the fit for 2 grid lines. The absence of thin films immediately upstream of the cooling holes, due to the presence of the plenum below the surface, meant there was a region on the endwall where no experimental data was available. It was found that if the contouring routine was applied to the actual data, the absence of information upstream of the cooling holes gave a false impression of lower heat transfer in this region. To compensate for this absence, it was assumed that the Nusselt number was constant along streamlines upstream of the cooling holes, and this enabled the contouring routine to give more realistic results in the region of coolant injection.

Results shown hereafter are interpolated data unless otherwise indicated.

7.3 Endwall Mach number distribution

Figs 7.5 and 7.6 compare the endwall Mach number distribution as predicted by a three-dimensional inviscid flow code with the Mach number distribution from uncooled experimental data^{7.1}. It can be seen that there is a slight tendency for the three-dimensional inviscid code to under-predict the flow velocity at a given location. However, at the place of film-cooling ($M=0.25$) this difference is minimal. Also, the Mach number contours for the experimental case exhibit a more dramatic change in direction towards the suction side. This may be due to extrapolation of the experimental data to the suction side where no data have been measured.

The sparsity of static pressure measurements in the region of film cooling can be seen in fig 5.7. This lack of data caused a distortion of the Mach number distribution for the cooled case when the data were interpolated. The data are, however, in reasonable agreement with the uncooled case and hand contouring of the Mach number distribution is shown in fig 7.7. Indeed, Bourguignon^{1.16} in her film-cooling study showed that the coolant had only a small influence on the Mach number distribution.

These results, in particular the agreement between the predicted and uncooled Mach number distributions, indicate that the film cooling holes must lie on or very close to the actual $M=0.25$ contour. Therefore, the original design criterion of uniform blowing rate across the platform has been achieved.

7.4 Endwall heat transfer distribution

In order to describe the results it is necessary to explain a few terms and definitions, as follows. Contouring grid lines in the direction of the potential flow are termed pseudo-streamlines and distances along a pseudo-streamline (s) are measured relative to the plane of film cooling. Streamline 1 is at the suction side of the endwall moving to streamline 19 which is at the pressure side.

Grid lines in the blade-to-blade direction parallel to the plane of film cooling are termed transverse gridlines and distances along these (s_2) are measured relative to the suction side. The tangential chord ($c_t = 70.1$ mm) and distance from suction side to pressure side at the leading edge ($c_2 = 49.9$ mm) are used as non-dimensionalising scaling parameters.

Fig 7.8 shows the variation of Nu with θ for a given blowing rate ($G=1.11$) and at a fixed location from the plane of film-cooling ($s/c_t=0.4$) for several pseudo-streamlines. This plot indicates that the extent of cooling is increased by increasing θ , as one would expect. However, this effect is somewhat diminished as the pressure side of the endwall is reached.

Fig 7.9 is the variation of Nu with G for $\theta=1.62$ and at a fixed location from the plane of film-cooling ($s/c_t=0.4$) along several pseudo-streamlines. This shows that cooling is increased as the blowing rate is increased for the range of blowing rates explored. It also shows similar results to fig 7.8 in that the level of Nu decreases as one moves from the pressure side to the suction side. Fig 7.10 is a plot of Nu against distance across the endwall at $s/c_t=0.4$ which shows this feature in more detail.

The streamwise variation of Nu on the endwall at the mid-passage location is shown in fig 7.11. It can be seen that Nu increases with increasing distance downstream of the cooling holes thus showing a reduction in the cooling capability of the coolant as it mixes with the mainstream flow. The greatest reduction in heat transfer is shown to be at the highest value of θ . For values of θ greater than 1.0 it is evident that there is a drop in Nusselt number at the point of coolant injection but for values of θ less than 1.0 (film-heating) the Nusselt number rises at the point of injection.

An overall picture of the film-cooling on the endwall can be seen from the colour contour plots shown in figs 7.12 to 7.17. It should be noted that the lack of data in the region of the film-cooling holes, see fig 5.7, means that the contours immediately upstream and downstream of the plane of film-cooling may not be fully

representative of the real flow situation. Fig 7.12 shows the datum uncooled case alongside the three values of θ investigated at $G=0.37$. This plot shows that there is little difference between the uncooled case and any of the film-cooled cases. This indicates that a combination of low blowing rate and partial ingestion have produced ineffective cooling. It is also clear that there is an area of high heat transfer ('hot spot') on the endwall at the pressure side trailing edge. Fig 7.13 shows the four values of θ explored at $G=0.52$. Here, there is a pronounced increase in cooling as θ is increased and even the $\theta=0.87$ case exhibits lower values of Nu than the uncooled case shown in fig 7.12. It is evident from fig 7.13 however that the 'hot-spot' region at the trailing edge is receiving little cooling flow. This is due to the secondary flow sweeping the cooling flow across the endwall from pressure side to suction side due to the blade-to-blade pressure gradient.

Fluorescing dye flow visualisations had previously been carried out on the uncooled platform, see fig 7.18, in order to indicate the nature of the secondary flow. A green dye was applied to the endwalls up to the plane of the blade leading edge and thereafter a red dye was used on both the endwalls and the blades. Fig 7.18 shows the outer endwall and indicates where the green dye has been swept into the red dye producing yellow streaking when illuminated under ultra-violet light. It is clear that there is a significant migration of the flow towards the suction side of the blade which subsequently reaches the vane mid-height at the trailing edge.

Figs 7.14 and 7.15 show all the values of θ investigated at the blowing rates of 0.83 and 1.11 respectively. These both show a similar picture as the $G=0.52$ case, see fig 7.13, in that cooling increases as θ is increased.

In comparing the three blowing rates at $\theta=1.62$ it can be seen that the level of cooling increases as blowing rate is increased, see fig.

7.16. In all cases, however, the 'hot-spot' region persists even for the high blowing rate case of $G=1.11$, $\theta=1.44$. Fig 7.17 shows this non-dimensionalised with the uncooled datum case. The level of Nusselt number is reduced by up to 80% immediately downstream of the film-cooling holes although at the pressure side trailing edge the reduction is only 25%. It is clear, therefore, that the level of cooling achieved is very significant. In terms of mean levels, this cooled to uncooled comparison indicates a reduction of 50% to 60% over the whole platform which will result in a significant reduction in metal temperature and consequently an improved life for the component.

8. ANALYSIS OF RESULTS

Harasgama and Burton^{4.1} concluded that the superposition model of film-cooling was the best way of scaling ILPC data to apply to engine representative conditions. This section discusses the application of the superposition model to the present film-cooling data and compares the experimental data with correlations in the absence of pressure gradients.

8.1 Application of the superposition model

A correction for property variations in the film-cooled boundary layer is applied to the data. This takes the form of correcting for gas-to-wall temperature ratio. It is shown (equation 3.7) that,

$$\text{Nu}/\text{Nu}_{\text{O,cp}} = \text{Nu}/\text{Nu}_{\text{O}} (T_w/T_g)^n.$$

where n is -0.07 for a laminar boundary layer and -0.25 for a turbulent boundary layer. The value for a turbulent boundary layer is used in this analysis.

Figs 8.1 to 8.3 show the application of superposition theory to the film-cooling data for several positions across the passage at different s/c's for three values of G . It can be seen that in all cases the data are well described by straight lines thus validating the use of superposition theory as an analysis tool for these data. Consequently, it is possible to extrapolate the experimental data to achieve a cooled to uncooled Nusselt number ratio at engine conditions. The nominal engine θ for the nozzle guide vane at the endwall region is 1.75.

Figs 8.4 to 8.6 show the film-cooling effectiveness $(-B/A)$ for various streamlines at different G 's. It is evident that in all cases there is a reduction in effectiveness in moving from the suction side to the pressure side. This is a consequence of the

secondary flow reducing the effectiveness at the pressure side by sweeping the cooling flow across the endwall platform to the suction side. It is also clear from figs 8.4 to 8.6 that there is a reduction in effectiveness along a pseudo-streamline, or in other words, the effectiveness decays as one moves along the passage away from the cooling holes. This is caused by the cooling jet mixing with the hot mainstream gas as it progresses downstream.

Fig 8.7 shows the cross-passage variation of the film-cooling effectiveness which again confirms the two observations made from the streamwise variation plots.

8.2 Empirical correlation of data

The data from the film-cooling experiments are compared with two-dimensional flat plate correlating parameters^{1.11}. For the weak injection regime film-cooling effectiveness $(-B/A)$ is correlated with a slot wall jet parameter $(x/d)(I)^{-2/3}$, and for the strong injection regime non-dimensionalised Nusselt number (at $\theta=1.3$) is correlated with slot wall jet parameter modified for strong blowing $(x/d)(u_i/u_g)^{-4/3}$. Figs 8.8 to 8.10 show film-cooling effectiveness against slot wall jet parameter $(x/d)(I)^{-2/3}$ for data at all positions on the endwall and at blowing rates of 0.52, 0.83 and 1.11 respectively.* As can be seen, for a given x-value the effectiveness is significantly below the correlating line. This is to be expected since the comparison is between experimental data from a row of holes and a correlation representing slot injection. However, apart from indicating the differences between the two types of injection, the results show the large increase in effectiveness between blowing rates of 0.52 and 0.83 and a smaller increase from 0.83 to 1.11.

The spread of data on these plots is attributed to the three-dimensional nature of the flow field where secondary flow, and axial and blade-to-blade pressure gradients will all have an effect. Fig 8.11 shows the case of $G=1.11$ with an empirical correction for streamwise pressure gradient of $(u/u_{inlet})^{0.2}$ as suggested by Eckert^{8.1}. This correction moves the data closer to the correlating line but does not help to reduce the spread. However, when a similar

* note that u_g is the local velocity at a particular wall location.

correction of $(u_{\text{blade-to-blade}}/u)^{0.2}$ is applied to the blade-to-blade pressure gradient on fig 8.12 the data start to collapse albeit with the exception of data near to the pressure side trailing edge of the blade. This area of the endwall, as previously discussed, does not receive very much cooling because the secondary flow sweeps the coolant away from this region. It is encouraging to note that making the streamwise and blade-to-blade pressure gradient corrections to the present data brings them reasonably close to the slot wall correlating parameter. In this manner it has been possible to account, to some extent, for the three-dimensional flow field in the present experiments. Such a procedure may then be applied to evaluate the cooling effectiveness in the preliminary design stages of a film-cooled NGV platform. The ability to correlate the present data with two-dimensional test cases is particularly important because a large amount of data for two-dimensional film-cooling geometries exists. The present correlating parameters may, therefore, be utilised on such two-dimensional data bases for the useful design of film-cooling configurations in a three-dimensional flow field.

The correlation technique is taken a stage further in figs 8.13 to 8.15 which show $(A + 1.3B)$ (ie Nu/Nu_0 at $\theta = 1.3$) against the slot wall jet parameter modified for strong blowing regime for blowing rates of 0.52, 0.83 and 1.11 respectively. In these cases the correlating line is for a single row of cooling holes and, therefore, allows a direct comparison with the experimental data. It is evident that the data are a lot closer to the single row correlation than the slot correlation presented earlier. The data at low x -values $((x/d)(u_i/u_0)^{-4/3} \leq 1)$, that move above the correlation, are data at injection rates beyond that giving a minimum in Nusselt number. The high blowing rate in these cases cause the cooling jets to lift off the surface.

In comparing the three blowing rates it can be seen that the data follow the trend of the correlation and move towards lower values of $Nu/Nu_{0,cp} = A + B\theta$ with increase in blowing rate as expected. Fig 8.16 shows the case of $G = 1.11$ with the same empirical correction to the data for streamwise pressure gradient as used in fig 8.11. This correction is successful in that it moves the data close to the

correlation with a maximum error of around $\pm 11\%$. It may, therefore, be concluded that by making the appropriate correction for streamwise pressure gradient the present data correlates with two-dimensional data even though the flow field is quite strongly three-dimensional. The present data were correlated along grid lines (pseudo-streamlines) following the geometric contours of the NGV endwall. It is also possible to apply these same techniques along an actual endwall streamwise path as indicated by the flow-visualisation tests, see fig 7.18, or by a computational technique which calculates the endwall streamline pattern. It is expected that by correlating along skewed streamlines more accurate results would be produced than correlating along grid lines following the geometric contours of the NGV endwall since the data would then have been analysed along true streamlines rather than assumed streamlines.

9. CONCLUSIONS

Endwall heat transfer measurements have been made on a turbine nozzle guide vane with and without film-cooling. The results allow the following conclusions to be drawn.

(1) The original design concept of placing film-cooling holes along an iso-Mach line has been shown to be an effective method of film-cooling an NGV platform except for some shortfall of cooling near the pressure side trailing edge due to secondary flow effects.

(2) The configuration tested, of holes along a constant static pressure line to give constant blowing rate, used 1.48% of the throat mass flow for the highest blowing rate ($G = 1.11$) and gave up to 75% reduction in heat transfer relative to the uncooled case, with a minimum reduction of heat transfer of 25% in the pressure side trailing edge corner.

(3) The use of carbon dioxide and air mixtures in simulating engine density ratios has proved successful.

(4) The superposition theory of film-cooling has been validated for endwall heat transfer and enables the present work to be extrapolated to other engine conditions operating at higher θ .

(5) Simple empirical correlation of the data have been reasonably successful. It is shown that by correcting for the axial pressure gradient it is possible to correlate the present data against two-dimensional flat plate zero pressure gradient data to within +11%.

It is considered that these correlations may be used in the preliminary design of film-cooled platforms in turbine NGV's.

10. RECOMMENDATIONS

Based upon the work to-date and the above-mentioned conclusions it is recommended that further work be done on improving the empirical correlation scheme. This would take the methodology further in applying it along the skewed streamline path on the endwall. Finally, it is clear that a calculation technique must be generated which gives reliable predictions of endwall streamlines if the correlation technique is to be progressed and this will require some computational effort.

APPENDIX

APPENDIX - Calibration of Injection Orifices

This appendix describes the theory used to analyse the orifice calibrations.

Each orifice (1.0, 1.5, 2.0 and 2.5 mm diameters) was calibrated separately with air and CO₂. The method of calibration is detailed in section 5.1 and a schematic diagram of the calibration arrangement is shown in Fig 5.1. Calibration curves for each combination of orifice and test gas are shown in Figs 5.2 and 5.3.

The theory to determine the mass flow through the British Standard orifice has been taken from BS 1042 and is given below.

$$P_1 = a - b + P_{amb} \quad (A.1)$$

$$\rho_1 = P_1 / RT_1 \quad (A.2)$$

$$\dot{m}_{uncorr} = C \times Z \times E \times EPS \times D^2 \times (\rho_1 a)^{\frac{1}{2}} \times \alpha \quad (A.3)$$

$$Re = 4\dot{m}_{uncorr} / D\mu \quad (A.4)$$

$$\dot{m} = \dot{m}_{uncorr} \times ZR \quad (A.5)$$

where a = pressure drop across BS orifice (Pa)

b = gauge pressure downstream of BS orifice (Pa)

P_{amb} = atmospheric pressure (Pa)

P₁ = pressure upstream of BS orifice (Pa)

T₁ = temperature of gas upstream of BS orifice (K)

R = characteristic gas constant (J/kgK)

ρ_1 = density of gas upstream of BS orifice (kg/m³)

C = discharge coefficient

Z = correction on C due to Reynolds number

E = velocity approach factor

EPS = expansibility factor

D = BS orifice diameter (m)

$\alpha = 3.4788 \times 10^{-6}$ (Imperial to SI conversion)

$\dot{m}_{uncorr}$ = mass flow through BS orifice (uncorrected) (kg/s)

μ = gas dynamic viscosity (Ns/m²)

Re = Reynolds number (based on D)
 D_{pipe} = pipe diameter (m)
 ZR = empirical correction to mass flow due to Re and D^2/D_{pipe}^2
 $\dot{m}$ = mass flow through BS orifice (corrected) (Kg/s)

The calibration yielded measured mass flow against cooling reservoir pressure in the form,

$$\dot{m} = A + B P_{res, gauge} \quad (A.6)$$

where A and B are constants of proportionality.

Hence,

$$\dot{m} = A + B P_{res, gauge} + B P_{amb} - B P_{amb} \quad (A.7)$$

giving,

$$\dot{m} = A + B P_{res, abs} - B P_{amb} \quad (A.8)$$

and correcting for injection gas temperature and incorporating $(R/\gamma)^{\frac{1}{2}}$ into the constants of proportionality gives,

$$\dot{m} T_i^{\frac{1}{2}} = A T_i^{\frac{1}{2}} + B T_i^{\frac{1}{2}} P_{res, abs} - B T_i^{\frac{1}{2}} P_{amb} \quad (A.9)$$

Let $A^* = A T_i^{\frac{1}{2}} - B T_i^{\frac{1}{2}} P_{amb}$
 and $B^* = B T_i^{\frac{1}{2}}$

Then the coolant mass flow at any driving pressure and temperature may be given as,

$$\dot{m} = (A^* + B^* P_{res, abs}) / T_i^{\frac{1}{2}} \quad (A.10)$$

Equation A.10 may now be used for both CO_2 and air independently, or for any combination thereof.

When using binary gas mixtures it will be necessary to modify the A^* and B^* values as follows.

An equation for air would be,

$$\dot{m}_a = (A_a^* + B_a^* P_{res,abs}) / T_i^{\frac{1}{2}} \quad (A.11)$$

and for CO_2 ,

$$\dot{m}_{CO_2} = (A_{CO_2}^* + B_{CO_2}^* P_{res,abs}) / T_i^{\frac{1}{2}} \quad (A.12)$$

Let the fraction of CO_2 used = x (say), then the amount of air would be $(1 - x) = y$ (say).

So total mass flow $\dot{m} = \dot{m}_a + \dot{m}_{CO_2}$

therefore,

$$\dot{m} = x(A_{CO_2}^* + B_{CO_2}^* P_{res,abs}) / T_i^{\frac{1}{2}} + y(A_a^* + B_a^* P_{res,abs}) / T_i^{\frac{1}{2}} \quad (A.13)$$

and rearranging gives,

$$\dot{m} = xA_{CO_2}^* / T_i^{\frac{1}{2}} + yA_a^* / T_i^{\frac{1}{2}} + P_{res,abs} (xB_{CO_2}^* / T_i^{\frac{1}{2}} + yB_a^* / T_i^{\frac{1}{2}}) \quad (A.14)$$

Therefore, when using a mixture of CO_2 and air the values of A^* and B^* may be modified to read,

$$A_{mix}^* = xA_{CO_2}^* + yA_a^* \quad (A.15)$$

$$B_{mix}^* = xB_{CO_2}^* + yB_a^* \quad (A.16)$$

Equations A.15 and A.16 may be substituted in equation A.10 to give,

$$\dot{m} = (A_{mix}^* + B_{mix}^* P_{res,abs}) / T_i^{\frac{1}{2}} \quad (A.17)$$

which is the injection mass flow for any combination of air and CO_2 at injection temperature T_i and reservoir pressure $P_{res,abs}$.

A tabulation of the raw data and derived A^* and B^* for both air and CO_2 for each orifice is given in table 5.1.

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ACKNOWLEDGEMENTS

This work was carried out at the Royal Aerospace Establishment at Pyestock and I am grateful for their permission to publish this thesis.

I would like to thank my colleague and industrial supervisor Dr. Prithi Harasgama of RAE (Pyestock) for providing me with the opportunity to do this research and for his considerable guidance and assistance in all aspects of the work.

I would also like to thank my academic supervisor Dr. Nick Baines of Imperial College for his valuable advice and suggestions.

Much of the foundation of this work was performed by Professor Terry Jones and the Thermofluids department of Oxford University and I am grateful for their contribution to this project. In particular, I would like to thank Mr. Trevor Godfrey for his technical skill in making the injection apparatus.

A big thank you also goes to Mrs. Joyce Vinnicombe for once again providing me with an excellently typed manuscript.

Lastly, but by no means least, I would like to thank my wife Jo for her unfailing support in my involvement in this work. It is to Jo that this thesis is dedicated.

TABLES

Table 5.1 Tabulation of Injection Orifice Calibrations

CALIBRATION OF ORIFICE NO.1, DIAMETER=1.0mm, USING AIR
OSNEY LABS., 9th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75750E+03	0.29700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CU.M)	W(KG/S)	RE
0.10000E+03	0.18700E+02	0.90000E-01	0.30000E-01	0.17940E+02	0.10108E+06	0.12074E+01	0.12816E-02	0.52877E+04
0.15000E+03	0.18700E+02	0.22000E+00	0.80000E-01	0.17940E+02	0.10110E+06	0.12076E+01	0.20040E-02	0.82680E+04
0.20000E+03	0.18700E+02	0.39000E+00	0.16000E+00	0.17940E+02	0.10112E+06	0.12079E+01	0.26585E-02	0.11010E+05
0.25000E+03	0.18500E+02	0.62000E+00	0.26000E+00	0.17940E+02	0.10115E+06	0.12091E+01	0.33663E-02	0.13888E+05
0.30000E+03	0.18400E+02	0.89000E+00	0.39000E+00	0.17940E+02	0.10119E+06	0.12099E+01	0.40346E-02	0.16646E+05
0.35000E+03	0.18100E+02	0.12200E+01	0.53000E+00	0.17940E+02	0.10123E+06	0.12117E+01	0.47272E-02	0.19503E+05
0.40000E+03	0.17800E+02	0.14400E+01	0.70000E+00	0.17940E+02	0.10125E+06	0.12131E+01	0.51388E-02	0.21201E+05
0.45000E+03	0.17300E+02	0.20200E+01	0.89000E+00	0.17940E+02	0.10134E+06	0.12164E+01	0.60945E-02	0.25144E+05
0.50000E+03	0.16700E+02	0.24800E+01	0.10900E+01	0.17940E+02	0.10141E+06	0.12197E+01	0.67620E-02	0.27898E+05
0.55000E+03	0.16100E+02	0.29800E+01	0.13100E+01	0.17940E+02	0.10148E+06	0.12231E+01	0.74226E-02	0.30624E+05
0.60000E+03	0.15500E+02	0.35100E+01	0.15500E+01	0.17940E+02	0.10155E+06	0.12265E+01	0.80669E-02	0.33282E+05

P(PSIG)	RE	M	ZR	W CORR(KG/S)
0.10000E+03	0.52877E+04	0.47610E+00	0.10400E+01	0.13329E-02
0.15000E+03	0.82680E+04	0.47610E+00	0.10390E+01	0.20822E-02
0.20000E+03	0.11010E+05	0.47610E+00	0.10370E+01	0.27672E-02
0.25000E+03	0.13888E+05	0.47610E+00	0.10350E+01	0.34841E-02
0.30000E+03	0.16646E+05	0.47610E+00	0.10330E+01	0.41677E-02
0.35000E+03	0.19503E+05	0.47610E+00	0.10290E+01	0.48643E-02
0.40000E+03	0.21201E+05	0.47610E+00	0.10270E+01	0.52775E-02
0.45000E+03	0.25144E+05	0.47610E+00	0.10250E+01	0.62468E-02
0.50000E+03	0.27898E+05	0.47610E+00	0.10240E+01	0.69243E-02
0.55000E+03	0.30624E+05	0.47610E+00	0.10230E+01	0.75933E-02
0.60000E+03	0.33282E+05	0.47610E+00	0.10220E+01	0.82444E-02

CALIBRATION CONSTANTS ; A = -0.101561E-05 B = 0.137651E-04

CORRECTED CONSTANTS ; A* = -0.345593E-02 B* = 0.234749E-03

CALIBRATION OF MT1 ORIFICE NO.1, DIAMETER=1.0mm, USING AIR
DSNEY LABS., 9th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.10300E+01	0.10000E+01	0.46650E+00	0.10000E+01	0.75750E+03	0.28700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CU.M)	W(KG/S)	RE
0.50000E+02	0.20700E+02	0.15000E+00	0.30000E-01	0.12700E+02	0.10109E+06	0.11993E+01	0.74926E-03	0.43667E+04
0.10000E+03	0.20600E+02	0.57000E+00	0.14000E+00	0.12700E+02	0.10117E+06	0.12006E+01	0.14614E-02	0.85170E+04
0.15000E+03	0.20600E+02	0.12000E+01	0.31000E+00	0.12700E+02	0.10128E+06	0.12020E+01	0.21216E-02	0.12365E+05
0.20000E+03	0.20500E+02	0.21200E+01	0.55000E+00	0.12700E+02	0.10145E+06	0.12044E+01	0.28228E-02	0.16451E+05
0.25000E+03	0.20300E+02	0.32800E+01	0.86000E+00	0.12700E+02	0.10167E+06	0.12078E+01	0.35160E-02	0.20491E+05
0.30000E+03	0.20100E+02	0.47000E+01	0.12200E+01	0.12700E+02	0.10193E+06	0.12117E+01	0.42157E-02	0.24569E+05
0.35000E+03	0.19700E+02	0.62800E+01	0.16500E+01	0.12700E+02	0.10222E+06	0.12168E+01	0.48833E-02	0.28460E+05
0.40000E+03	0.19300E+02	0.81200E+01	0.21400E+01	0.12700E+02	0.10255E+06	0.12225E+01	0.55657E-02	0.32437E+05
0.45000E+03	0.18900E+02	0.10380E+02	0.27200E+01	0.12700E+02	0.10297E+06	0.12291E+01	0.63099E-02	0.36774E+05
0.50000E+03	0.18300E+02	0.12700E+02	0.33200E+01	0.12700E+02	0.10340E+06	0.12368E+01	0.70012E-02	0.40803E+05
0.55000E+03	0.17600E+02	0.16300E+02	0.39900E+01	0.12700E+02	0.10389E+06	0.12455E+01	0.77116E-02	0.44944E+05

P(PSIG)	RE	M	ZR	WCORR(KG/S)
0.50000E+02	0.43667E+04	0.23859E+00	0.10300E+01	0.77174E-03
0.10000E+03	0.85170E+04	0.23859E+00	0.10250E+01	0.14979E-02
0.15000E+03	0.12365E+05	0.23859E+00	0.10210E+01	0.21662E-02
0.20000E+03	0.16451E+05	0.23859E+00	0.10170E+01	0.28708E-02
0.25000E+03	0.20491E+05	0.23859E+00	0.10140E+01	0.35652E-02
0.30000E+03	0.24569E+05	0.23859E+00	0.10130E+01	0.42705E-02
0.35000E+03	0.28460E+05	0.23859E+00	0.10130E+01	0.49467E-02
0.40000E+03	0.32437E+05	0.23859E+00	0.10120E+01	0.56325E-02
0.45000E+03	0.36774E+05	0.23859E+00	0.10110E+01	0.63793E-02
0.50000E+03	0.40803E+05	0.23859E+00	0.10110E+01	0.70782E-02
0.55000E+03	0.44944E+05	0.23859E+00	0.10100E+01	0.77887E-02

CALIBRATION CONSTANTS ; A = 0.725011E-04 B = 0.139910E-04

CORRECTED CONSTANTS ; A* = -0.226629E-02 B* = 0.239422E-03

CALIBRATION OF MT1 ORIFICE NO.2, DIAMETER=1.5mm, USING AIR
OSNEY LABS., 9th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.10300E+01	0.10000E+01	0.60650E+00	0.10000E+01	0.75750E+03	0.28700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM.M)	W(KG/S)	RE
0.50000E+02	0.18900E+02	0.60000E+00	0.15000E+00	0.12700E+02	0.10117E+06	0.12077E+01	0.15037E-02	0.87639E+04
0.10000E+03	0.19100E+02	0.20500E+01	0.54000E+00	0.12700E+02	0.10144E+06	0.12100E+01	0.27822E-02	0.16215E+05
0.15000E+03	0.18900E+02	0.43500E+01	0.11600E+01	0.12700E+02	0.10186E+06	0.12158E+01	0.40626E-02	0.23677E+05
0.20000E+03	0.18800E+02	0.76000E+01	0.20000E+01	0.12700E+02	0.10246E+06	0.12234E+01	0.53866E-02	0.31393E+05
0.25000E+03	0.18400E+02	0.12100E+02	0.31200E+01	0.12700E+02	0.10330E+06	0.12352E+01	0.68293E-02	0.39902E+05
0.30000E+03	0.17900E+02	0.16950E+02	0.44000E+01	0.12700E+02	0.10419E+06	0.12400E+01	0.81247E-02	0.47351E+05
0.32500E+03	0.16900E+02	0.19950E+02	0.51200E+01	0.12700E+02	0.10476E+06	0.12591E+01	0.88536E-02	0.51599E+05

P(PSIG)	RE	M	ZR	W CORR(KG/S)
0.50000E+02	0.87639E+04	0.23859E+00	0.10000E+01	0.15037E-02
0.10000E+03	0.16215E+05	0.23859E+00	0.10140E+01	0.28212E-02
0.15000E+03	0.23677E+05	0.23859E+00	0.10140E+01	0.41195E-02
0.20000E+03	0.31393E+05	0.23859E+00	0.10120E+01	0.54513E-02
0.25000E+03	0.39902E+05	0.23859E+00	0.10110E+01	0.69045E-02
0.30000E+03	0.47351E+05	0.23859E+00	0.10100E+01	0.82059E-02
0.32500E+03	0.51599E+05	0.23859E+00	0.10100E+01	0.89422E-02

CALIBRATION CONSTANTS ; A = 0.106711E-03 B = 0.270355E-04

CORRECTED CONSTANTS ; A* = -0.494479E-02 B* = 0.461979E-03

CALIBRATION OF MT1 ORIFICE NO.2, DIAMETER=1.5mm, USING AIR

CSNEY LABS., 9th Nov 1987

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75750E+03	0.28700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CU.M)	W(KG/S)	RE
0.50000E+02	0.19000E+02	0.11000E+00	0.40000E-01	0.17940E+02	0.10108E+06	0.12061E+01	0.14162E-02	0.58428E+04
0.10000E+03	0.18900E+02	0.29000E+00	0.16000E+00	0.17940E+02	0.10110E+06	0.12067E+01	0.23000E-02	0.94893E+04
0.15000E+03	0.18900E+02	0.84000E+00	0.36000E+00	0.17940E+02	0.10118E+06	0.12082E+01	0.39168E-02	0.16160E+05
0.20000E+03	0.18600E+02	0.15000E+01	0.65000E+00	0.17940E+02	0.10127E+06	0.12101E+01	0.52382E-02	0.21612E+05
0.25000E+03	0.18100E+02	0.23200E+01	0.10000E+01	0.17940E+02	0.10139E+06	0.12136E+01	0.65239E-02	0.26916E+05
0.30000E+03	0.17600E+02	0.33000E+01	0.14500E+01	0.17940E+02	0.10152E+06	0.12173E+01	0.77925E-02	0.32150E+05
0.35000E+03	0.17000E+02	0.43600E+01	0.19200E+01	0.17940E+02	0.10167E+06	0.12216E+01	0.89727E-02	0.37019E+05
0.40000E+03	0.16100E+02	0.57000E+01	0.25000E+01	0.17940E+02	0.10186E+06	0.12276E+01	0.10285E-01	0.42433E+05
0.45000E+03	0.15100E+02	0.72200E+01	0.32000E+01	0.17940E+02	0.10206E+06	0.12344E+01	0.11607E-01	0.47887E+05
0.50000E+03	0.13900E+02	0.89000E+01	0.39000E+01	0.17940E+02	0.10231E+06	0.12425E+01	0.12929E-01	0.53342E+05

P(PSIG)	RE	M	ZR	W CORR(KG/S)
0.50000E+02	0.58428E+04	0.47610E+00	0.10400E+01	0.14728E-02
0.10000E+03	0.94893E+04	0.47610E+00	0.10380E+01	0.23874E-02
0.15000E+03	0.16160E+05	0.47610E+00	0.10320E+01	0.40421E-02
0.20000E+03	0.21612E+05	0.47610E+00	0.10280E+01	0.53849E-02
0.25000E+03	0.26916E+05	0.47610E+00	0.10260E+01	0.66933E-02
0.30000E+03	0.32150E+05	0.47610E+00	0.10240E+01	0.79795E-02
0.35000E+03	0.37019E+05	0.47610E+00	0.10220E+01	0.91701E-02
0.40000E+03	0.42433E+05	0.47610E+00	0.10210E+01	0.10501E-01
0.45000E+03	0.47887E+05	0.47610E+00	0.10200E+01	0.11839E-01
0.50000E+03	0.53342E+05	0.47610E+00	0.10190E+01	0.13175E-01

CALIBRATION CONSTANTS ; A = 0.507096E-04 B = 0.262320E-04

CORRECTED CONSTANTS ; A* = -0.568428E-02 B* = 0.447069E-03

CALIBRATION OF MT1 ORIFICE NO.2, DIAMETER=1.5mm, USING AIR

OSNEY LABS., 9th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75750E+03	0.29700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CU.M)	W(KG/S)	RE
0.50000E+02	0.18300E+02	0.10000E+00	0.40000E-01	0.17940E+02	0.10108E+06	0.12090E+01	0.13519E-02	0.55775E+04
0.10000E+03	0.18400E+02	0.40000E+00	0.17000E+00	0.17940E+02	0.10112E+06	0.12091E+01	0.27039E-02	0.11156E+05
0.15000E+03	0.18400E+02	0.86000E+00	0.36000E+00	0.17940E+02	0.10119E+06	0.12099E+01	0.39660E-02	0.16363E+05
0.20000E+03	0.18300E+02	0.15200E+01	0.66000E+00	0.17940E+02	0.10128E+06	0.12114E+01	0.52758E-02	0.21767E+05
0.25000E+03	0.17900E+02	0.23300E+01	0.10200E+01	0.17940E+02	0.10139E+06	0.12144E+01	0.65401E-02	0.26983E+05
0.30000E+03	0.17400E+02	0.33200E+01	0.14500E+01	0.17940E+02	0.10153E+06	0.12182E+01	0.78189E-02	0.32259E+05
0.35000E+03	0.16800E+02	0.43900E+01	0.19200E+01	0.17940E+02	0.10168E+06	0.12225E+01	0.90070E-02	0.37161E+05
0.40000E+03	0.16000E+02	0.57000E+01	0.25000E+01	0.17940E+02	0.10186E+06	0.12281E+01	0.10287E-01	0.42440E+05
0.45000E+03	0.15000E+02	0.72300E+01	0.31800E+01	0.17940E+02	0.10207E+06	0.12349E+01	0.11617E-01	0.47931E+05
0.50000E+03	0.13800E+02	0.89500E+01	0.37800E+01	0.17940E+02	0.10235E+06	0.12435E+01	0.12970E-01	0.53512E+05

P(PSIG)	RE	M	ZR	WCORR(KG/S)
0.50000E+02	0.55775E+04	0.47610E+00	0.10400E+01	0.14060E-02
0.10000E+03	0.11156E+05	0.47610E+00	0.10350E+01	0.27985E-02
0.15000E+03	0.16363E+05	0.47610E+00	0.10340E+01	0.41008E-02
0.20000E+03	0.21767E+05	0.47610E+00	0.10280E+01	0.54235E-02
0.25000E+03	0.26983E+05	0.47610E+00	0.10270E+01	0.67167E-02
0.30000E+03	0.32259E+05	0.47610E+00	0.10250E+01	0.80144E-02
0.35000E+03	0.37161E+05	0.47610E+00	0.10230E+01	0.92142E-02
0.40000E+03	0.42440E+05	0.47610E+00	0.10210E+01	0.10503E-01
0.45000E+03	0.47931E+05	0.47610E+00	0.10200E+01	0.11850E-01
0.50000E+03	0.53512E+05	0.47610E+00	0.10180E+01	0.13204E-01

CALIBRATION CONSTANTS ; A = 0.182436E-03 B = 0.259658E-04

CORRECTED CONSTANTS ; A* = -0.337120E-02 B* = 0.442319E-03

CALIBRATION OF MT1 ORIFICE NO.3, DIAMETER=2.0mm, USING AIR
OSNEY LABS., 9th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75750E+03	0.28700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CU.M)	W(KG/S)	RE
0.25000E+02	0.18400E+02	0.11000E+00	0.40000E-01	0.17940E+02	0.10108E+06	0.12086E+01	0.14176E-02	0.58489E+04
0.50000E+02	0.18500E+02	0.36000E+00	0.15000E+00	0.17940E+02	0.10111E+06	0.12086E+01	0.25646E-02	0.10581E+05
0.75000E+02	0.18500E+02	0.76000E+00	0.33000E+00	0.17940E+02	0.10117E+06	0.12093E+01	0.37273E-02	0.15378E+05
0.10000E+03	0.18500E+02	0.12700E+01	0.56000E+00	0.17940E+02	0.10124E+06	0.12101E+01	0.48199E-02	0.19886E+05
0.12500E+03	0.18400E+02	0.19200E+01	0.86000E+00	0.17940E+02	0.10133E+06	0.12116E+01	0.59300E-02	0.24466E+05
0.15000E+03	0.18000E+02	0.26500E+01	0.12000E+01	0.17940E+02	0.10142E+06	0.12144E+01	0.69748E-02	0.28776E+05
0.17500E+03	0.17500E+02	0.35500E+01	0.15700E+01	0.17940E+02	0.10156E+06	0.12181E+01	0.80849E-02	0.33356E+05
0.20000E+03	0.17200E+02	0.45500E+01	0.20100E+01	0.17940E+02	0.10170E+06	0.12210E+01	0.91641E-02	0.37809E+05
0.22500E+03	0.16700E+02	0.56100E+01	0.25000E+01	0.17940E+02	0.10184E+06	0.12248E+01	0.10192E-01	0.42048E+05
0.25000E+03	0.16200E+02	0.68900E+01	0.30800E+01	0.17940E+02	0.10201E+06	0.12291E+01	0.11314E-01	0.46679E+05
0.27500E+03	0.15400E+02	0.83800E+01	0.36300E+01	0.17940E+02	0.10225E+06	0.12353E+01	0.12509E-01	0.51610E+05
0.30000E+03	0.14600E+02	0.99200E+01	0.43900E+01	0.17940E+02	0.10244E+06	0.12411E+01	0.13642E-01	0.56285E+05

P(PSIG)	RE	M	ZR	WCDRR(KG/S)
0.25000E+02	0.58489E+04	0.47610E+00	0.10400E+01	0.14744E-02
0.50000E+02	0.10581E+05	0.47610E+00	0.10370E+01	0.26595E-02
0.75000E+02	0.15378E+05	0.47610E+00	0.10330E+01	0.38503E-02
0.10000E+03	0.19886E+05	0.47610E+00	0.10290E+01	0.49597E-02
0.12500E+03	0.24466E+05	0.47610E+00	0.10270E+01	0.60901E-02
0.15000E+03	0.28776E+05	0.47610E+00	0.10250E+01	0.71491E-02
0.17500E+03	0.33356E+05	0.47610E+00	0.10240E+01	0.82790E-02
0.20000E+03	0.37809E+05	0.47610E+00	0.10220E+01	0.93657E-02
0.22500E+03	0.42048E+05	0.47610E+00	0.10210E+01	0.10406E-01
0.25000E+03	0.46679E+05	0.47610E+00	0.10200E+01	0.11540E-01
0.27500E+03	0.51610E+05	0.47610E+00	0.10190E+01	0.12747E-01
0.30000E+03	0.56285E+05	0.47610E+00	0.10180E+01	0.13888E-01

CALIBRATION CONSTANTS ; A = 0.442720E-03 B = 0.446646E-04

CORRECTED CONSTANTS ; A* = -0.360486E-02 B* = 0.761233E-03

CALIBRATION OF ORIFICE NO.3, DIAMETER=2.0mm, USING AIR
OSNEY LABS., 9th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75750E+03	0.28700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM3)	W(KG/S)	RE
0.25000E+02	0.18900E+02	0.10000E+00	0.40000E-01	0.17940E+02	0.10108E+06	0.12065E+01	0.13505E-02	0.55718E+04
0.50000E+02	0.19000E+02	0.33000E+00	0.13000E+00	0.17940E+02	0.10111E+06	0.12065E+01	0.24533E-02	0.10122E+05
0.75000E+02	0.19100E+02	0.71000E+00	0.30000E+00	0.17940E+02	0.10116E+06	0.12067E+01	0.35988E-02	0.14848E+05
0.10000E+03	0.19100E+02	0.12400E+01	0.52000E+00	0.17940E+02	0.10124E+06	0.12077E+01	0.47578E-02	0.19630E+05
0.12500E+03	0.18800E+02	0.19100E+01	0.87000E+00	0.17940E+02	0.10132E+06	0.12099E+01	0.59103E-02	0.24384E+05
0.15000E+03	0.18700E+02	0.26700E+01	0.11700E+01	0.17940E+02	0.10144E+06	0.12116E+01	0.69931E-02	0.28852E+05
0.17500E+03	0.18200E+02	0.35500E+01	0.15600E+01	0.17940E+02	0.10156E+06	0.12152E+01	0.80753E-02	0.33317E+05
0.20000E+03	0.17700E+02	0.45200E+01	0.20000E+01	0.17940E+02	0.10169E+06	0.12189E+01	0.91258E-02	0.37651E+05
0.22500E+03	0.17100E+02	0.56000E+01	0.25000E+01	0.17940E+02	0.10184E+06	0.12231E+01	0.10175E-01	0.41981E+05
0.25000E+03	0.15500E+02	0.69000E+01	0.31000E+01	0.17940E+02	0.10201E+06	0.12320E+01	0.11336E-01	0.46769E+05
0.27500E+03	0.15100E+02	0.82000E+01	0.37000E+01	0.17940E+02	0.10218E+06	0.12358E+01	0.12377E-01	0.51064E+05
0.30000E+03	0.14200E+02	0.99500E+01	0.43500E+01	0.17940E+02	0.10246E+06	0.12430E+01	0.13673E-01	0.56413E+05

P(PSIG)	RE	M	ZR	WCORR(KG/S)
0.25000E+02	0.55718E+04	0.47610E+00	0.10400E+01	0.14045E-02
0.50000E+02	0.10122E+05	0.47610E+00	0.10370E+01	0.25441E-02
0.75000E+02	0.14848E+05	0.47610E+00	0.10330E+01	0.37176E-02
0.10000E+03	0.19630E+05	0.47610E+00	0.10290E+01	0.48958E-02
0.12500E+03	0.24384E+05	0.47610E+00	0.10270E+01	0.60699E-02
0.15000E+03	0.28852E+05	0.47610E+00	0.10250E+01	0.71679E-02
0.17500E+03	0.33317E+05	0.47610E+00	0.10240E+01	0.82691E-02
0.20000E+03	0.37651E+05	0.47610E+00	0.10220E+01	0.93266E-02
0.22500E+03	0.41981E+05	0.47610E+00	0.10210E+01	0.10389E-01
0.25000E+03	0.46769E+05	0.47610E+00	0.10200E+01	0.11563E-01
0.27500E+03	0.51064E+05	0.47610E+00	0.10190E+01	0.12612E-01
0.30000E+03	0.56413E+05	0.47610E+00	0.10180E+01	0.13919E-01

CALIBRATION CONSTANTS ; A = 0.349077E-03 B = 0.449691E-04

CORRECTED CONSTANTS ; A* = -0.527951E-02 B* = 0.766807E-03

CALIBRATION OF DRIFICE NO.4, DIAMETER=2.5mm, USING AIR
OSNEY LABS., 9th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75750E+03	0.28700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM)	W(KG/S)	RE
0.25000E+02	0.18800E+02	0.28000E+00	0.11000E+00	0.17940E+02	0.10110E+06	0.12073E+01	0.22605E-02	0.93263E+04
0.50000E+02	0.19000E+02	0.95000E+00	0.43000E+00	0.17940E+02	0.10119E+06	0.12075E+01	0.41642E-02	0.17180E+05
0.75000E+02	0.18900E+02	0.19000E+01	0.86000E+00	0.17940E+02	0.10132E+06	0.12094E+01	0.58938E-02	0.24316E+05
0.10000E+03	0.18700E+02	0.31600E+01	0.13800E+01	0.17940E+02	0.10151E+06	0.12125E+01	0.76104E-02	0.31398E+05
0.12500E+03	0.18300E+02	0.47000E+01	0.20500E+01	0.17940E+02	0.10172E+06	0.12167E+01	0.92976E-02	0.38360E+05
0.15000E+03	0.17900E+02	0.64000E+01	0.28500E+01	0.17940E+02	0.10195E+06	0.12211E+01	0.10869E-01	0.44843E+05
0.17500E+03	0.17200E+02	0.86800E+01	0.38400E+01	0.17940E+02	0.10227E+06	0.12279E+01	0.12693E-01	0.52368E+05
0.20000E+03	0.16000E+02	0.11400E+02	0.49400E+01	0.17940E+02	0.10267E+06	0.12379E+01	0.14605E-01	0.60258E+05

P(PSIG)	RE	M	ZR	WCORR(KG/S)
0.25000E+02	0.93263E+04	0.47610E+00	0.10400E+01	0.23509E-02
0.50000E+02	0.17180E+05	0.47610E+00	0.10300E+01	0.42891E-02
0.75000E+02	0.24316E+05	0.47610E+00	0.10260E+01	0.60470E-02
0.10000E+03	0.31398E+05	0.47610E+00	0.10240E+01	0.77930E-02
0.12500E+03	0.38360E+05	0.47610E+00	0.10220E+01	0.95022E-02
0.15000E+03	0.44843E+05	0.47610E+00	0.10200E+01	0.11086E-01
0.17500E+03	0.52368E+05	0.47610E+00	0.10190E+01	0.12934E-01
0.20000E+03	0.60258E+05	0.47610E+00	0.10180E+01	0.14868E-01

CALIBRATION CONSTANTS ; A = 0.697758E-03 B = 0.703211E-04

CORRECTED CONSTANTS ; A* = -0.567074E-02 B* = 0.120010E-02

CALIBRATION OF MT1 ORIFICE NO.4, DIAMETER 2.5mm, USING AIR
GSNEY LABS., 9th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75750E+03	0.28700E+03	0.17200E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM.M)	W(KG/S)	RE
0.50000E+02	0.20100E+02	0.96000E+00	0.42000E+00	0.17940E+02	0.10120E+06	0.12030E+01	0.41783E-02	0.17238E+05
0.10000E+03	0.20300E+02	0.30500E+01	0.13900E+01	0.17940E+02	0.10148E+06	0.12055E+01	0.74552E-02	0.30758E+05
0.15000E+03	0.20000E+02	0.64000E+01	0.28500E+01	0.17940E+02	0.10195E+06	0.12123E+01	0.10830E-01	0.44682E+05
0.20000E+03	0.19000E+02	0.11200E+02	0.48000E+01	0.17940E+02	0.10266E+06	0.12250E+01	0.14401E-01	0.59415E+05

P(PSIG)	RE	M	ZR	W CORR(KG/S)
0.50000E+02	0.17238E+05	0.47610E+00	0.10310E+01	0.43078E-02
0.10000E+03	0.30758E+05	0.47610E+00	0.10250E+01	0.76416E-02
0.15000E+03	0.44682E+05	0.47610E+00	0.10230E+01	0.11079E-01
0.20000E+03	0.59415E+05	0.47610E+00	0.10180E+01	0.14660E-01

CALIBRATION CONSTANTS ; A = 0.798413E-03 B = 0.689902E-04

CORRECTED CONSTANTS ; A* = -0.363112E-02 B* = 0.118092E-02

CALIBRATION OF MT1 ORIFICE NO.1, DIAMETER=1.0mm, USING CO2

OSNEY LABS., 10th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	OPIE(mm)
0.10300E+01	0.10000E+01	0.50650E+00	0.10000E+01	0.75550E+03	0.18900E+03	0.13800E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM)	W(KG/S)	RE
0.50000E+02	0.20400E+02	0.16000E+00	0.20000E-01	0.12700E+02	0.10083E+06	0.18183E+01	0.95283E-03	0.69213E+04
0.10000E+03	0.20200E+02	0.56000E+00	0.14000E+00	0.12700E+02	0.10090E+06	0.18208E+01	0.17839E-02	0.12957E+05
0.15000E+03	0.19300E+02	0.12300E+01	0.32000E+00	0.12700E+02	0.10102E+06	0.18286E+01	0.26493E-02	0.19245E+05
0.20000E+03	0.18300E+02	0.21500E+01	0.57000E+00	0.12700E+02	0.10119E+06	0.18379E+01	0.35116E-02	0.25508E+05
0.25000E+03	0.16800E+02	0.34100E+01	0.90000E+00	0.12700E+02	0.10142E+06	0.18517E+01	0.44390E-02	0.32244E+05
0.30000E+03	0.14400E+02	0.49500E+01	0.13000E+01	0.12700E+02	0.10171E+06	0.18724E+01	0.53780E-02	0.39065E+05
0.35000E+03	0.11000E+02	0.67800E+01	0.17800E+01	0.12700E+02	0.10204E+06	0.19011E+01	0.63421E-02	0.46069E+05
0.40000E+03	0.78000E+01	0.89800E+01	0.23600E+01	0.12700E+02	0.10245E+06	0.19303E+01	0.73549E-02	0.53425E+05
0.45000E+03	0.38000E+01	0.11400E+02	0.30000E+01	0.12700E+02	0.10289E+06	0.19667E+01	0.83646E-02	0.60760E+05
0.50000E+03	-0.80000E+00	0.14200E+02	0.37200E+01	0.12700E+02	0.10341E+06	0.20100E+01	0.94377E-02	0.68555E+05

P(PSIG)	RE	M	ZR	WCORR(KG/S)
0.50000E+02	0.69213E+04	0.23859E+00	0.10250E+01	0.97665E-03
0.10000E+03	0.12957E+05	0.23859E+00	0.10190E+01	0.18177E-02
0.15000E+03	0.19245E+05	0.23859E+00	0.10140E+01	0.26864E-02
0.20000E+03	0.25508E+05	0.23859E+00	0.10130E+01	0.35573E-02
0.25000E+03	0.32244E+05	0.23859E+00	0.10120E+01	0.44922E-02
0.30000E+03	0.39065E+05	0.23859E+00	0.10120E+01	0.54425E-02
0.35000E+03	0.46069E+05	0.23859E+00	0.10110E+01	0.64119E-02
0.40000E+03	0.53425E+05	0.23859E+00	0.10100E+01	0.74294E-02
0.45000E+03	0.60760E+05	0.23859E+00	0.10090E+01	0.84399E-02
0.50000E+03	0.68555E+05	0.23859E+00	0.10080E+01	0.95132E-02

CALIBRATION CONSTANTS ; A = -0.136983E-03 B = 0.189586E-04

CORRECTED CONSTANTS ; A* = -0.700381E-02 B* = 0.320770E-03

CALIBRATION OF MT1 ORIFICE NO.1,DIAMETER=1.0mm,USING CO2
DSNEY LABS., 10th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.10300E+01	0.10000E+01	0.60650E+00	0.10000E+01	0.75550E+03	0.18900E+03	0.13800E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM3)	W(KG/S)	RE
0.50000E+02	0.18800E+02	0.15000E+00	0.30000E-01	0.12700E+02	0.10083E+06	0.18282E+01	0.92508E-03	0.67197E+04
0.10000E+03	0.18400E+02	0.56000E+00	0.14000E+00	0.12700E+02	0.10090E+06	0.18321E+01	0.17893E-02	0.12997E+05
0.15000E+03	0.17800E+02	0.12000E+01	0.32000E+00	0.12700E+02	0.10102E+06	0.18379E+01	0.26235E-02	0.19057E+05
0.20000E+03	0.16600E+02	0.21600E+01	0.56000E+00	0.12700E+02	0.10119E+06	0.18488E+01	0.35302E-02	0.25643E+05
0.25000E+03	0.14800E+02	0.33000E+01	0.87000E+00	0.12700E+02	0.10140E+06	0.18642E+01	0.43815E-02	0.31827E+05
0.22500E+03	0.14300E+02	0.26500E+01	0.70000E+00	0.12700E+02	0.10128E+06	0.18652E+01	0.39275E-02	0.28529E+05
0.17500E+03	0.14400E+02	0.16100E+01	0.42000E+00	0.12700E+02	0.10109E+06	0.18611E+01	0.30579E-02	0.22212E+05
0.12500E+03	0.14800E+02	0.85000E+00	0.22000E+00	0.12700E+02	0.10095E+06	0.18559E+01	0.22188E-02	0.16117E+05
0.75000E+02	0.15400E+02	0.32000E+00	0.70000E-01	0.12700E+02	0.10086E+06	0.18503E+01	0.13593E-02	0.98740E+04

P(PSIG)	RE	M	ZR	W CORR(KG/S)
0.50000E+02	0.67197E+04	0.23859E+00	0.10250E+01	0.94821E-03
0.10000E+03	0.12997E+05	0.23859E+00	0.10190E+01	0.18233E-02
0.15000E+03	0.19057E+05	0.23859E+00	0.10140E+01	0.26602E-02
0.20000E+03	0.25643E+05	0.23859E+00	0.10130E+01	0.35761E-02
0.25000E+03	0.31827E+05	0.23859E+00	0.10120E+01	0.44341E-02
0.22500E+03	0.28529E+05	0.23859E+00	0.10130E+01	0.39785E-02
0.17500E+03	0.22212E+05	0.23859E+00	0.10140E+01	0.31607E-02
0.12500E+03	0.16117E+05	0.23859E+00	0.10150E+01	0.22521E-02
0.75000E+02	0.98740E+04	0.23859E+00	0.10200E+01	0.13865E-02

CALIBRATION CONSTANTS ; A = 0.770374E-04 B = 0.173825E-04

CORRECTED CONSTANTS ; A* = -0.300888E-02 B* = 0.295652E-03

CALIBRATION OF MT1 ORIFICE NO.2, DIAMETER=1.5mm, USING CO2
OSNEY LABS., 10th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.10300E+01	0.10000E+01	0.60650E+00	0.10000E+01	0.75550E+03	0.19900E+03	0.13800E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM3)	W(KG/S)	RE
0.50000E+02	0.21900E+02	0.64000E+00	0.16000E+00	0.12700E+02	0.10092E+06	0.18106E+01	0.19016E-02	0.13813E+05
0.10000E+03	0.21200E+02	0.20800E+01	0.55000E+00	0.12700E+02	0.10118E+06	0.18196E+01	0.34367E-02	0.24964E+05
0.15000E+03	0.19800E+02	0.43800E+01	0.11300E+01	0.12700E+02	0.10161E+06	0.18361E+01	0.50096E-02	0.36389E+05
0.20000E+03	0.17500E+02	0.80000E+01	0.21000E+01	0.12700E+02	0.10227E+06	0.18626E+01	0.68191E-02	0.49534E+05
0.25000E+03	0.14500E+02	0.12520E+02	0.33000E+01	0.12700E+02	0.10309E+06	0.18973E+01	0.86097E-02	0.62540E+05
0.30000E+03	0.10200E+02	0.17850E+02	0.46700E+01	0.12700E+02	0.10408E+06	0.19445E+01	0.10408E-01	0.75599E+05

P(PSIG)	RE	M	ZR	W CORR(KG/S)
0.50000E+02	0.13813E+05	0.23859E+00	0.10200E+01	0.19396E-02
0.10000E+03	0.24964E+05	0.23859E+00	0.10130E+01	0.34814E-02
0.15000E+03	0.36389E+05	0.23859E+00	0.10120E+01	0.50697E-02
0.20000E+03	0.49534E+05	0.23859E+00	0.10100E+01	0.68873E-02
0.25000E+03	0.62540E+05	0.23859E+00	0.10090E+01	0.86872E-02
0.30000E+03	0.75599E+05	0.23859E+00	0.10080E+01	0.10491E-01

CALIBRATION CONSTANTS ; A = 0.735959E-04 B = 0.343947E-04

CORRECTED CONSTANTS ; A* = -0.731188E-02 B* = 0.586393E-03

CALIBRATION OF MT1 DRIFICE NO.2, DIAMETER=1.5mm, USING CO2

OSNEY LABS., 10th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75550E+03	0.18900E+03	0.13800E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/DU.M)	W(KG/S)	RE
0.25000E+03	-0.30000E+01	0.25100E+01	0.11000E+01	0.17940E+02	0.10115E+06	0.19821E+01	0.86721E-02	0.44594E+05
0.40000E+03	-0.42000E+01	0.63500E+01	0.28000E+01	0.17940E+02	0.10168E+06	0.20015E+01	0.13861E-01	0.71275E+05
0.37500E+03	-0.75000E+01	0.56500E+01	0.24800E+01	0.17940E+02	0.10159E+06	0.20244E+01	0.13149E-01	0.67617E+05
0.35000E+03	-0.54000E+01	0.48600E+01	0.21200E+01	0.17940E+02	0.10148E+06	0.20064E+01	0.12141E-01	0.62432E+05
0.32500E+03	-0.65000E+01	0.42000E+01	0.18300E+01	0.17940E+02	0.10139E+06	0.20129E+01	0.11305E-01	0.58131E+05
0.30000E+03	-0.52000E+01	0.36200E+01	0.15600E+01	0.17940E+02	0.10131E+06	0.20016E+01	0.10466E-01	0.53817E+05

P(PSIG)	RE	M	ZR	WCORR(KG/S)
0.25000E+03	0.44594E+05	0.47610E+00	0.10230E+01	0.88716E-02
0.40000E+03	0.71275E+05	0.47610E+00	0.10170E+01	0.14096E-01
0.37500E+03	0.67617E+05	0.47610E+00	0.10170E+01	0.13373E-01
0.35000E+03	0.62432E+05	0.47610E+00	0.10180E+01	0.12360E-01
0.32500E+03	0.58131E+05	0.47610E+00	0.10190E+01	0.11508E-01
0.30000E+03	0.53817E+05	0.47610E+00	0.10190E+01	0.10665E-01

CALIBRATION CONSTANTS ; A = 0.103288E-03 B = 0.351266E-04

CORRECTED CONSTANTS ; A* = -0.670808E-02 B* = 0.574886E-03

CALIBRATION OF MT1 ORIFICE NO.3, DIAMETER=2.0mm, USING CO2

OSNEY LABS., 10th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.75550E+03	0.18900E+03	0.13800E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM)	W(KG/S)	RE
0.35000E+03	-0.44000E+01	0.14250E+02	0.63000E+01	0.17940E+02	0.10278E+06	0.20245E+01	0.20883E-01	0.10739E+06
0.32500E+03	-0.27000E+01	0.12500E+02	0.55200E+01	0.17940E+02	0.10254E+06	0.20071E+01	0.19474E-01	0.10014E+06
0.30000E+03	-0.12000E+01	0.10680E+02	0.46400E+01	0.17940E+02	0.10230E+06	0.19914E+01	0.17931E-01	0.92203E+05
0.27500E+03	-0.10000E+00	0.88500E+01	0.39000E+01	0.17940E+02	0.10203E+06	0.19781E+01	0.16268E-01	0.83652E+05
0.25000E+03	0.23000E+01	0.74500E+01	0.32300E+01	0.17940E+02	0.10185E+06	0.19574E+01	0.14847E-01	0.76348E+05
0.20000E+03	0.56000E+01	0.47800E+01	0.21000E+01	0.17940E+02	0.10146E+06	0.19269E+01	0.11300E-01	0.60677E+05
0.15000E+03	0.69000E+01	0.27000E+01	0.12200E+01	0.17940E+02	0.10116E+06	0.19123E+01	0.88346E-02	0.45430E+05
0.10000E+03	0.89000E+01	0.13000E+01	0.58000E+00	0.17940E+02	0.10093E+06	0.18952E+01	0.61027E-02	0.31332E+05
0.75000E+02	0.10100E+02	0.78000E+00	0.35000E+00	0.17940E+02	0.10090E+06	0.18858E+01	0.47154E-02	0.24248E+05
0.50000E+02	0.12400E+02	0.40000E+00	0.16000E+00	0.17940E+02	0.10086E+06	0.18698E+01	0.33624E-02	0.17290E+05

P(PSIG)	RE	M	ZR	W CORR(KG/S)
0.35000E+03	0.10739E+06	0.47610E+00	0.10140E+01	0.21175E-01
0.32500E+03	0.10014E+06	0.47610E+00	0.10140E+01	0.19747E-01
0.30000E+03	0.92203E+05	0.47610E+00	0.10150E+01	0.18200E-01
0.27500E+03	0.83652E+05	0.47610E+00	0.10160E+01	0.16528E-01
0.25000E+03	0.76348E+05	0.47610E+00	0.10160E+01	0.15085E-01
0.20000E+03	0.60677E+05	0.47610E+00	0.10170E+01	0.12000E-01
0.15000E+03	0.45430E+05	0.47610E+00	0.10190E+01	0.90025E-02
0.10000E+03	0.31332E+05	0.47610E+00	0.10210E+01	0.62309E-02
0.75000E+02	0.24248E+05	0.47610E+00	0.10260E+01	0.48380E-02
0.50000E+02	0.17290E+05	0.47610E+00	0.10300E+01	0.34632E-02

CALIBRATION CONSTANTS ; A = 0.303363E-03 B = 0.593908E-04

CORRECTED CONSTANTS ; A* = -0.939024E-02 B* = 0.988336E-03

CALIBRATION OF MT1 ORIFICE NO.3, DIAMETER=2.0MM, USING CO2
OSNEY LABS., 11th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	OPIE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.74700E+03	0.18900E+03	0.13800E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM3)	W(KG/S)	RE
0.50000E+02	0.16600E+02	0.34000E+00	0.14000E+00	0.17940E+02	0.99712E+05	0.18217E+01	0.30599E-02	0.15735E+05
0.10000E+03	0.15500E+02	0.11000E+01	0.50000E+00	0.17940E+02	0.99811E+05	0.18305E+01	0.55170E-02	0.28370E+05
0.15000E+03	0.12900E+02	0.27000E+01	0.12000E+01	0.17940E+02	0.10004E+06	0.18513E+01	0.86925E-02	0.44699E+05
0.20000E+03	0.92000E+01	0.47000E+01	0.20400E+01	0.17940E+02	0.10032E+06	0.18810E+01	0.11560E-01	0.59446E+05
0.25000E+03	0.29000E+01	0.73500E+01	0.32000E+01	0.17940E+02	0.10070E+06	0.19311E+01	0.14648E-01	0.75322E+05
0.30000E+03	-0.33000E+01	0.10600E+02	0.46000E+01	0.17940E+02	0.10116E+06	0.19845E+01	0.17932E-01	0.91697E+05
0.35000E+03	-0.12600E+02	0.14400E+02	0.63000E+01	0.17940E+02	0.10168E+06	0.20660E+01	0.21207E-01	0.10905E+06

P(PSIG)	RE	M	ZR	WCORR(KG/S)
0.50000E+02	0.15735E+05	0.47610E+00	0.10350E+01	0.31670E-02
0.10000E+03	0.28370E+05	0.47610E+00	0.10270E+01	0.56660E-02
0.15000E+03	0.44699E+05	0.47610E+00	0.10210E+01	0.88751E-02
0.20000E+03	0.59446E+05	0.47610E+00	0.10190E+01	0.11768E-01
0.25000E+03	0.75322E+05	0.47610E+00	0.10160E+01	0.14882E-01
0.30000E+03	0.91697E+05	0.47610E+00	0.10150E+01	0.18100E-01
0.35000E+03	0.10905E+06	0.47610E+00	0.10140E+01	0.21504E-01

CALIBRATION CONSTANTS ; A = -0.274606E-03 B = 0.613456E-04

CORRECTED CONSTANTS ; A* = -0.193891E-01 B* = 0.102474E-02

CALIBRATION OF MT1 ORIFICE NO.4, DIAMETER=2.5MM, USING CO2
 DENNEY LABS., 11th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DPIPE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.74400E+03	0.18900E+03	0.13800E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CU.M)	W(KG/S)	RE
0.25000E+02	0.19800E+02	0.60000E-01	0.10000E+00	0.17940E+02	0.99252E+05	0.17935E+01	0.12754E-02	0.65585E+04
0.50000E+02	0.19600E+02	0.10000E+01	0.42000E+00	0.17940E+02	0.99406E+05	0.18037E+01	0.52216E-02	0.26851E+05
0.75000E+02	0.16400E+02	0.18200E+01	0.78000E+00	0.17940E+02	0.99521E+05	0.18195E+01	0.70752E-02	0.36382E+05
0.10000E+03	0.12600E+02	0.32400E+01	0.14000E+01	0.17940E+02	0.99720E+05	0.18474E+01	0.95121E-02	0.48914E+05
0.15000E+03	0.64000E+01	0.70000E+01	0.30000E+01	0.17940E+02	0.10026E+06	0.18986E+01	0.14174E-01	0.72986E+05
0.20000E+03	-0.25000E+01	0.12100E+02	0.52000E+01	0.17940E+02	0.10098E+06	0.19752E+01	0.19007E-01	0.97740E+05
0.22500E+03	-0.72000E+01	0.15200E+02	0.65000E+01	0.17940E+02	0.10143E+06	0.20190E+01	0.21539E-01	0.11076E+06

P(PSIG)	RE	M	ZR	WCDRR(KG/S)
0.25000E+02	0.65585E+04	0.47610E+00	0.10400E+01	0.13264E-02
0.50000E+02	0.26851E+05	0.47610E+00	0.10270E+01	0.53626E-02
0.75000E+02	0.36382E+05	0.47610E+00	0.10250E+01	0.72520E-02
0.10000E+03	0.48914E+05	0.47610E+00	0.10200E+01	0.97024E-02
0.15000E+03	0.72986E+05	0.47610E+00	0.10160E+01	0.14401E-01
0.20000E+03	0.97740E+05	0.47610E+00	0.10150E+01	0.19292E-01
0.22500E+03	0.11076E+06	0.47610E+00	0.10140E+01	0.21840E-01

CALIBRATION CONSTANTS ; A = -0.312247E-03 B = 0.986213E-04

CORRECTED CONSTANTS ; A* = -0.290855E-01 B* = 0.165704E-02

CALIBRATION OF MT1 ORIFICE NO.4, DIAMETER=2.5MM, USING CO2

OSNEY LABS., 11th Nov 1987.

E	EPS	C	Z	PAMB(MM.HG)	R(J/KG.K)	XMU	DIPIE(mm)
0.11370E+01	0.10000E+01	0.60600E+00	0.10000E+01	0.74400E+03	0.18900E+03	0.13800E-04	0.26000E+02

PROCESSED - RESULTS FOLLOW

P(PSIG)	T(DEG.C)	A(IN.H2O)	B(IN.H2O)	D(MM)	P1(PA)	RHO(KG/CM.M)	W(KG/S)	RE
0.25000E+02	0.20100E+02	0.24000E+00	0.12000E+00	0.17940E+02	0.99291E+05	0.17924E+01	0.25500E-02	0.13113E+05
0.50000E+02	0.18800E+02	0.59000E+00	0.42000E+00	0.17940E+02	0.99404E+05	0.18024E+01	0.51936E-02	0.26707E+05
0.75000E+02	0.15700E+02	0.19000E+01	0.96000E+00	0.17940E+02	0.99521E+05	0.18239E+01	0.72377E-02	0.37218E+05
0.10000E+03	0.12700E+02	0.32000E+01	0.14200E+01	0.17940E+02	0.99705E+05	0.13465E+01	0.94509E-02	0.48599E+05
0.15000E+03	0.71000E+01	0.70000E+01	0.30000E+01	0.17940E+02	0.10026E+06	0.18938E+01	0.14156E-01	0.72794E+05
0.20000E+03	-0.30000E+00	0.12100E+02	0.52000E+01	0.17940E+02	0.10098E+06	0.19593E+01	0.18931E-01	0.97345E+05
0.22500E+03	-0.69000E+01	0.15100E+02	0.66000E+01	0.17940E+02	0.10138E+06	0.20158E+01	0.21450E-01	0.11030E+06

P(PSIG)	RE	M	ZR	W CORR(KG/S)
0.25000E+02	0.13113E+05	0.47610E+00	0.10370E+01	0.26444E-02
0.50000E+02	0.26707E+05	0.47610E+00	0.10270E+01	0.53338E-02
0.75000E+02	0.37218E+05	0.47610E+00	0.10250E+01	0.74187E-02
0.10000E+03	0.48599E+05	0.47610E+00	0.10200E+01	0.96399E-02
0.15000E+03	0.72794E+05	0.47610E+00	0.10160E+01	0.14383E-01
0.20000E+03	0.97345E+05	0.47610E+00	0.10150E+01	0.19214E-01
0.22500E+03	0.11030E+06	0.47610E+00	0.10140E+01	0.21751E-01

CALIBRATION CONSTANTS ; A = 0.346912E-03 B = 0.944924E-04

CORRECTED CONSTANTS ; A* = -0.170256E-01 B* = 0.158891E-02

Table 6.1 Tabulation of Film-Cooling Experiments

Run	Re	XRe	M	XM	Po	To	Tamb	Tinj	ϵ		δ	I	Di/Dq	WIP	SIP	Cd
									iso	meas						
695	2.554	-0.024	0.928	-0.254	3.397	373.5	290.1	269.0	1.253	1.461	0.366	0.316	1.773	0.313	0.177	0.489
694	2.573	0.720	0.936	0.606	3.416	374.0	289.1	269.1	1.236	1.474	0.364	0.367	1.776	0.364	0.205	0.451
692	2.564	0.368	0.932	0.176	3.429	375.7	290.3	290.0	1.003	1.205	0.369	0.355	1.736	0.351	0.202	0.470
691	2.567	0.485	0.936	0.606	3.421	375.0	289.8	288.8	1.012	1.197	0.372	0.329	1.740	0.325	0.187	0.491
690	2.567	0.485	0.939	0.929	3.425	375.6	290.4	312.8	0.737	0.867	0.360	0.359	1.752	0.356	0.203	0.454
689	2.568	0.524	0.939	0.929	3.432	376.1	290.0	311.6	0.749	0.881	0.360	0.340	1.761	0.337	0.191	0.466
688	2.565	0.407	0.930	-0.039	3.393	372.1	289.9	255.3	1.421	1.575	0.837	0.952	1.771	0.951	0.537	0.645
687	2.564	0.368	0.931	0.069	3.409	373.8	289.3	254.5	1.412	1.589	0.836	0.942	1.785	0.941	0.527	0.645
686	2.532	-0.885	0.931	0.069	3.396	376.4	291.9	258.2	1.399	1.585	0.827	0.954	1.763	0.954	0.541	0.638
685	2.530	-0.963	0.930	-0.039	3.395	376.5	291.5	257.1	1.405	1.582	0.829	0.955	1.771	0.955	0.539	0.638
684	2.533	-0.846	0.933	0.284	3.404	377.2	292.3	274.3	1.212	1.390	0.826	0.959	1.766	0.959	0.543	0.635
683	2.533	-0.846	0.931	0.069	3.395	376.2	291.6	271.0	1.244	1.419	0.837	0.937	1.793	0.937	0.526	0.647
682	2.543	-0.454	0.932	0.176	3.409	376.3	290.5	269.3	1.247	1.413	0.836	0.895	1.792	0.894	0.499	0.660
681	2.541	-0.533	0.930	-0.039	3.404	375.9	290.5	269.0	1.252	1.424	0.837	0.953	1.795	0.953	0.531	0.640
680	2.554	-0.024	0.931	0.069	3.407	374.8	289.2	286.1	1.036	1.195	0.828	0.919	1.782	0.919	0.516	0.647
678	2.543	-0.454	0.930	-0.039	3.396	375.0	290.5	287.9	1.031	1.185	0.833	0.912	1.753	0.911	0.520	0.659
676	2.561	0.250	0.945	1.574	3.464	380.5	292.9	319.4	0.697	0.835	0.819	0.818	1.749	0.817	0.467	0.685
675	2.535	-0.768	0.936	0.606	3.429	379.5	292.5	320.4	0.679	0.808	0.825	0.874	1.739	0.874	0.502	0.669
674	2.545	-0.376	0.938	0.821	3.435	379.1	292.1	315.2	0.734	0.866	0.830	0.843	1.765	0.842	0.477	0.680
673	2.553	-0.063	0.941	1.144	3.427	377.7	291.7	316.6	0.710	0.826	0.828	0.829	1.750	0.827	0.473	0.688
672	2.517	-1.472	0.931	0.069	3.405	379.0	292.5	257.8	1.401	1.611	0.521	0.590	1.771	0.587	0.331	0.510
671	2.544	-0.415	0.936	0.606	3.419	377.5	292.0	256.5	1.415	1.635	0.519	0.588	1.773	0.585	0.330	0.508
670	2.509	-1.785	0.930	-0.039	3.406	379.9	293.1	256.7	1.419	1.651	0.523	0.618	1.783	0.614	0.345	0.498
669	2.523	-1.237	0.930	-0.039	3.408	378.3	292.1	255.6	1.424	1.675	0.522	0.606	1.784	0.603	0.338	0.502
667	2.529	-1.003	0.928	-0.254	3.403	377.0	292.7	270.4	1.265	1.500	0.524	0.570	1.784	0.566	0.317	0.520
666	2.523	-1.237	0.931	0.069	3.411	378.9	292.0	268.0	1.276	1.498	0.526	0.581	1.808	0.578	0.320	0.513
665	2.541	-0.533	0.931	0.069	3.395	375.2	290.9	269.3	1.256	1.453	0.525	0.576	1.783	0.572	0.321	0.518
664	2.536	-0.728	0.927	-0.361	3.402	376.0	290.4	271.1	1.225	1.437	0.523	0.562	1.773	0.558	0.315	0.524
663	2.522	-1.277	0.925	-0.576	3.406	377.7	291.9	289.7	1.026	1.242	0.522	0.535	1.763	0.531	0.301	0.538
662	2.535	-0.768	0.932	0.176	3.419	378.1	291.6	289.7	1.022	1.215	0.520	0.556	1.765	0.552	0.313	0.525
661	2.537	-0.689	0.930	-0.039	3.421	377.8	290.9	288.7	1.025	1.235	0.521	0.552	1.772	0.548	0.309	0.527
660	2.550	-0.180	0.933	0.284	3.424	376.9	290.5	287.8	1.031	1.239	0.520	0.531	1.771	0.528	0.298	0.537
659	2.537	-0.689	0.930	-0.039	3.413	377.2	290.5	313.8	0.731	0.882	0.522	0.497	1.758	0.494	0.281	0.558
658	2.534	-0.807	0.930	-0.039	3.401	376.5	291.1	315.6	0.713	0.844	0.522	0.509	1.745	0.505	0.289	0.554
657	2.540	-0.572	0.926	-0.469	3.414	376.4	290.0	313.7	0.726	0.891	0.521	0.545	1.756	0.542	0.308	0.533
656	2.549	-0.220	0.926	-0.469	3.407	374.8	289.0	315.7	0.689	0.839	0.520	0.526	1.737	0.522	0.301	0.544
649	2.576	0.837	0.931	0.069	3.423	373.6	288.1	274.3	1.161	1.427	0.206	0.326	1.737	0.322	0.186	0.274
648	2.583	1.111	0.926	-0.469	3.406	370.8	286.9	272.5	1.172	1.443	0.207	0.326	1.735	0.322	0.186	0.276
647	2.552	-0.102	0.926	-0.469	3.409	374.7	288.6	270.6	1.209	1.456	0.209	0.350	1.766	0.347	0.196	0.265
646	2.573	0.720	0.933	0.284	3.421	374.1	288.1	272.6	1.180	1.424	0.207	0.343	1.750	0.340	0.194	0.267
643	2.516	-1.511	0.931	0.069	3.417	380.3	293.3	292.7	1.007	1.221	0.208	0.307	1.762	0.304	0.173	0.283
642	2.537	-0.689	0.930	-0.039	3.412	377.2	290.8	290.8	1.000	1.214	0.208	0.321	1.753	0.317	0.181	0.278
641	2.490	-2.529	0.927	-0.361	3.414	382.6	295.5	293.8	1.020	1.261	0.208	0.342	1.759	0.338	0.192	0.269
640	2.502	-2.059	0.928	-0.254	3.417	381.5	294.7	293.5	1.014	1.235	0.208	0.334	1.757	0.330	0.188	0.272
639	2.497	-2.255	0.928	-0.254	3.406	381.2	294.0	316.1	0.746	0.894	0.208	0.332	1.753	0.329	0.187	0.273
638	2.510	-1.746	0.932	0.176	3.414	380.6	293.6	315.0	0.754	0.899	0.208	0.310	1.756	0.307	0.175	0.282
637	2.494	-2.373	0.933	0.284	3.419	383.2	295.9	316.6	0.763	0.923	0.208	0.321	1.759	0.318	0.181	0.276
636	2.478	-2.999	0.929	-0.146	3.405	383.5	295.8	315.1	0.780	0.931	0.209	0.316	1.769	0.313	0.177	0.280

Run	Re	%Re	M	%M	Po	To	Tamb	Tinj	Θ		G	I	Di/Dg	WIP	SIP	Cd
									iso	meas						
552	2.592	1.464	0.928	-0.254	3.378	367.7	284.7	267.4	1.208	1.375	1.094	1.285	1.757	1.292	0.735	0.728
551	2.611	2.207	0.930	-0.039	3.379	365.7	284.0	264.9	1.234	1.427	1.096	1.298	1.765	1.305	0.739	0.724
550	2.598	1.698	0.925	-0.576	3.372	366.0	284.3	266.9	1.213	1.417	1.095	1.370	1.754	1.379	0.786	0.706
549	2.614	2.325	0.927	-0.361	3.376	364.8	283.6	263.3	1.250	1.442	1.100	1.323	1.773	1.331	0.751	0.718
548	2.611	2.207	0.930	-0.039	3.393	367.0	284.7	256.7	1.340	1.547	1.112	1.275	1.829	1.281	0.701	0.728
547	2.613	2.286	0.929	-0.146	3.382	365.7	283.3	245.4	1.460	1.673	1.126	1.078	1.867	1.080	0.578	0.793
546	2.616	2.403	0.929	-0.146	3.379	365.1	282.8	248.0	1.423	1.616	1.120	1.374	1.850	1.383	0.748	0.702
545	2.624	2.716	0.929	-0.146	3.375	363.9	282.6	255.0	1.340	1.562	1.105	1.128	1.792	1.131	0.631	0.777
540	2.639	3.303	0.925	-0.576	3.372	361.5	281.7	244.2	1.470	1.674	1.125	1.508	1.865	1.521	0.815	0.671
538	2.591	1.424	0.922	-0.899	3.370	366.3	285.2	248.7	1.450	1.646	1.123	1.369	1.852	1.378	0.744	0.705
536	2.595	1.581	0.931	0.069	3.383	367.9	285.4	283.8	1.020	1.196	1.102	1.348	1.716	1.356	0.790	0.724
535	2.586	1.229	0.919	-1.221	3.364	366.1	284.4	282.8	1.020	1.215	1.110	1.426	1.715	1.437	0.838	0.710
532	2.576	0.837	0.928	-0.254	3.368	368.6	286.9	309.0	0.730	0.882	1.098	1.243	1.812	1.250	0.689	0.732
531	2.597	1.659	0.925	-0.576	3.369	365.9	286.2	308.0	0.727	0.879	1.096	1.208	1.804	1.214	0.673	0.742
530	2.604	1.933	0.927	-0.361	3.358	364.4	284.2	307.0	0.716	0.856	1.099	1.265	1.803	1.273	0.706	0.728
529	2.569	0.563	0.930	-0.039	3.371	369.7	286.9	308.0	0.745	0.877	1.101	1.238	1.822	1.244	0.683	0.733

Re = Blade Reynolds number (Mean = 2.555E6)
 M = Mach number (Mean = 0.930)
 Po = Inlet total pressure (bar)
 To = Inlet total temperature (K)
 Tamb = Ambient temperature (K)
 Tinj = Injection temperature (K)
 Θ = Non-dimensional temperature difference ratio *
 (iso = isothermal wall value ; meas = measure point value)
 G = Blowing rate
 I = Momentum flux ratio
 Di/Dg = Injection to freestream density ratio
 WIP = Weak injection parameter
 SIP = Strong injection parameter
 Cd = Coefficient of discharge

*
 iso = isothermal wall value based on initial wall temperature (ambient)
 meas = measure point value based on a measured wall temperature of 302K

Error analysis was by a 95% confidence level student T-fit.

%Re and %M are deviations from mean values of Reynolds number and Mach number respectively.

RUN	Ti(K)	Tmeas(K)	XTmeas	XPo	XTo	XTamb	XRe	XM	XDi/Dg	X θ		XG
										iso	meas	
695	269.0	302.0	-0.11	-0.17	-0.22	0.18	-0.02	-0.25	0.01	2.09	1.63	0.23
694	269.1	302.8	0.17	0.38	-0.09	-0.17	0.72	0.61	0.18	0.70	2.54	-0.32
692	290.0	304.6	0.76	0.77	0.36	0.25	0.37	0.18	-2.08	-1.58	-1.08	1.05
691	288.8	303.0	0.22	0.53	0.18	0.07	0.49	0.61	-1.85	-0.69	-1.73	1.87
690	312.8	303.1	0.27	0.65	0.34	0.28	0.49	0.93	-1.17	1.07	-0.51	-1.41
689	311.6	302.9	0.20	0.85	0.47	0.14	0.52	0.93	-0.67	2.71	1.18	-1.41
688	255.3	298.0	-1.45	-0.29	-0.60	0.11	0.41	-0.04	-0.10	0.58	-2.51	0.77
687	254.5	298.7	-1.19	0.18	-0.14	-0.10	0.37	0.07	0.69	-0.06	-1.65	0.65
686	258.2	301.8	-0.16	-0.20	0.55	0.80	-0.89	0.07	-0.55	-0.98	-1.89	-0.43
685	257.1	301.0	-0.43	-0.23	0.58	0.66	-0.96	-0.04	-0.10	-0.55	-2.06	-0.19
684	274.3	303.2	0.28	0.03	0.76	0.94	-0.85	0.28	-0.38	-1.25	-3.33	-0.55
683	271.0	302.0	-0.10	-0.23	0.50	0.70	-0.85	0.07	0.57	1.35	-1.33	0.77
682	269.3	300.6	-0.58	0.18	0.52	0.32	-0.45	0.18	1.08	1.60	-1.73	0.65
681	269.0	300.8	-0.50	0.03	0.42	0.32	-0.53	-0.04	1.25	2.01	-0.97	0.77
680	286.1	300.6	-0.57	0.12	0.12	-0.13	-0.02	0.07	0.52	1.66	-1.88	-0.31
678	287.9	301.5	-0.27	-0.20	0.18	0.32	-0.45	-0.04	-1.12	1.17	-2.69	0.29
676	319.4	307.4	1.68	1.79	1.65	1.14	0.25	1.57	-1.34	-4.42	-4.14	-1.39
675	320.4	306.4	1.33	0.77	1.38	1.01	-0.77	0.61	-1.91	-6.89	-7.30	-0.67
674	315.2	305.4	1.00	0.94	1.27	0.87	-0.38	0.82	-0.44	0.66	-0.61	-0.07
673	316.6	303.8	0.49	0.71	0.90	0.73	-0.06	1.14	-1.29	-2.64	-5.17	-0.31
672	257.8	303.8	0.48	0.06	1.25	1.01	-1.47	0.07	-0.10	-0.83	-0.30	-0.18
671	256.5	303.5	0.39	0.47	0.84	0.83	-0.42	0.61	0.01	0.16	1.17	-0.56
670	256.7	305.3	0.99	0.09	1.49	1.21	-1.79	-0.04	0.57	0.44	2.20	0.20
669	255.6	305.0	0.89	0.15	1.06	0.87	-1.24	-0.04	0.63	0.79	3.64	0.01
667	270.4	305.9	1.18	0.00	0.71	1.08	-1.00	-0.25	0.63	3.06	4.32	0.40
666	268.0	304.9	0.85	0.24	1.22	0.83	-1.24	0.07	1.98	3.96	4.21	0.78
665	269.3	302.3	0.01	-0.23	0.23	0.45	-0.53	0.07	0.57	2.33	1.08	0.59
664	271.1	303.0	0.23	-0.03	0.44	0.28	-0.73	-0.36	0.01	-0.19	-0.05	0.20
663	289.7	306.8	1.48	0.09	0.90	0.80	-1.28	-0.58	-0.55	0.68	1.92	0.01
662	289.7	305.3	1.00	0.47	1.00	0.70	-0.77	0.18	-0.44	0.29	-0.28	-0.37
661	288.7	305.6	1.10	0.53	0.92	0.45	-0.69	-0.04	-0.05	0.58	1.34	-0.18
660	287.8	305.0	0.88	0.62	0.68	0.32	-0.18	0.28	-0.10	1.17	1.67	-0.37
659	313.8	305.4	1.00	0.30	0.76	0.32	-0.69	-0.04	-0.84	0.24	1.25	0.01
658	315.6	304.4	0.67	-0.06	0.58	0.52	-0.81	-0.04	-1.57	-2.22	-3.11	0.01
657	313.7	306.0	1.22	0.32	0.55	0.14	-0.57	-0.47	-0.95	-0.44	2.30	-0.18
656	315.7	304.4	0.68	0.12	0.12	-0.20	-0.22	-0.47	-2.02	-5.52	-3.64	-0.37
649	274.3	304.0	0.57	0.59	-0.20	-0.51	0.84	0.07	-2.02	-5.41	-0.73	-0.88
648	272.5	302.6	0.11	0.09	-0.95	-0.93	1.11	-0.47	-2.13	-4.51	0.34	-0.40
647	270.6	303.2	0.29	0.18	0.10	-0.34	-0.10	-0.47	-0.38	-1.50	1.28	0.56
646	272.6	302.8	0.17	0.53	-0.06	-0.51	0.72	0.28	-1.29	-3.86	-0.96	-0.40
643	292.7	308.6	2.07	0.41	1.59	1.28	-1.51	0.07	-0.61	-1.18	0.26	0.08
642	290.8	306.0	1.23	0.27	0.76	0.42	-0.69	-0.04	-1.12	-1.87	-0.33	0.08
641	293.8	312.1	3.24	0.32	2.21	2.04	-2.53	-0.36	-0.78	0.09	3.47	0.08
640	293.5	310.3	2.63	0.41	1.91	1.77	-2.06	-0.25	-0.89	-0.50	1.41	0.08
639	316.1	308.5	2.03	0.09	1.83	1.52	-2.26	-0.25	-1.12	2.30	2.64	0.08
638	315.0	307.6	1.76	0.32	1.67	1.39	-1.75	0.18	-0.95	3.40	3.19	0.08
637	316.6	311.1	2.89	0.47	2.37	2.18	-2.37	0.28	-0.78	4.63	6.00	0.08
636	315.1	310.1	2.56	0.06	2.45	2.15	-3.00	-0.15	-0.22	6.96	6.92	0.56
552	267.4	294.8	-2.50	-0.73	-1.77	-1.69	1.46	-0.25	-0.89	-1.58	-4.39	-1.12
551	264.9	295.0	-2.41	-0.70	-2.31	-1.93	2.21	-0.04	-0.44	0.54	-0.77	-0.94
550	266.9	296.1	-2.07	-0.91	-2.23	-1.83	1.70	-0.58	-1.06	-1.17	-1.43	-1.03
549	263.3	294.4	-2.62	-0.79	-2.55	-2.07	2.32	-0.36	0.01	1.84	0.30	-0.58

RUN	Ti(K)	Tmeas(K)	%Tmeas	%Po	%To	%Tamb	%Re	%M	%Di/Dg	% Θ		%S
										iso	meas	
548	256.7	295.7	-2.19	-0.29	-1.96	-1.69	2.21	-0.04	3.17	-5.15	-4.27	0.51
547	245.4	293.8	-2.83	-0.62	-2.31	-2.17	2.29	-0.15	5.31	3.34	3.53	1.77
546	248.0	292.6	-3.20	-0.70	-2.47	-2.34	2.40	-0.15	4.35	0.72	0.04	1.23
545	255.0	294.1	-2.71	-0.82	-2.79	-2.41	2.72	-0.15	1.08	-5.15	-3.35	-0.12
540	244.2	291.4	-3.61	-0.91	-3.43	-2.72	3.30	-0.58	5.20	4.05	3.60	1.68
538	248.7	294.9	-2.47	-0.97	-2.15	-1.51	1.42	-0.90	4.47	2.63	1.86	1.50
536	283.8	297.5	-1.59	-0.59	-1.72	-1.45	1.58	0.07	-3.20	0.09	-1.85	-0.40
535	282.8	297.5	-1.58	-1.14	-2.20	-1.79	1.23	-1.22	-3.26	0.09	-0.23	0.33
532	309.0	301.0	-0.45	-1.03	-1.53	-0.93	0.84	-0.25	2.21	0.11	1.20	-0.76
531	308.0	300.0	-0.77	-1.00	-2.25	-1.17	1.66	-0.58	1.76	-0.30	0.93	-0.94
530	307.0	297.3	-1.67	-1.32	-2.66	-1.86	1.93	-0.36	1.70	-1.81	-1.80	-0.67
529	308.0	299.4	-0.98	-0.94	-1.24	-0.93	0.56	-0.04	2.77	2.16	0.66	-0.49
Maximum positive error			3.241	1.794	2.447	2.180	3.303	1.574	5.313	6.963	6.919	1.871
Maximum negative error			-3.606	-1.321	-3.430	-2.723	-2.999	-1.221	-3.261	-6.887	-7.302	-1.415

Mean values:-

Po = 3.403 bar
 To = 374.339 K
 Tamb = 289.586 K
 Re = 2.555
 M = 0.930
 Di/Dg = 1.773
 Tmeas = 302.321 K

%values are deviations from the given mean values.

Θ ,iso values:-

0.729 ; 1.019 ; 1.227 ; 1.413

Θ ,meas values:-

0.871 ; 1.218 ; 1.438 ; 1.616

Blowing rates:-

0.208 ; 0.365 ; 0.522 ; 0.831 ; 1.106

I/D	Runs		Re	M	Po	To	Tamb	Tmeas	Θ		G	I	Di/Dg
									iso	meas			
3DL	636	638	2.494	0.931	3.410	382.050	294.700	315.048	0.915	0.767	0.209	0.313	1.763
3DM	637	639	2.496	0.931	3.412	382.200	294.950	316.369	0.909	0.755	0.208	0.326	1.756
3DN	640	642	2.520	0.929	3.414	379.350	292.750	292.142	1.225	1.007	0.208	0.328	1.755
3DO	641	643	2.503	0.929	3.416	381.450	294.400	293.224	1.241	1.013	0.208	0.325	1.760
3DP	646	648	2.578	0.930	3.414	372.450	287.500	272.545	1.433	1.176	0.207	0.335	1.743
3DQ	647	649	2.564	0.928	3.416	374.150	288.350	272.470	1.442	1.185	0.208	0.338	1.752
3AH	689	690	2.568	0.939	3.428	375.850	290.200	312.209	0.874	0.743	0.360	0.350	1.757
3AI	691	692	2.566	0.934	3.425	375.350	290.050	289.411	1.201	1.008	0.370	0.342	1.738
3AJ	694	695	2.563	0.932	3.407	373.750	289.600	269.032	1.468	1.245	0.365	0.342	1.775
3DR	656	658	2.542	0.928	3.404	375.650	290.050	315.647	0.842	0.701	0.521	0.518	1.741
3DS	657	659	2.539	0.928	3.414	376.800	290.250	313.748	0.887	0.729	0.522	0.521	1.757
3DT	660	662	2.543	0.933	3.421	377.500	291.050	288.759	1.227	1.026	0.520	0.544	1.768
3DU	661	663	2.530	0.928	3.414	377.750	291.400	289.198	1.238	1.026	0.522	0.544	1.768
3DV	664	666	2.530	0.929	3.407	377.450	291.200	269.578	1.468	1.251	0.525	0.572	1.791
3DW	665	667	2.535	0.929	3.399	376.100	291.800	269.840	1.477	1.261	0.525	0.573	1.784
3DX	670	671	2.526	0.933	3.412	378.700	292.550	256.624	1.643	1.417	0.521	0.603	1.778
3DY	669	672	2.520	0.931	3.407	378.650	292.300	256.682	1.643	1.413	0.522	0.598	1.778
3AA	673	675	2.544	0.938	3.428	378.600	292.100	318.534	0.817	0.695	0.826	0.852	1.745
3AB	674	676	2.553	0.942	3.450	379.800	292.500	317.342	0.851	0.716	0.825	0.831	1.757
3AC	678	680	2.549	0.931	3.401	374.900	289.850	286.999	1.190	1.034	0.831	0.916	1.768
3AD	681	683	2.537	0.931	3.400	376.050	291.050	269.968	1.421	1.248	0.837	0.945	1.789
3AE	682	684	2.538	0.933	3.407	376.750	291.400	271.804	1.401	1.230	0.831	0.927	1.779
3AF	685	687	2.547	0.931	3.402	375.150	290.400	255.781	1.586	1.408	0.833	0.948	1.778
3AG	686	688	2.549	0.931	3.395	374.250	290.900	256.739	1.580	1.410	0.832	0.953	1.767
3DA	529	531	2.583	0.928	3.370	367.800	286.550	307.986	0.878	0.736	1.099	1.223	1.813
3DB	530	532	2.590	0.928	3.363	366.500	285.550	307.968	0.869	0.723	1.099	1.254	1.808
3DG	535	536	2.591	0.925	3.374	367.000	284.900	283.258	1.206	1.020	1.106	1.387	1.715
3DJ	551	552	2.602	0.929	3.378	366.700	284.350	266.159	1.401	1.221	1.095	1.291	1.761
3DK	549	550	2.606	0.926	3.374	365.400	283.950	265.099	1.430	1.232	1.098	1.347	1.763
3DF	545	548	2.618	0.930	3.384	365.450	283.650	255.838	1.554	1.340	1.109	1.202	1.811
3DH	538	540	2.615	0.924	3.371	363.900	283.450	246.450	1.660	1.460	1.124	1.439	1.859
3DI	546	547	2.615	0.929	3.381	365.400	283.050	246.692	1.645	1.442	1.123	1.226	1.859

FIGURES

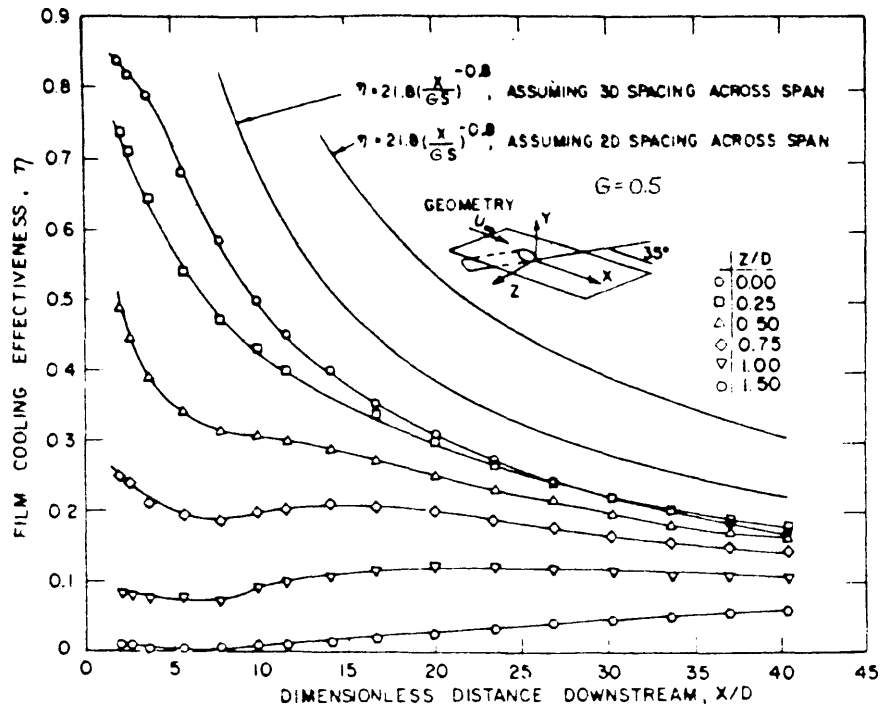


Fig. 1.1 Axial effectiveness distributions for injection through a single hole at an injection angle of 35° and blowing rate of 0.5 [Ref.1.2].

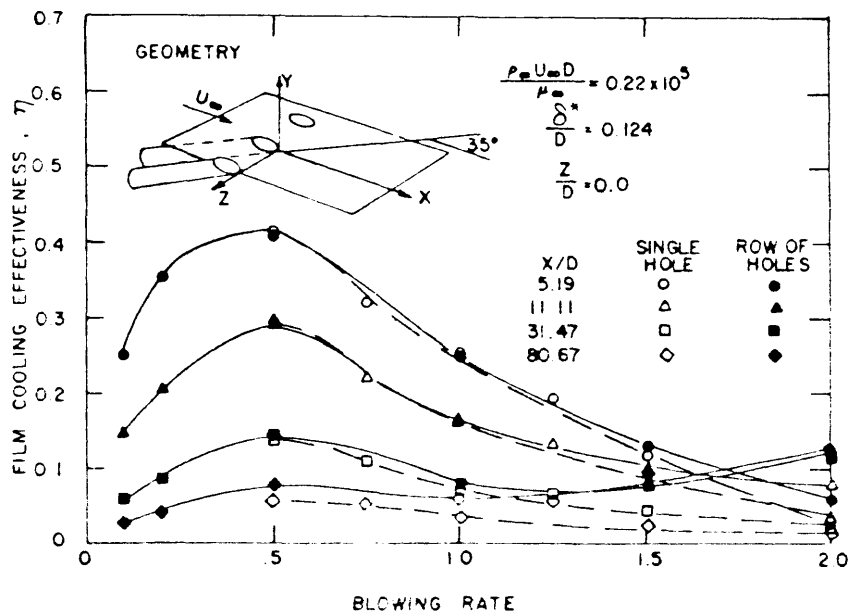


Fig. 1.2 Comparison of the centre-line film cooling effectiveness for single hole and multiple hole injection at an injection angle of 35° and various blowing rates [Ref.1.2].

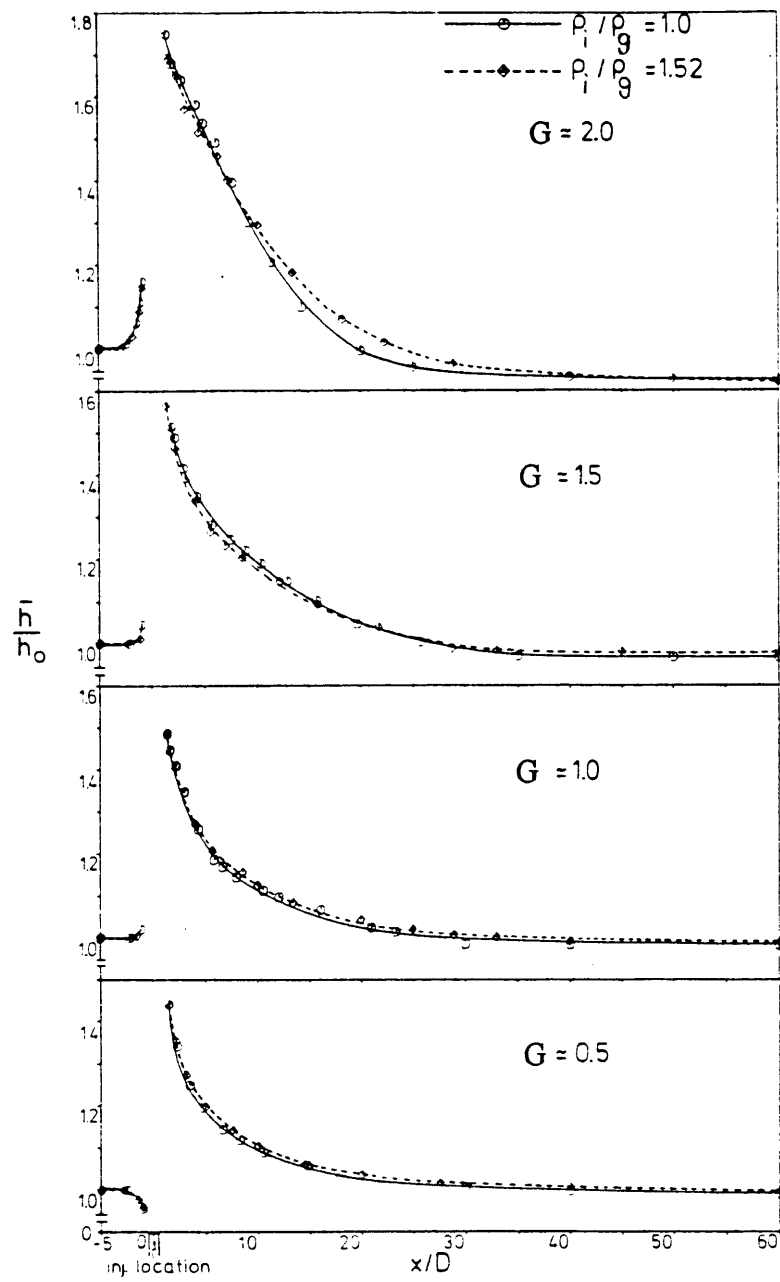


Fig. 1.3 Effect of density ratio on $\bar{h}/h_0$ for normal injection through a row of holes [Ref.1.4].

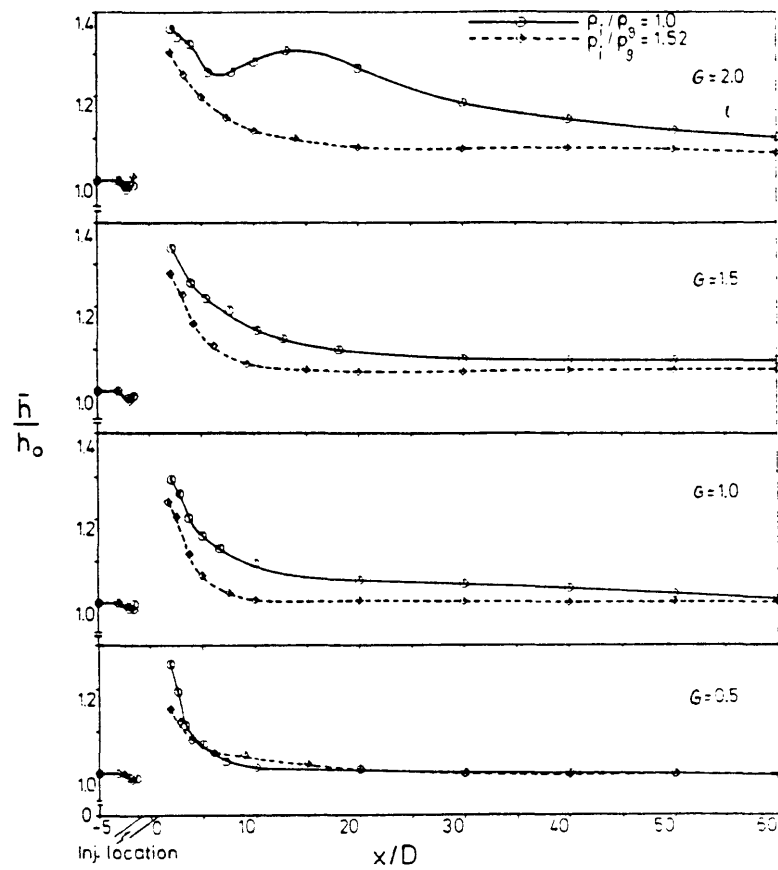


Fig. 1.4 Effect of density ratio on $\bar{h}/h_0$ for 35° injection through a row of holes [Ref.1.4].

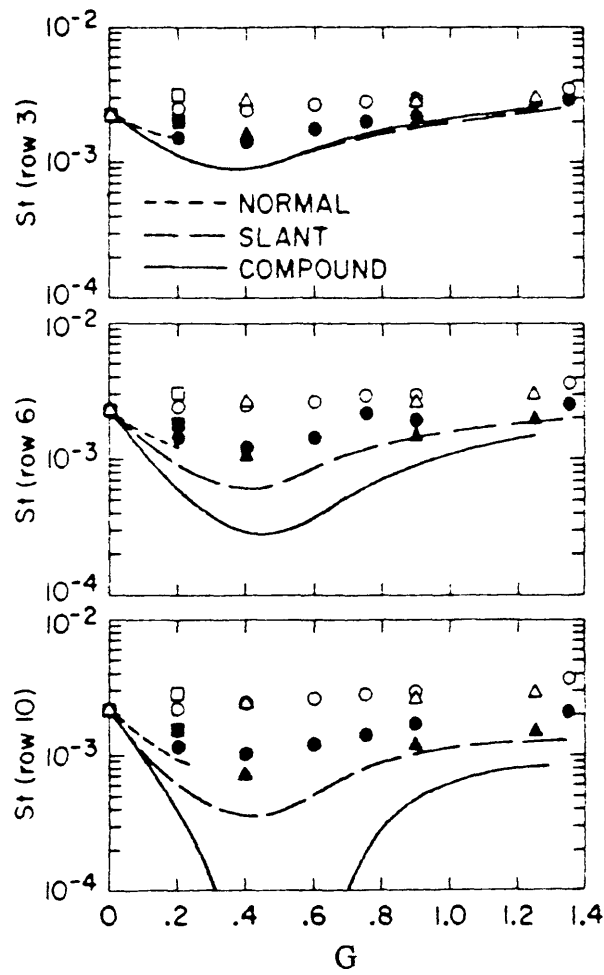


Fig. 1.5 Variation of Stanton number with blowing rate for three injection geometries [Ref.1.7].

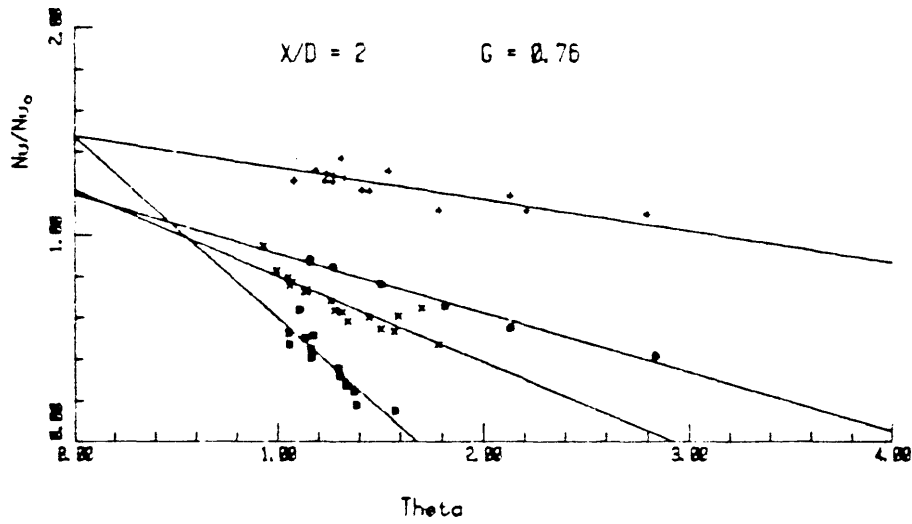


Fig. 1.6 Non-dimensionalised Nusselt number against Θ for four injection-to-freestream temperature ratios [Ref.1.10].

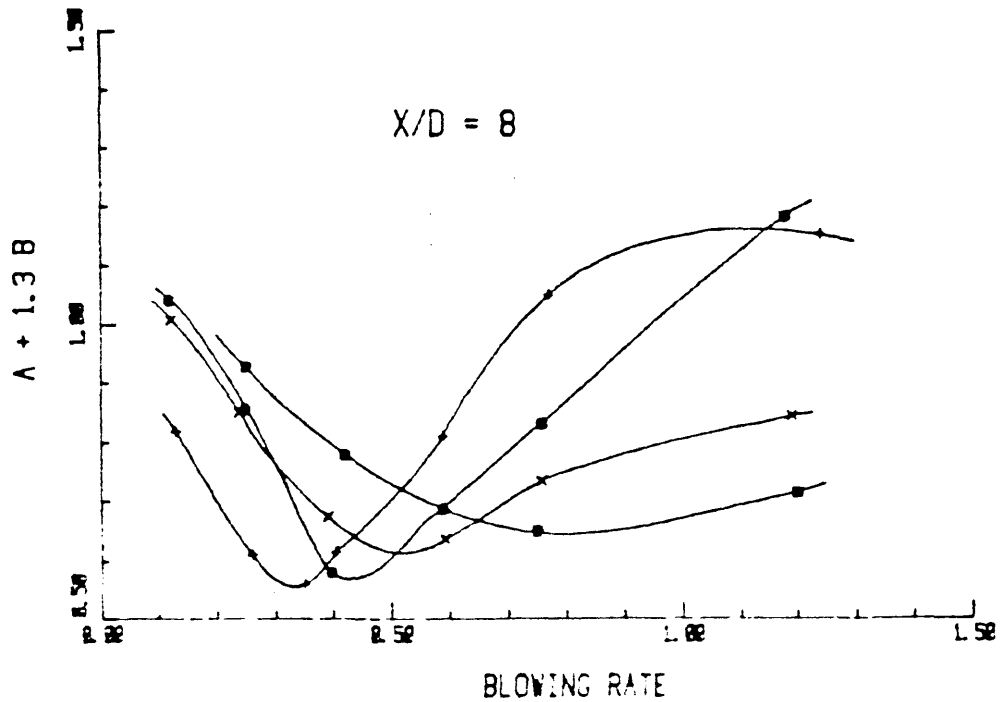


Fig. 1.7 Variation of level of heat transfer with blowing rate and injection-to-freestream temperature ratios at $\Theta=1.3$ [Ref.1.10].

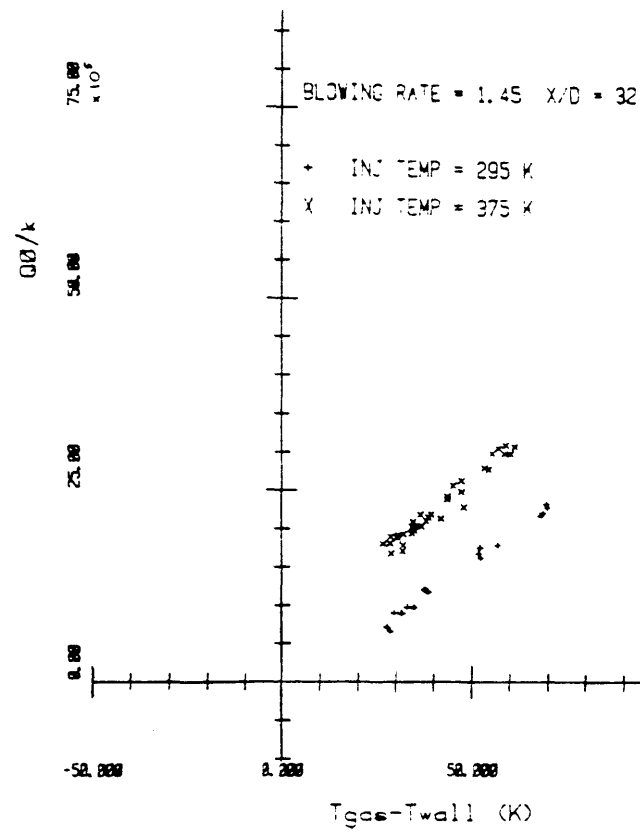


Fig. 1.8 Variation of heat transfer with gas-to-wall temperature difference at a blowing rate of 1.45 [Ref.1.10].

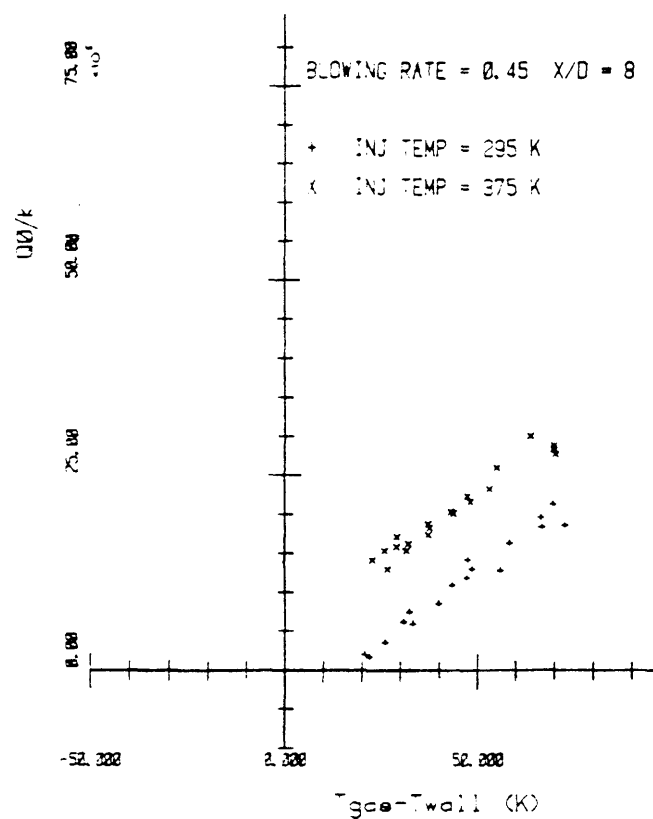


Fig. 1.9 Variation of heat transfer with gas-to-wall temperature difference at a blowing rate of 0.45 [Ref.1.10].

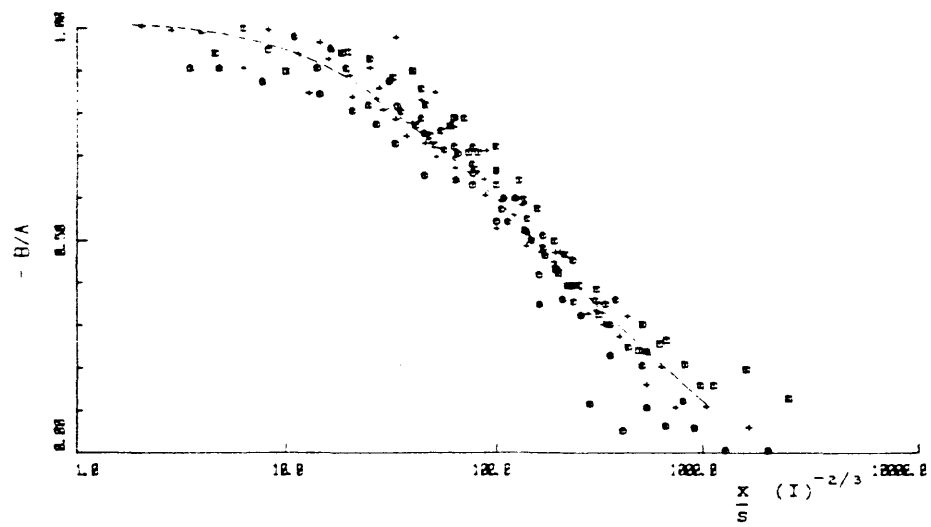


Fig. 1.10 Correlation of film-cooling data - slot data [Ref.1.11].

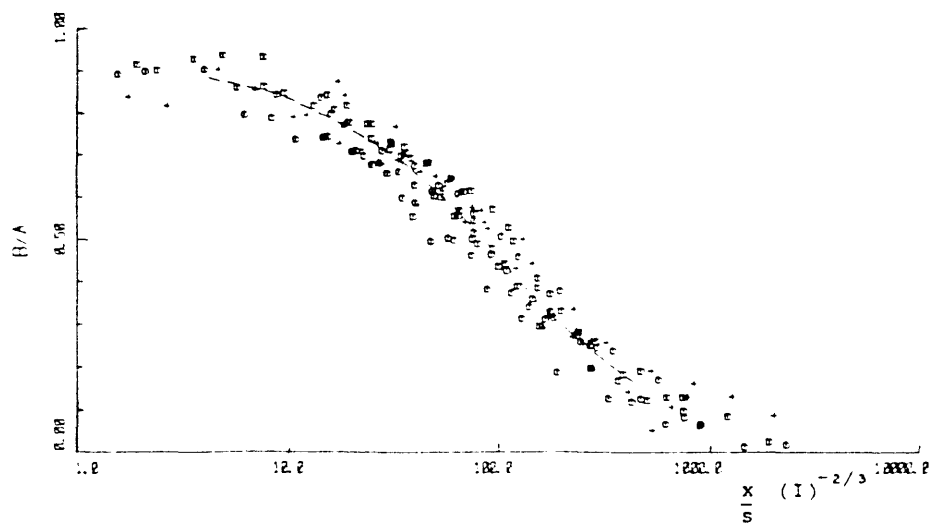


Fig. 1.11 Correlation of film-cooling data - double row data [Ref.1.11].

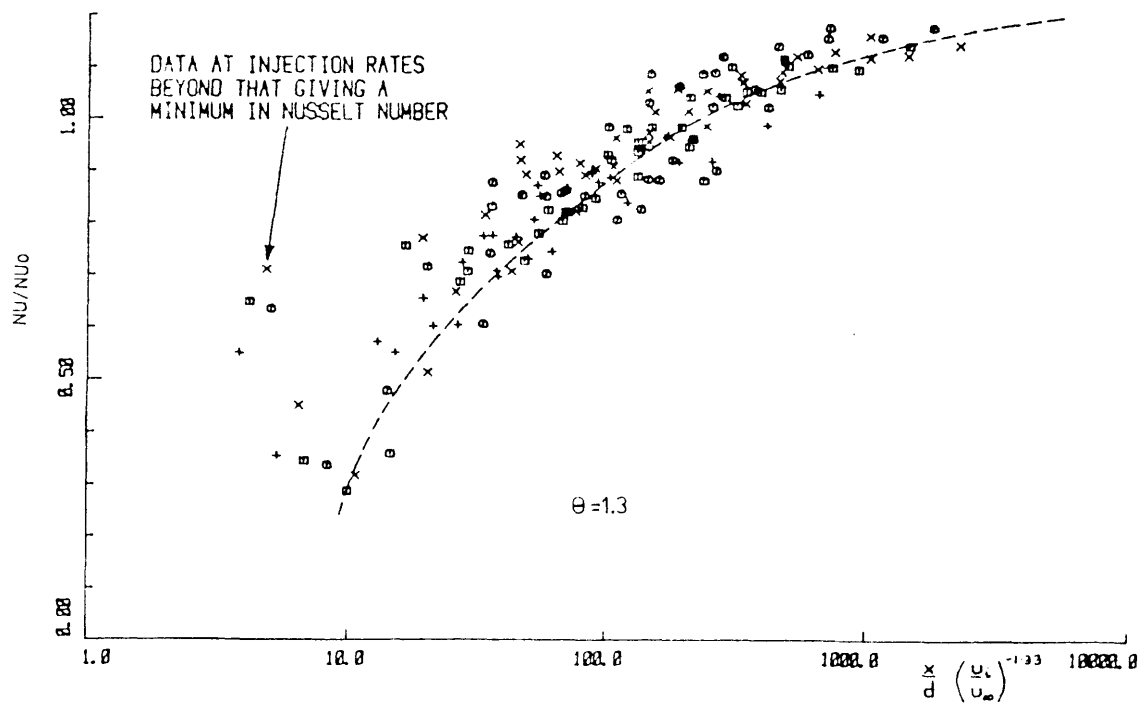


Fig. 1.12 Correlation of data for four injection-to-freestream temperature ratios at $\Theta=1.3$ - single row data [Ref.1.11].

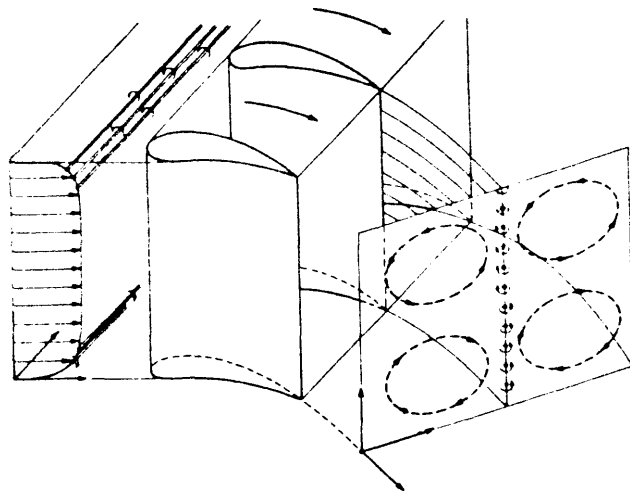


Fig. 1.13 Classical secondary flow model of Hawthorne [Ref.1.12].

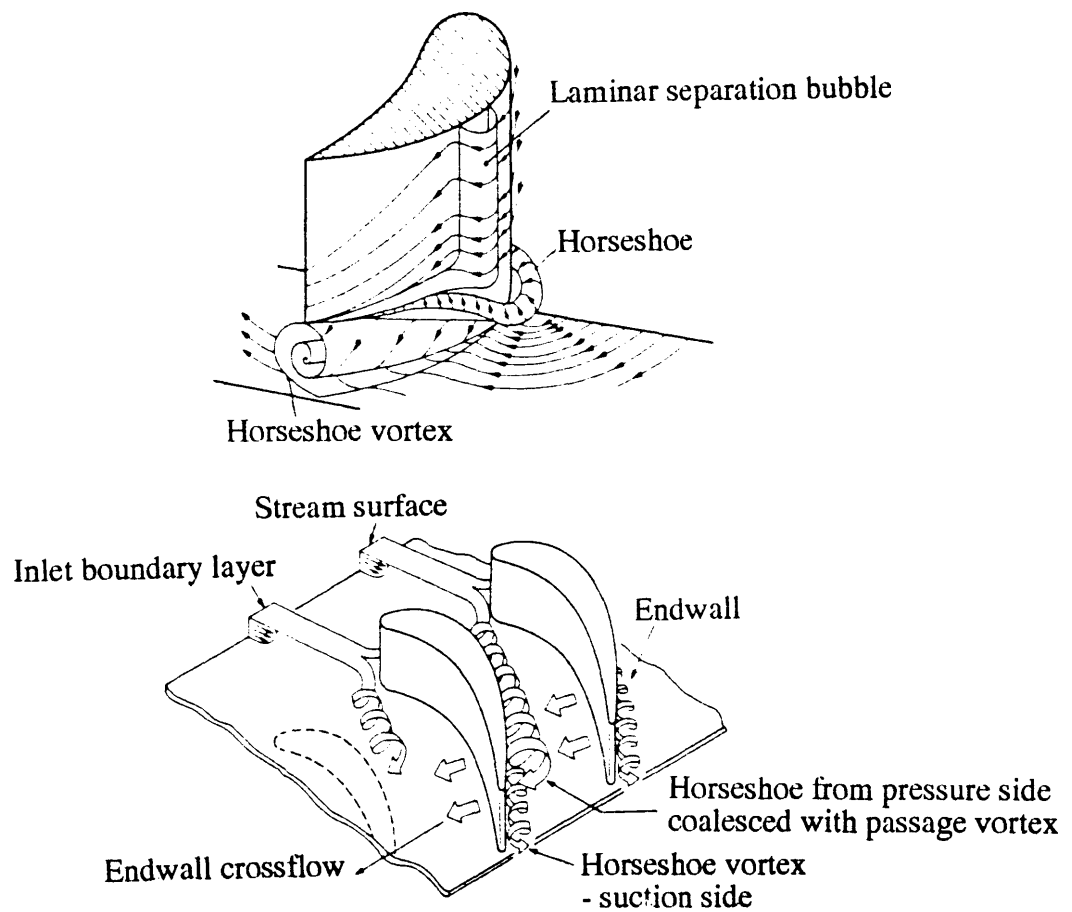
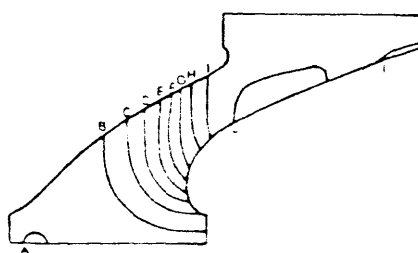
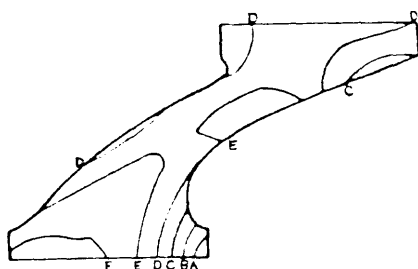


Fig. 1.14 Endwall flow models by Klein and Langston [Ref.1.12].



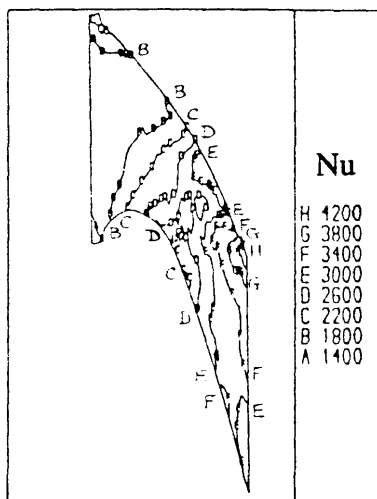
Symbol	Contour (kPa)
A	234
B	228
C	221
D	214
E	207
F	200
G	193
H	186
I	179
J	172

Fig. 1.15 Endwall static pressure contours [Ref.1.13].



Symbol	Contour (K)
A	653
B	649
C	644
D	640
E	636
F	631

Fig. 1.16 Endwall adiabatic temperature contours [Ref.1.13].



Nu
H 4200
G 3800
F 3400
E 3000
D 2600
C 2200
B 1800
A 1400

Fig. 1.17 Endwall Nusselt number contours [Ref.1.14].

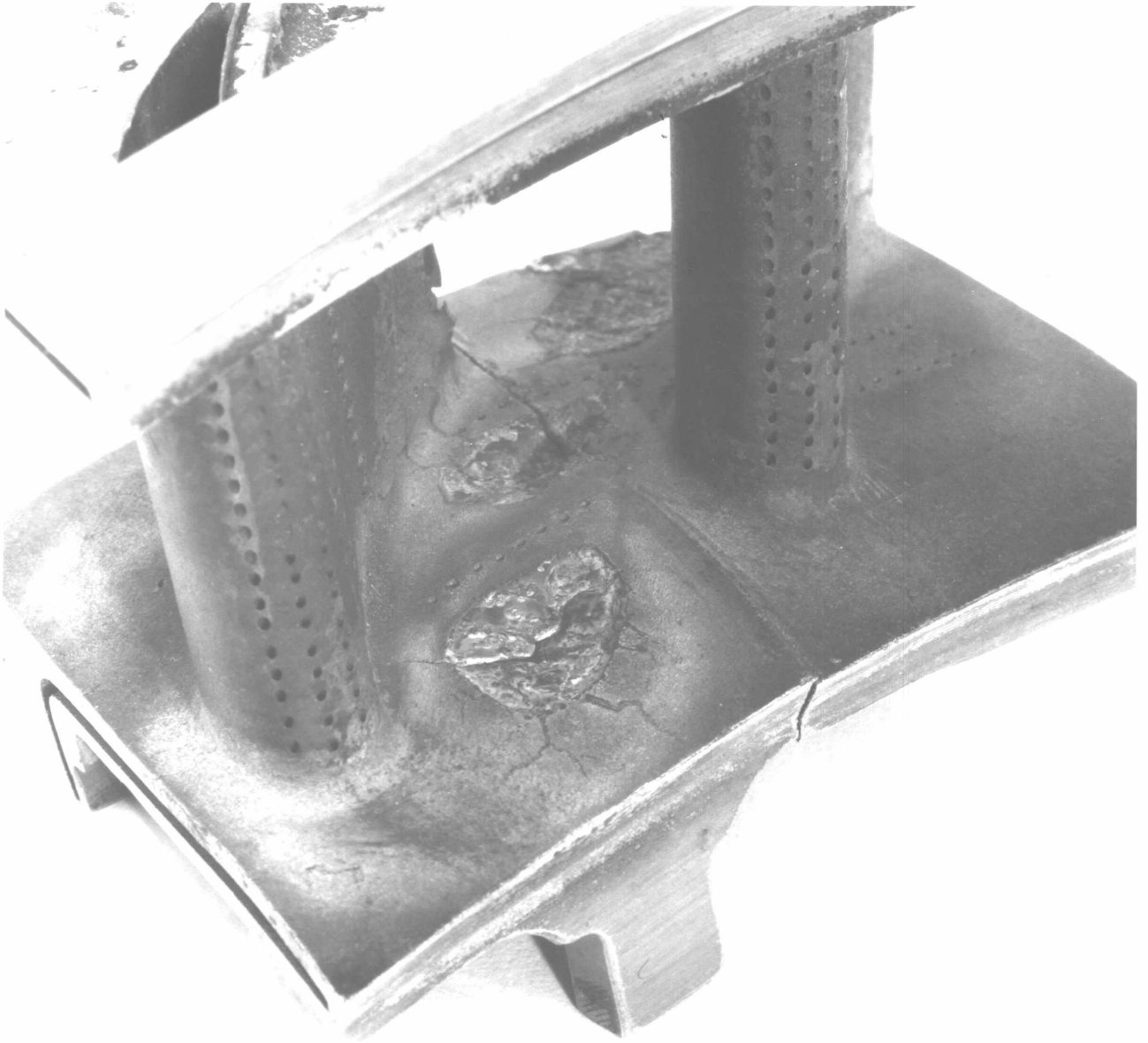


Figure 1.19 Burnt Out Platform

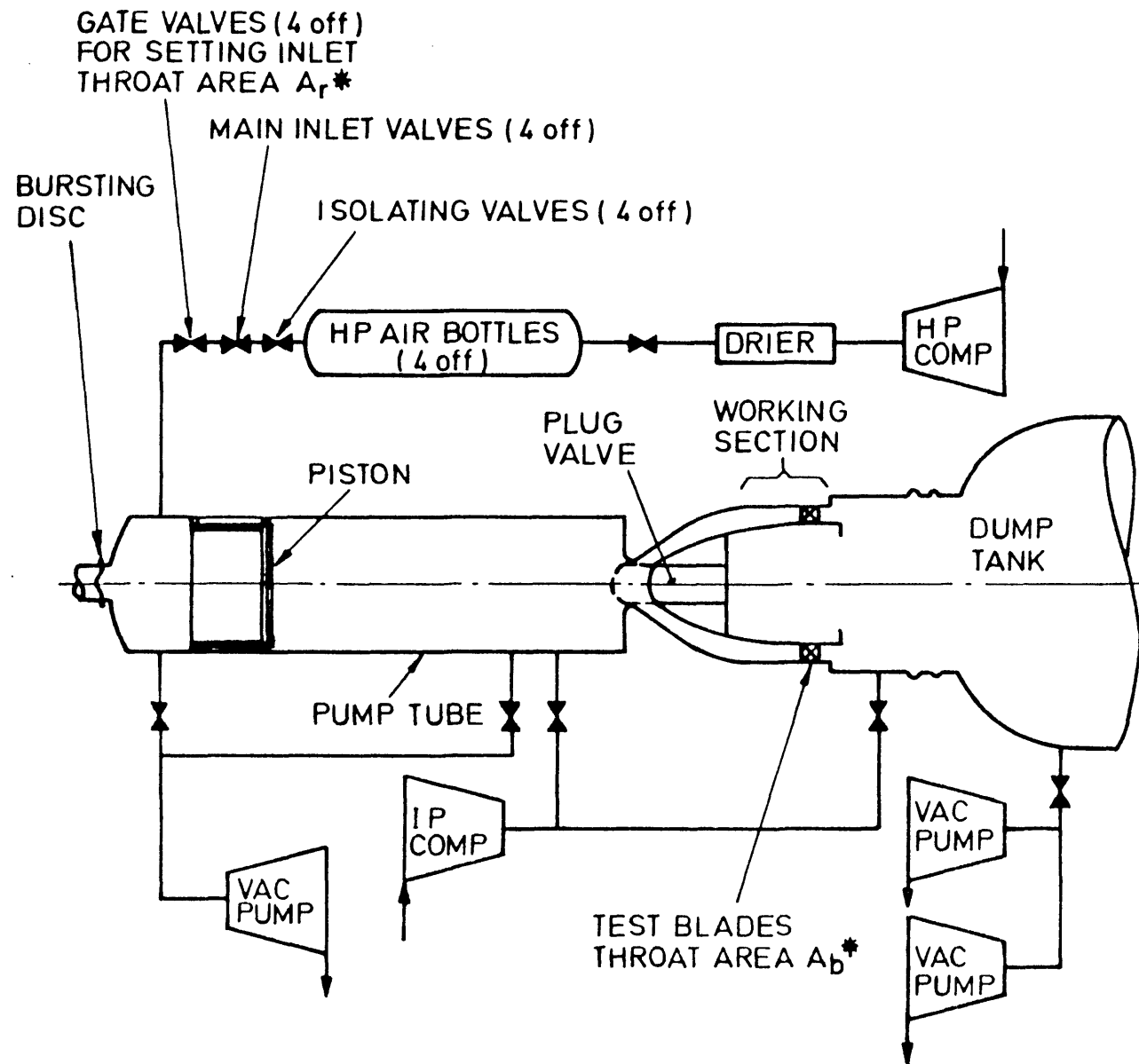


Fig. 2.1 Schematic representation of the ILPC facility [Ref.2.1].

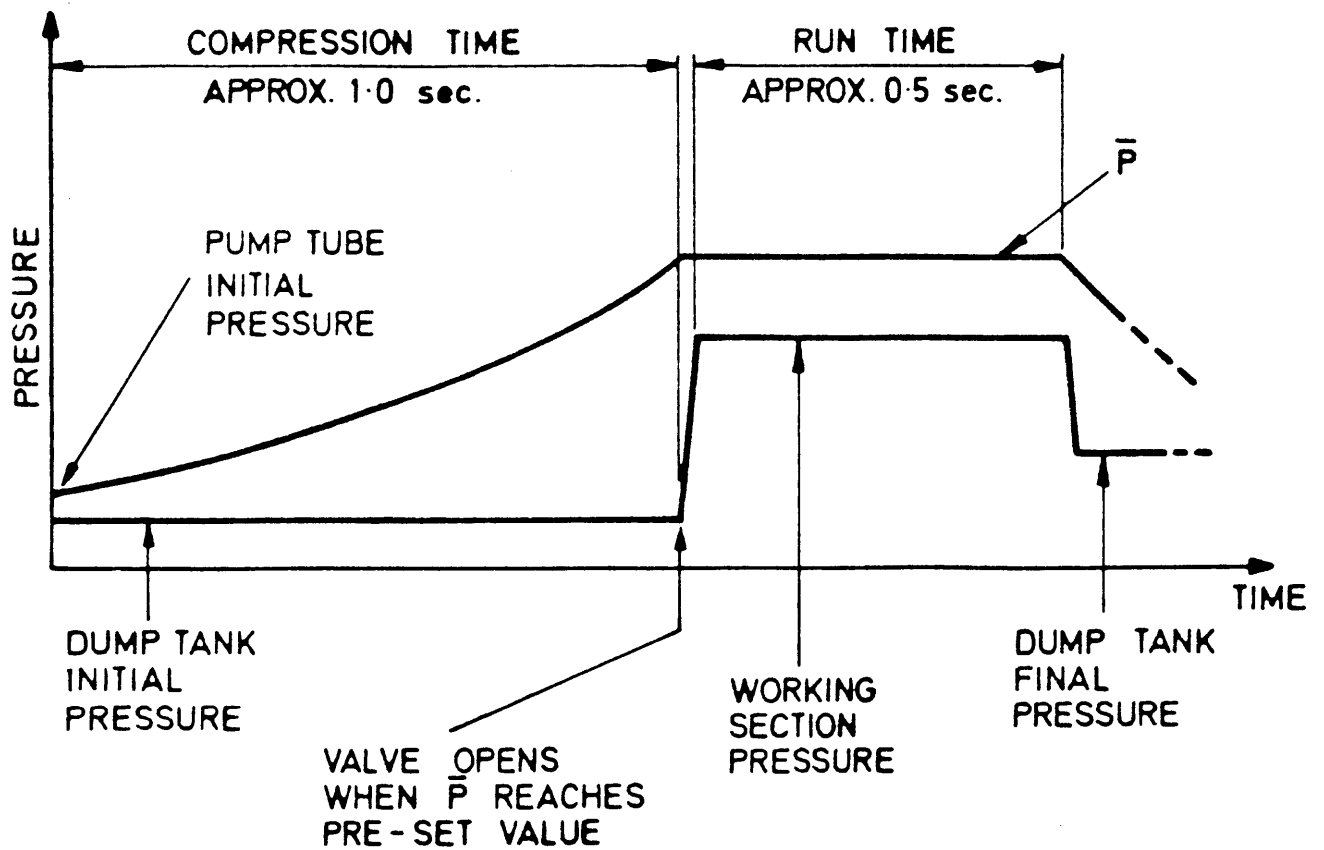


Fig. 2.2 Idealised pressure-time history [Ref.2.1].

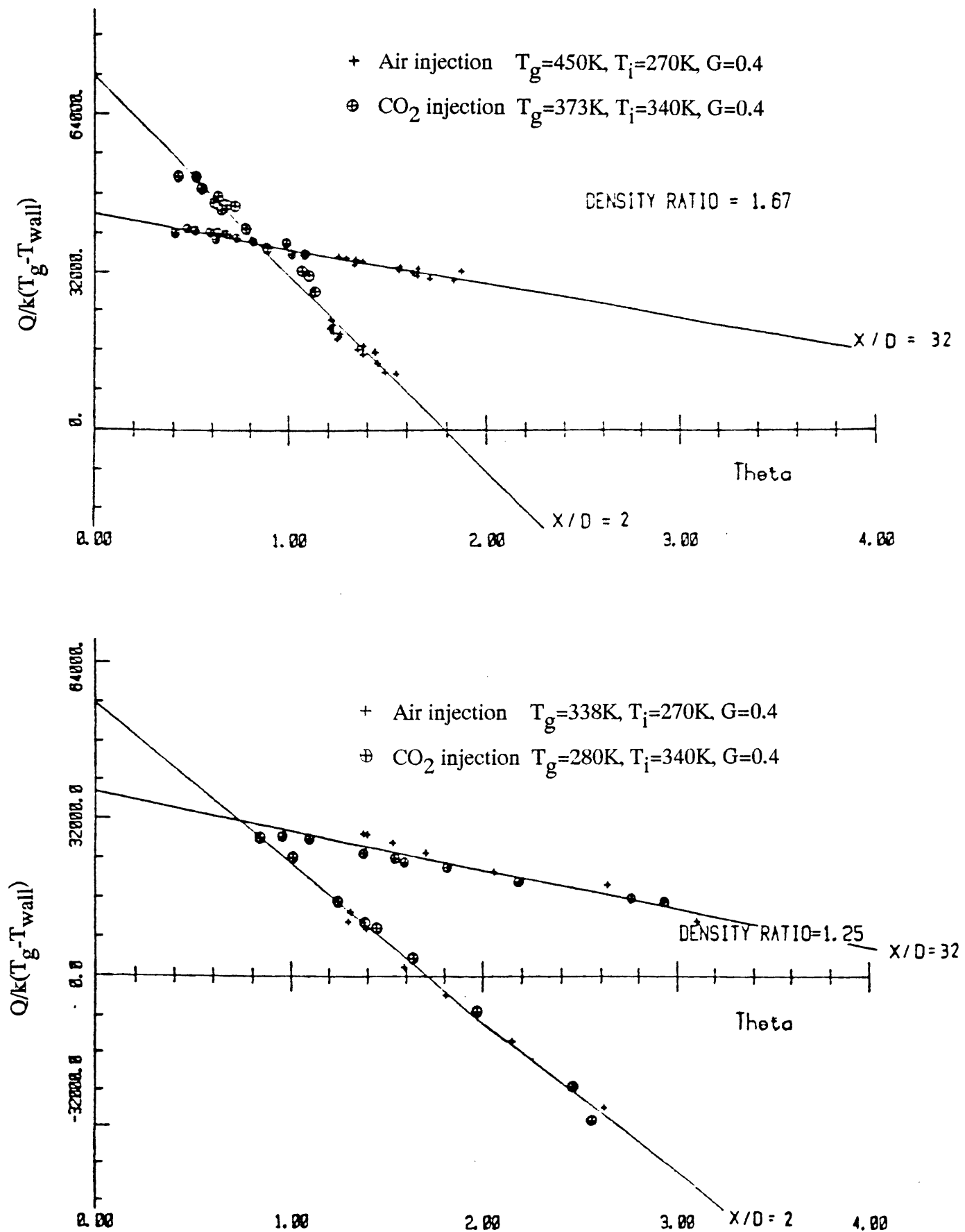


Fig. 2.3 Similarity in the thermofluid behaviour of air and CO_2 in the film-cooling process [Ref.2.3].

NGV OUTER PLATFORM
SURFACE STATIC PRESSURE CONTOURS

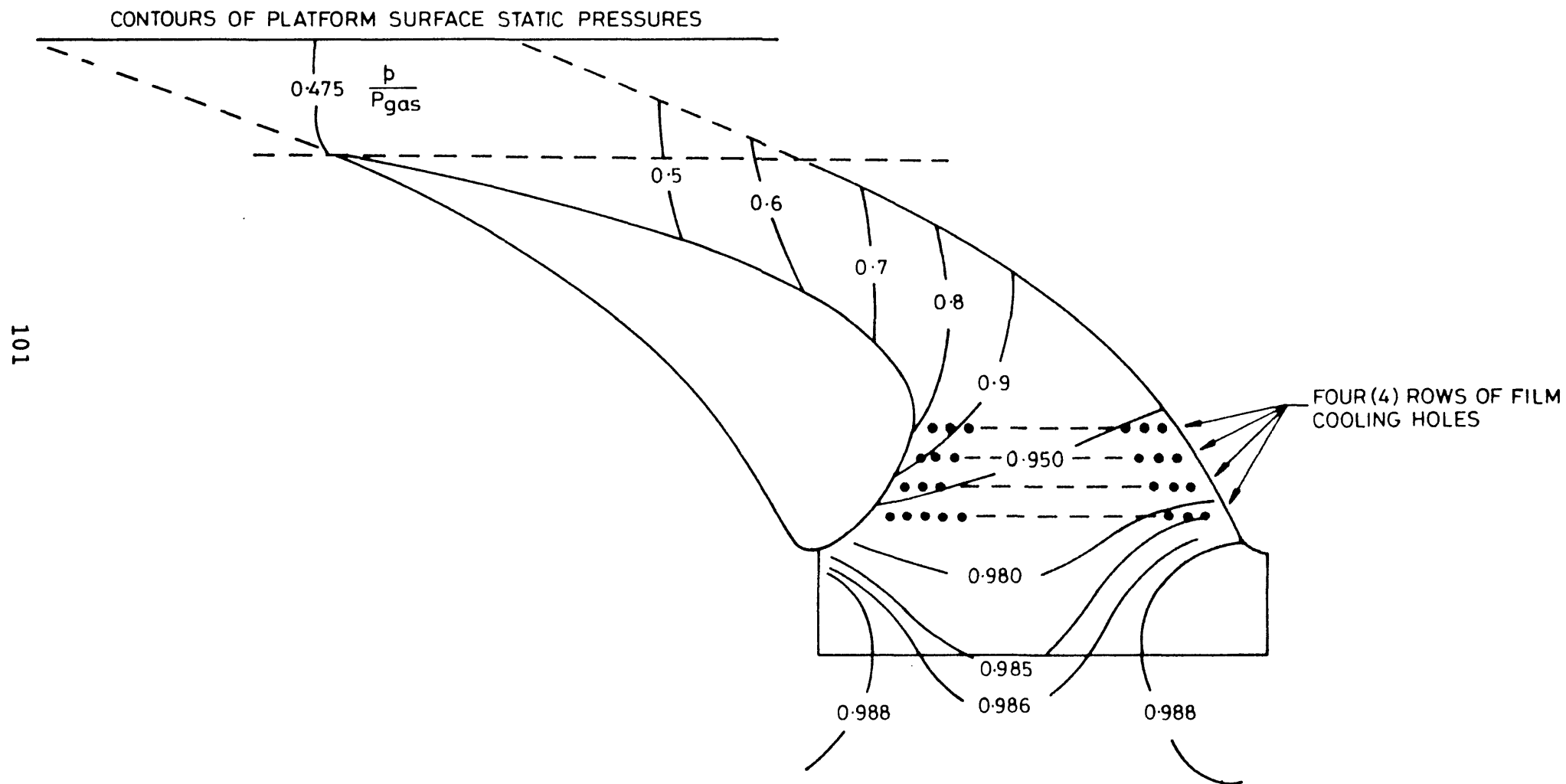


Fig. 4.1 Current engine endwall cooling configuration [Ref.4.1].

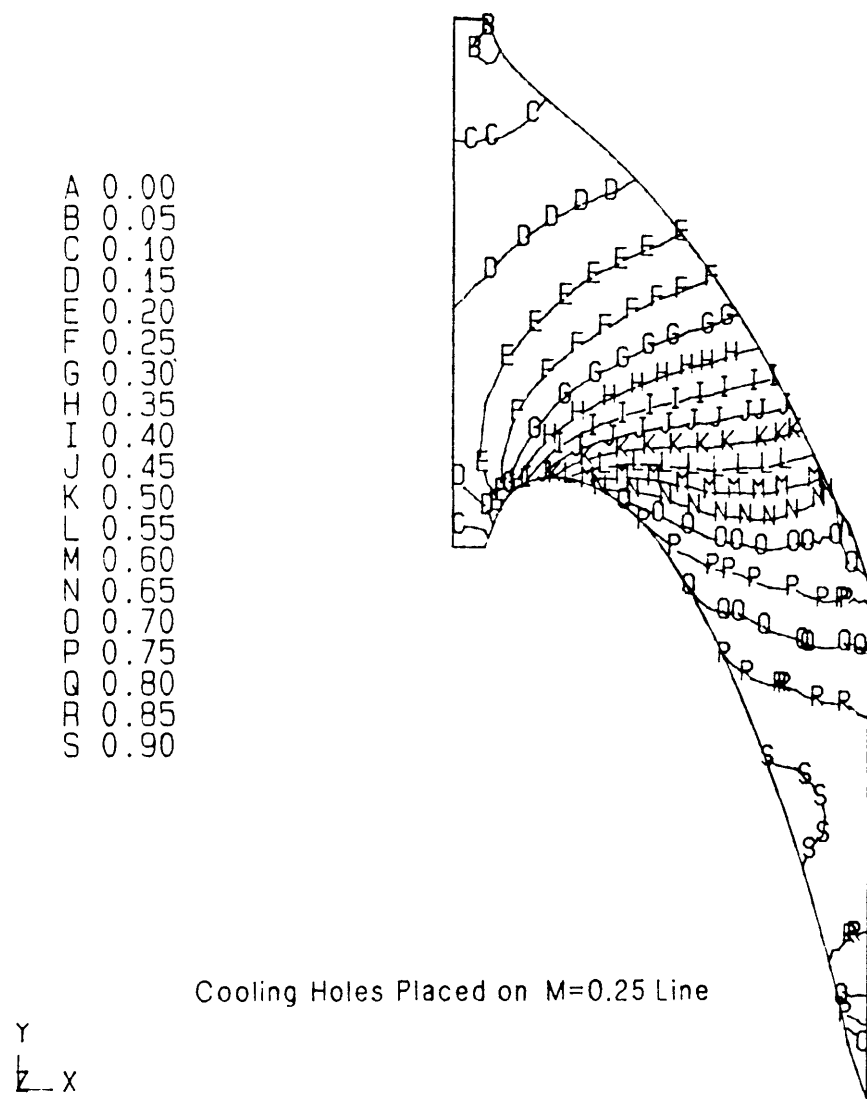


Fig. 4.2 Predicted endwall Mach number distribution [Ref.4.1].

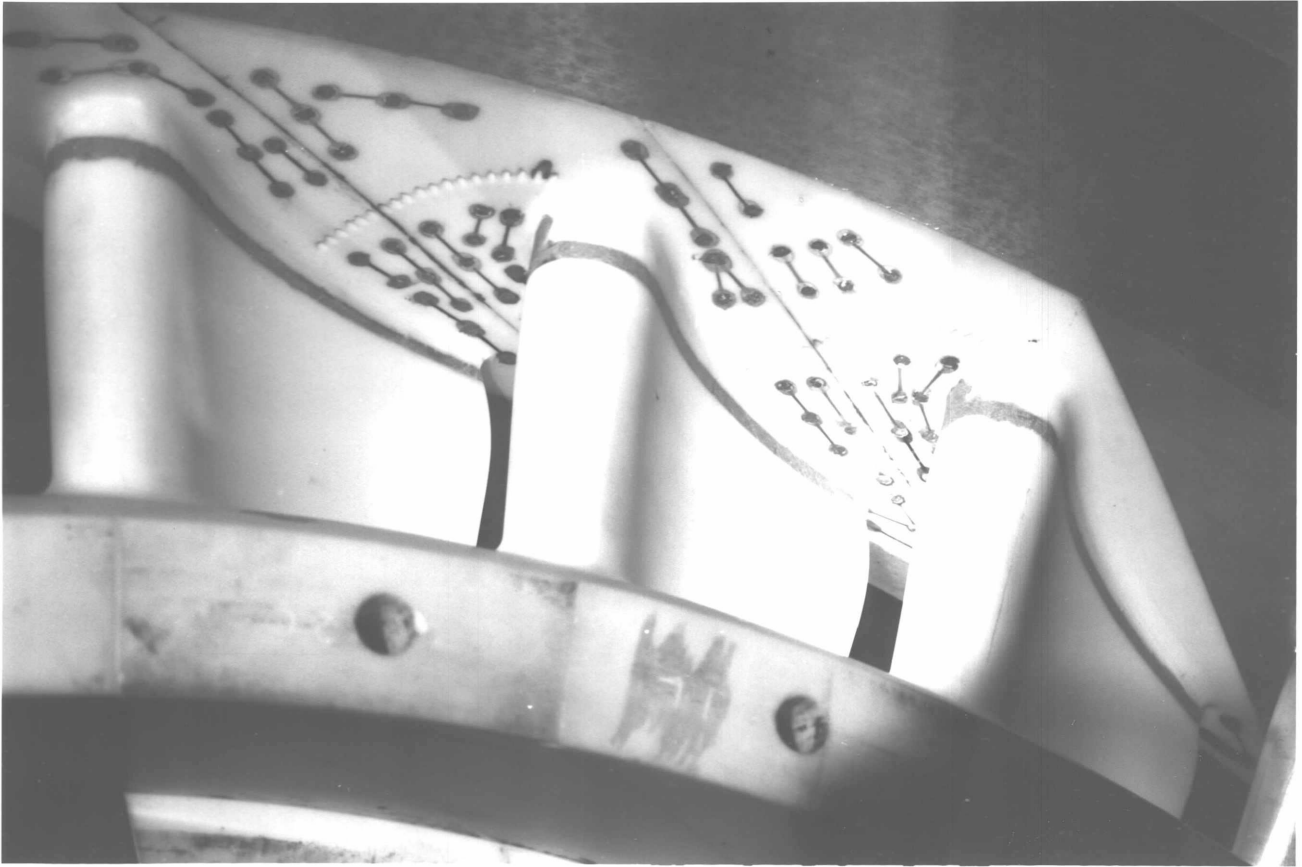


Figure 4.3 Test Blade and Endwall
with Film-Cooling Holes
and Heat Transfer Gauges

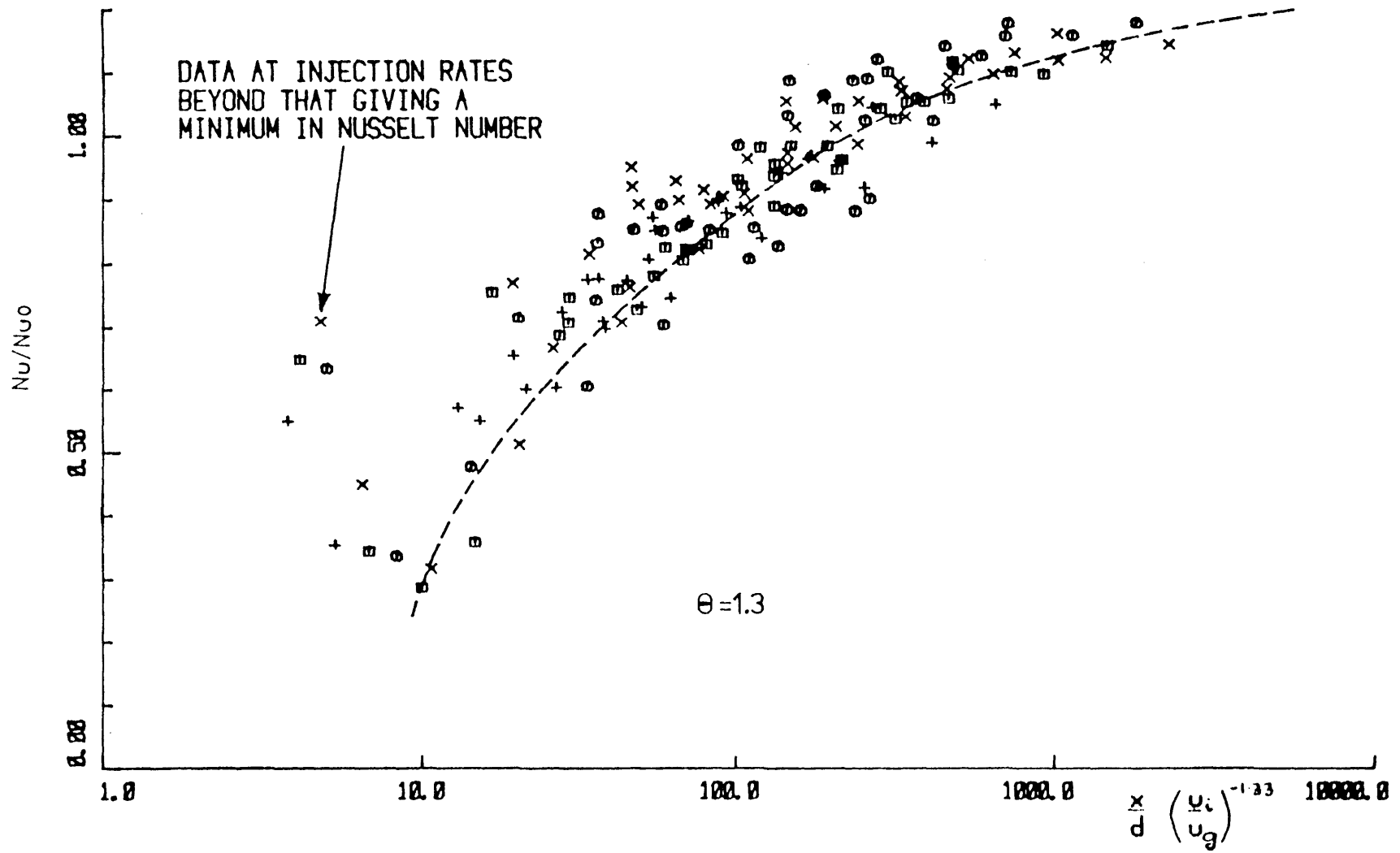


Fig. 4.4 Correlation of film-cooling data - single row data [Ref.1.11].

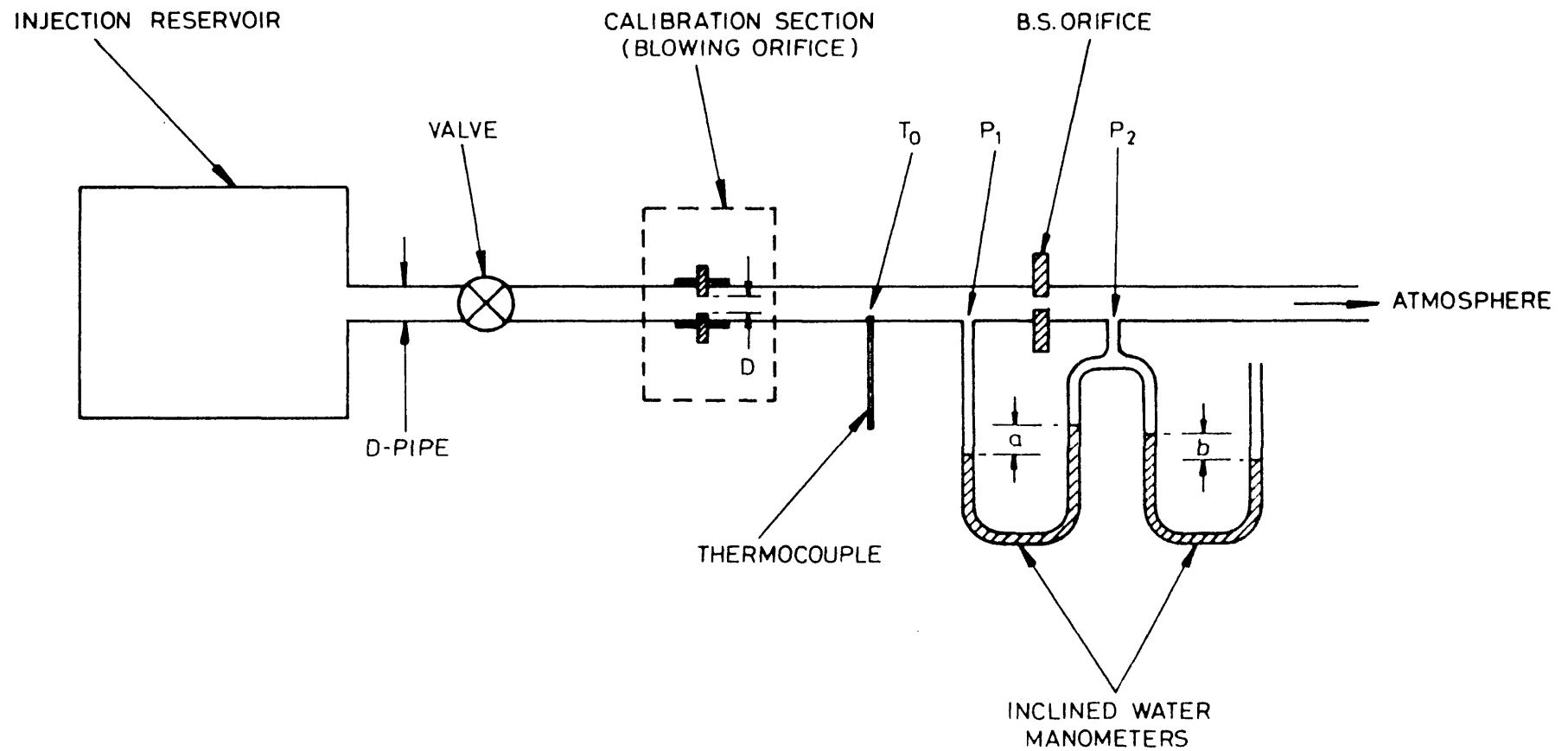


Fig. 5.1 Schematic diagram of injection orifice calibration system.

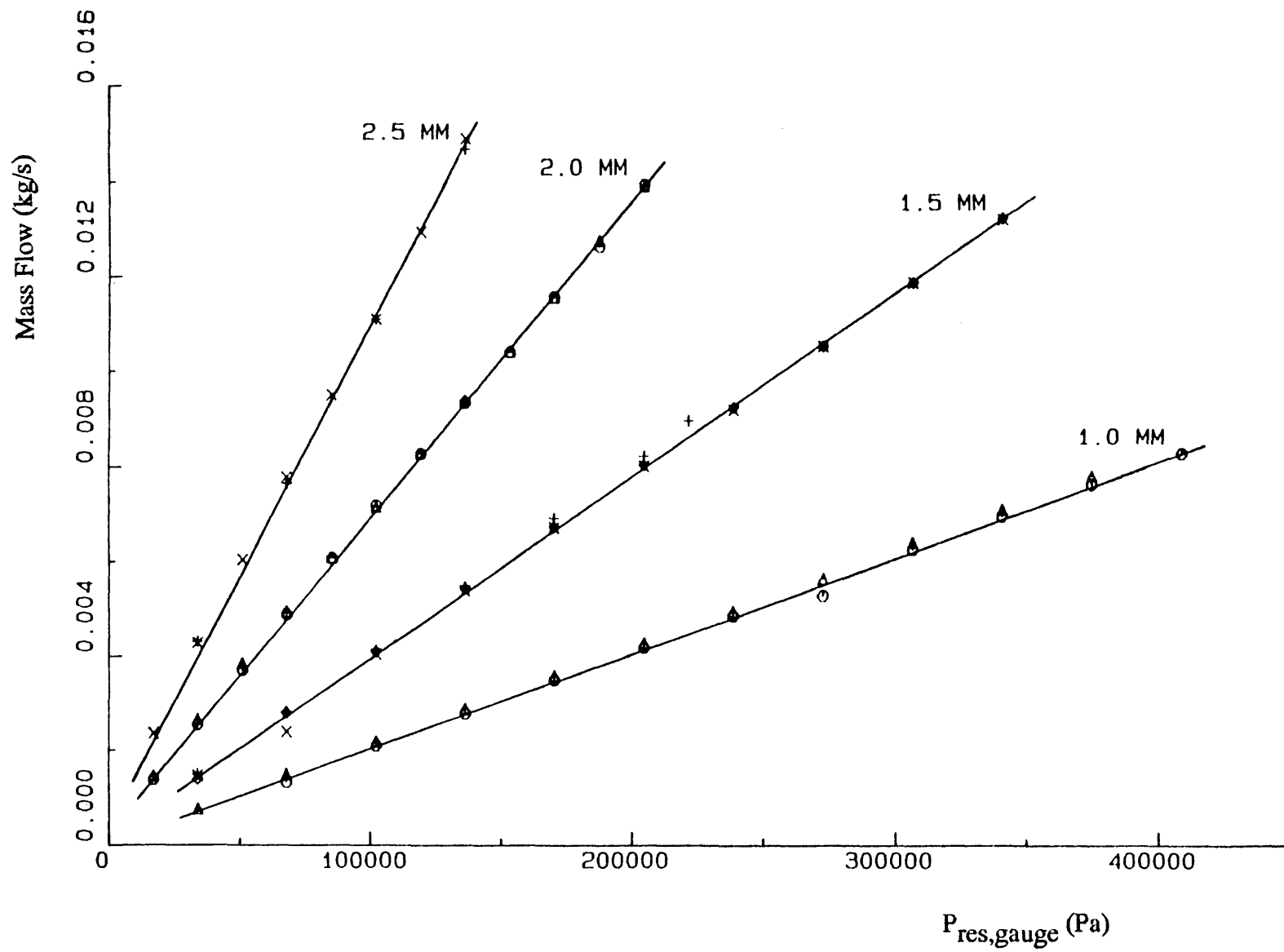


Fig. 5.2 Injection orifice calibrations for air.

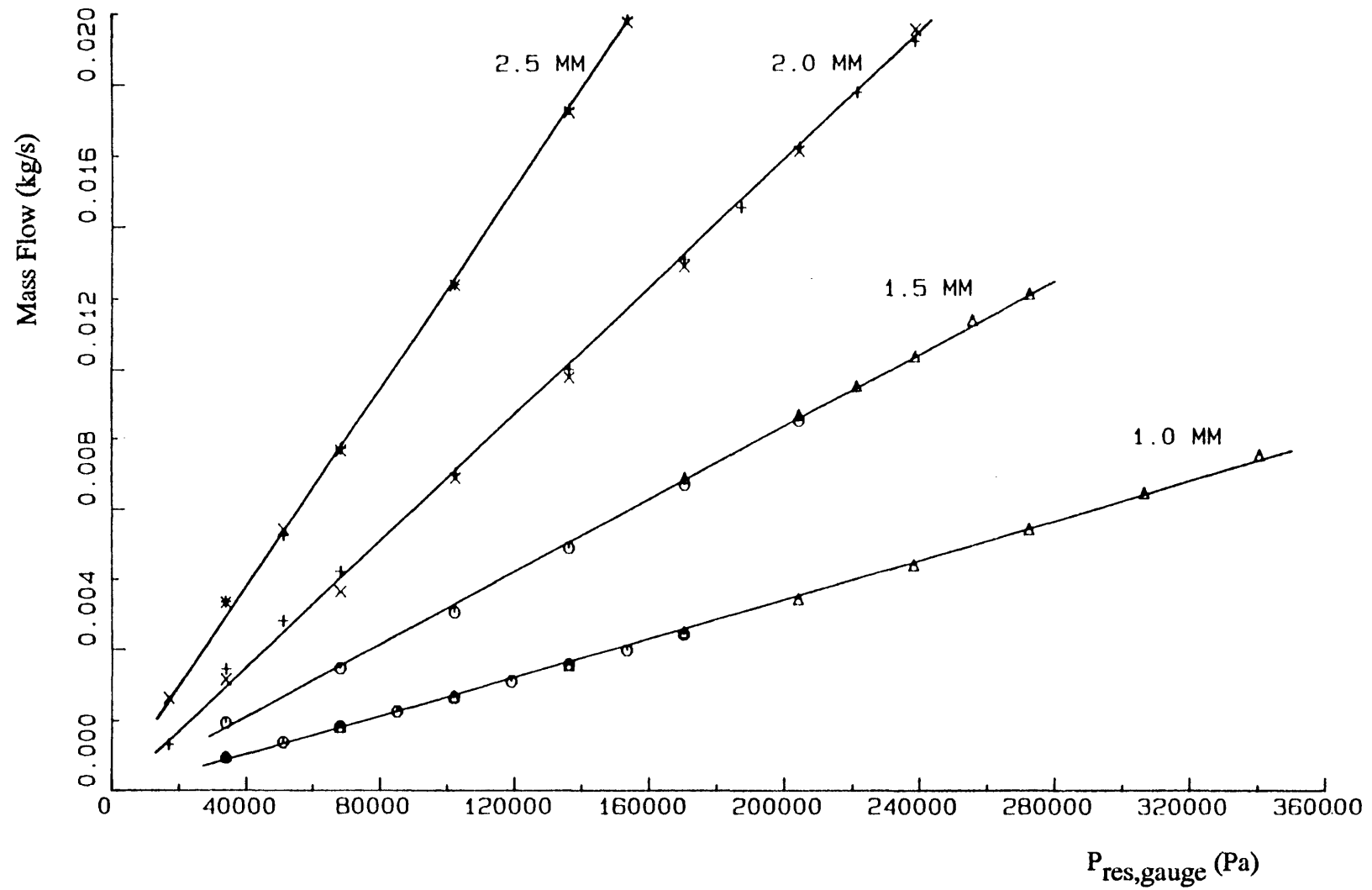


Fig. 5.3 Injection orifice calibrations for CO_2 .

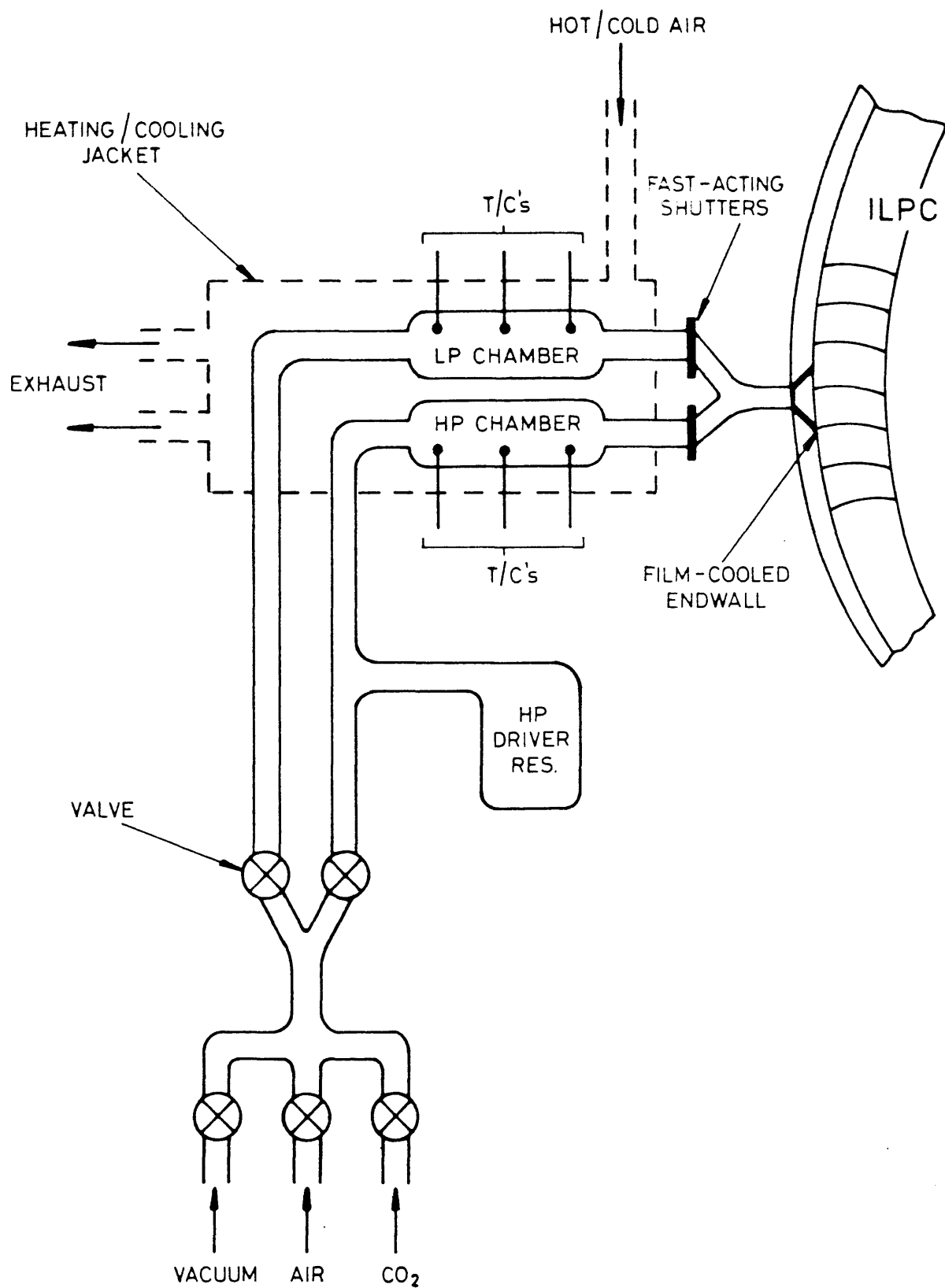


Fig. 5.4 Film-cooling injection system.

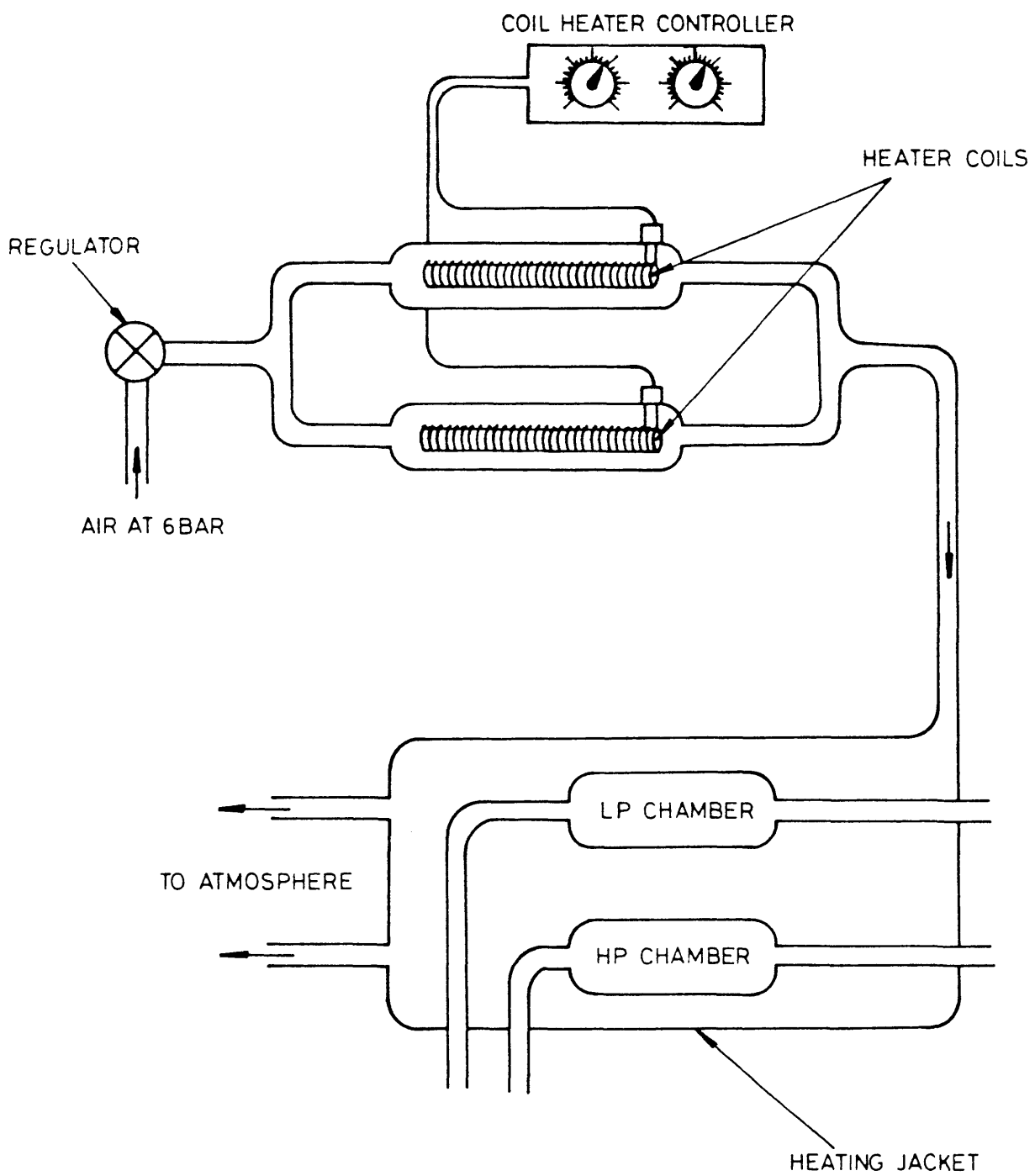


Fig. 5.5 Injection gas heating system.

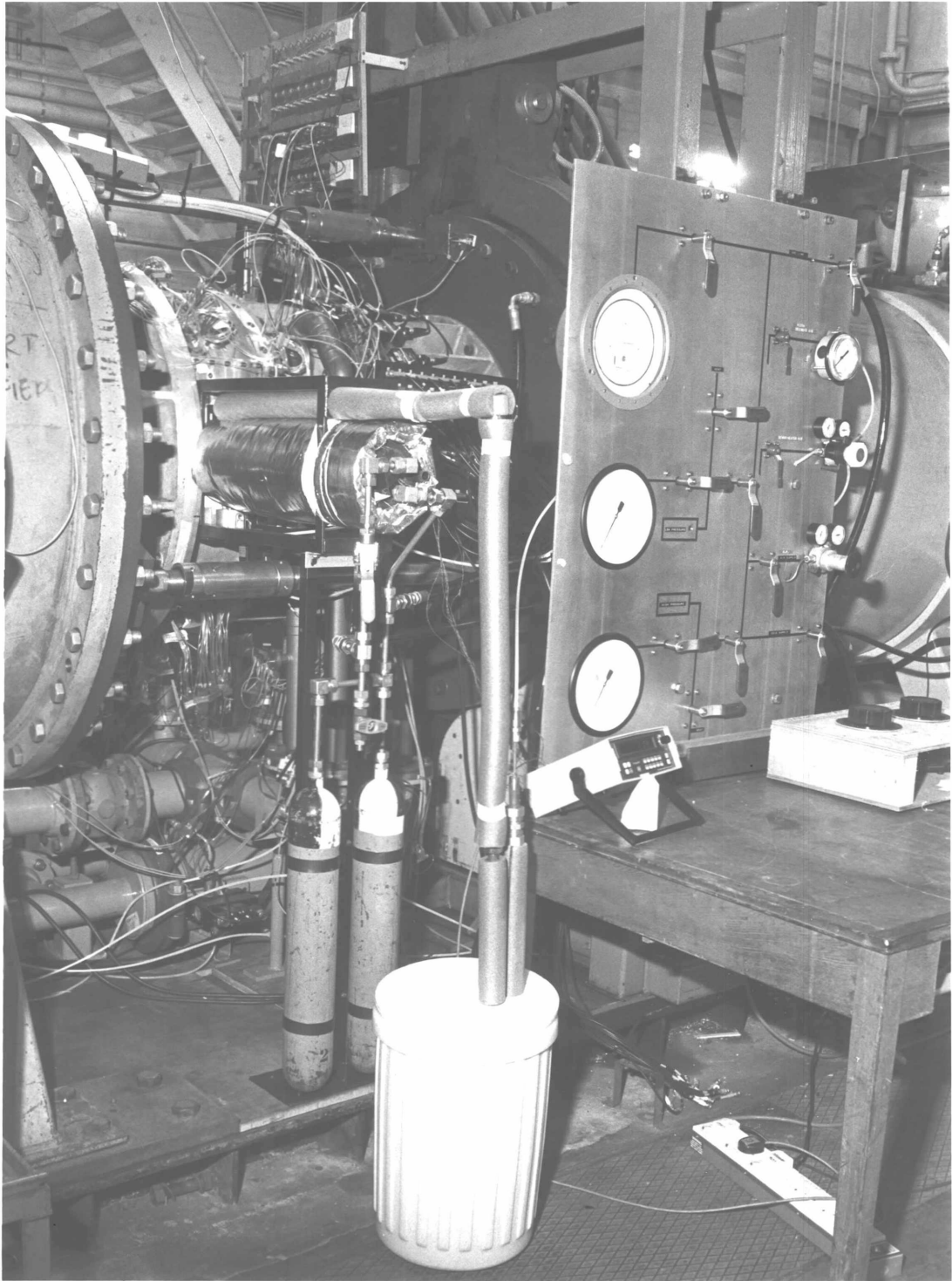


Figure 5.6 Injection Gas Cooling System

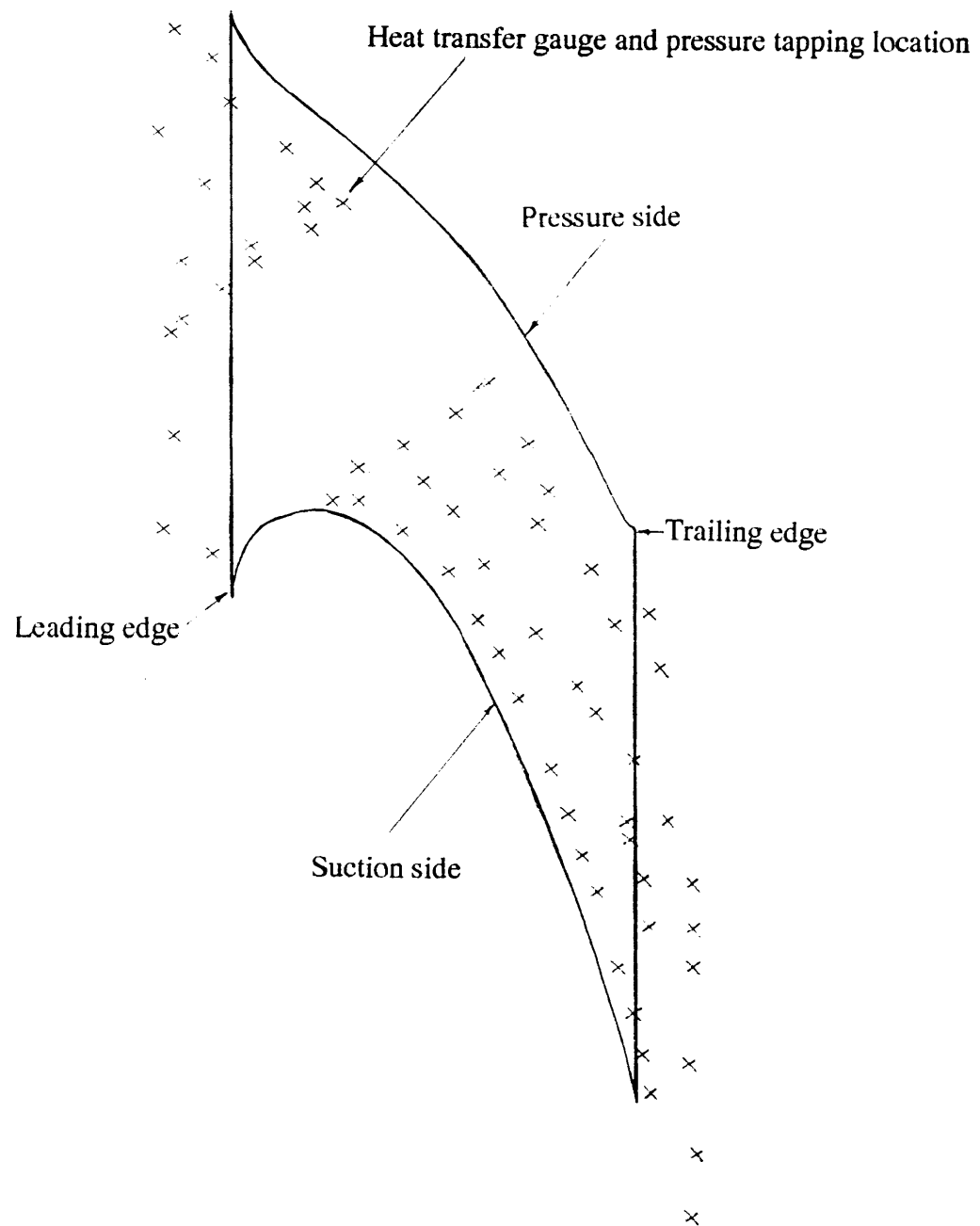


Fig.5.7 Endwall instrumentation coverage.

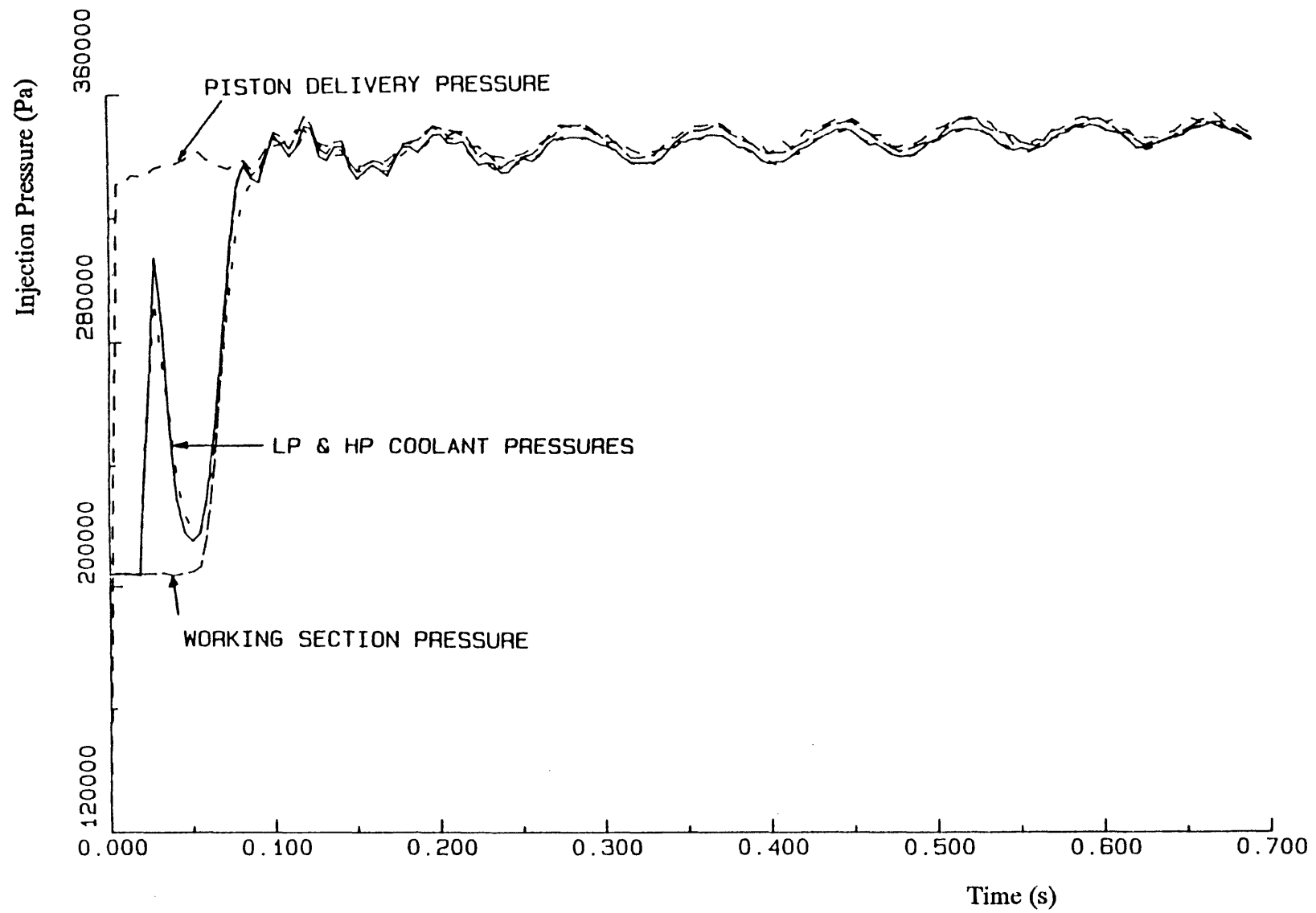


Fig. 7.1 Injection pressure versus time trace for high blowing rates.

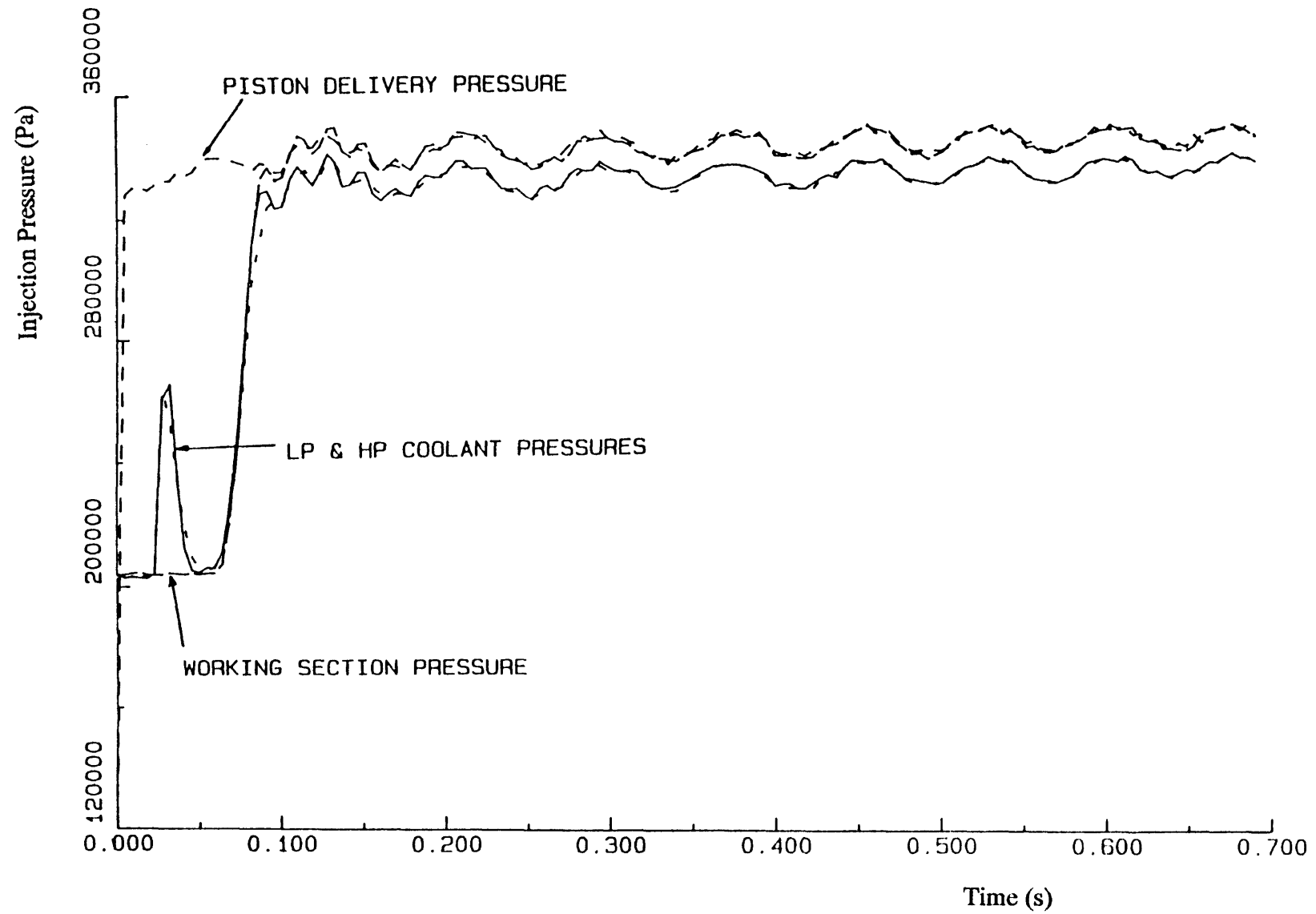


Fig. 7.2 Injection pressure versus time trace for low blowing rates.

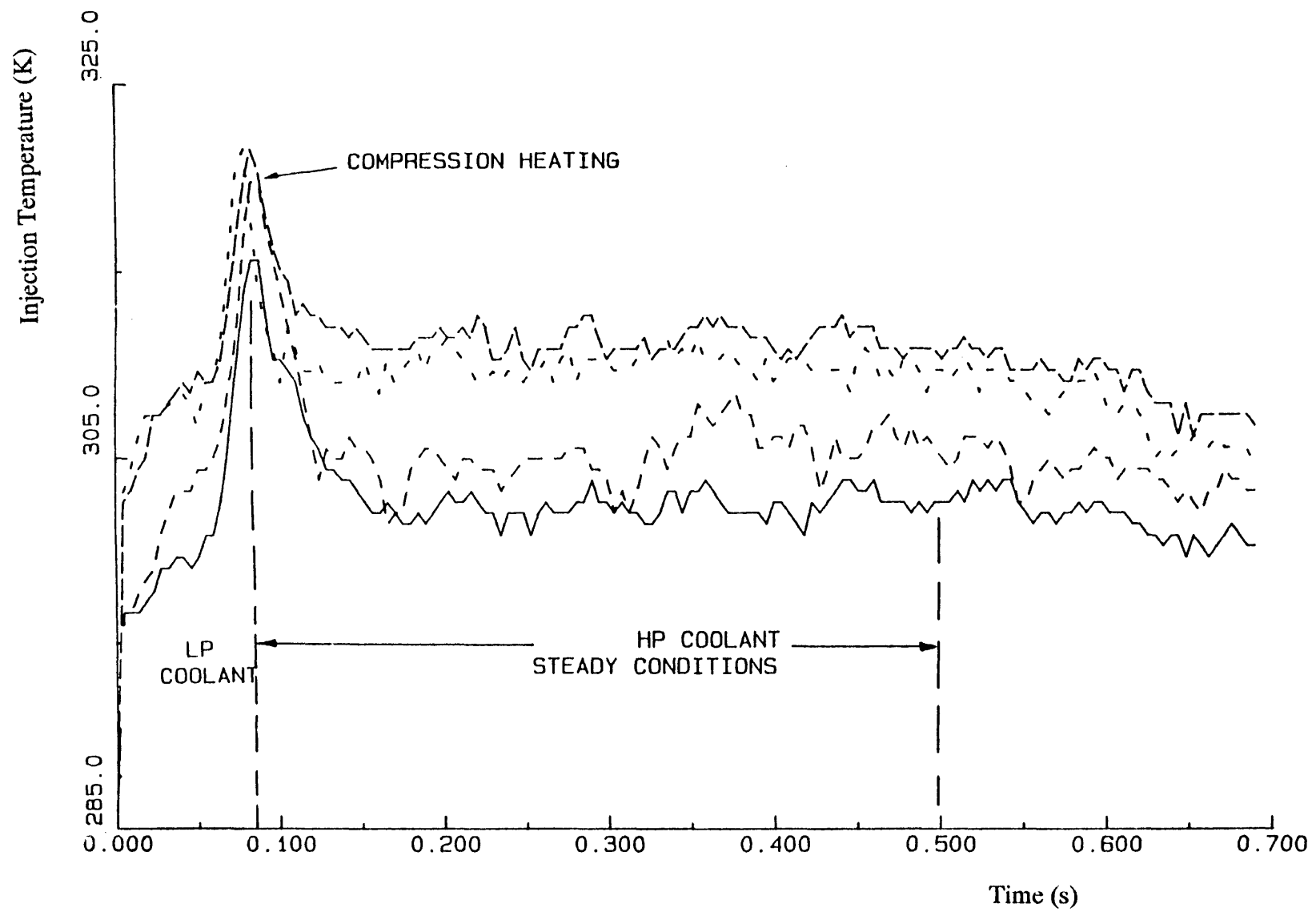


Fig. 7.3 Injection temperature versus time trace.

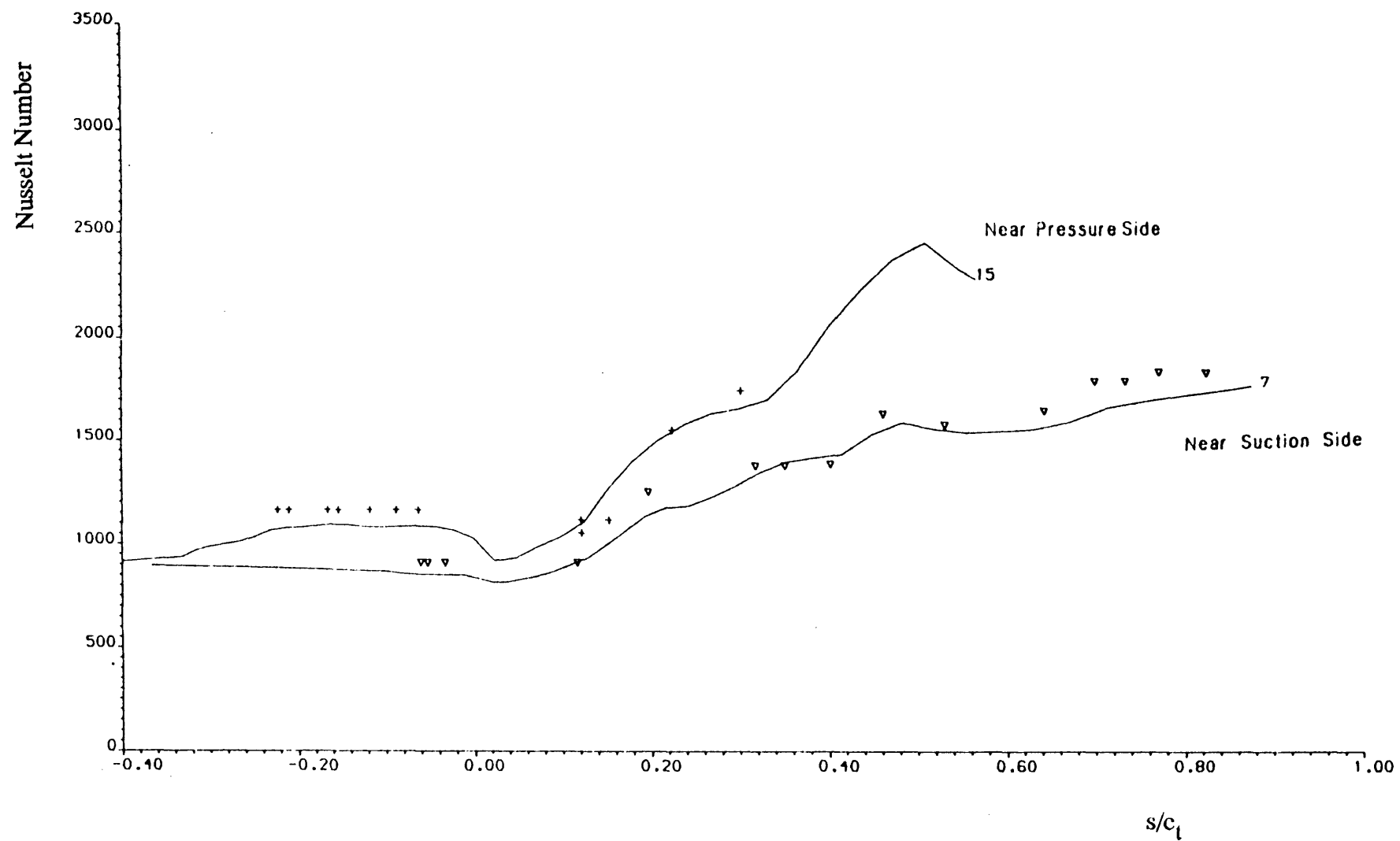
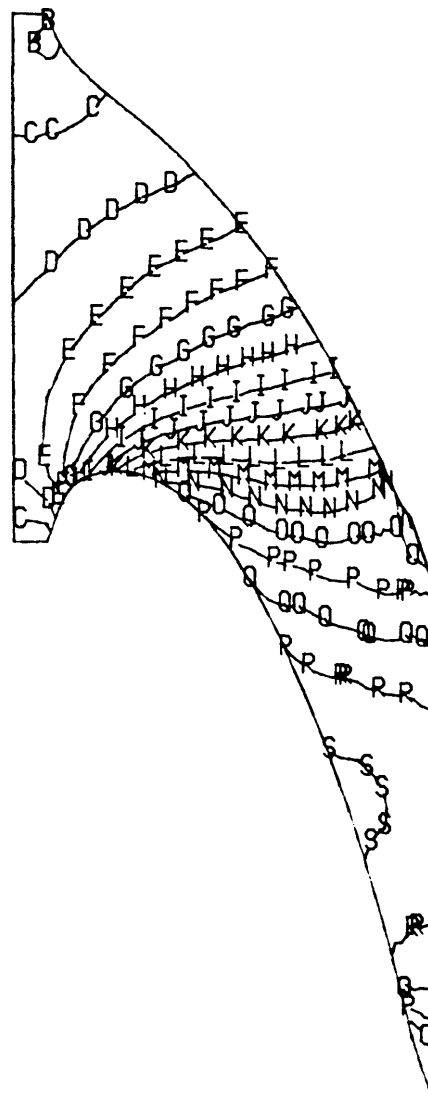


Fig. 7.4 Comparison of experimental data with interpolated fit of these data.



A	0.00
B	0.05
C	0.10
D	0.15
E	0.20
F	0.25
G	0.30
H	0.35
I	0.40
J	0.45
K	0.50
L	0.55
M	0.60
N	0.65
O	0.70
P	0.75
Q	0.80
R	0.85
S	0.90

Fig. 7.5 Predicted Mach number distribution without cooling.

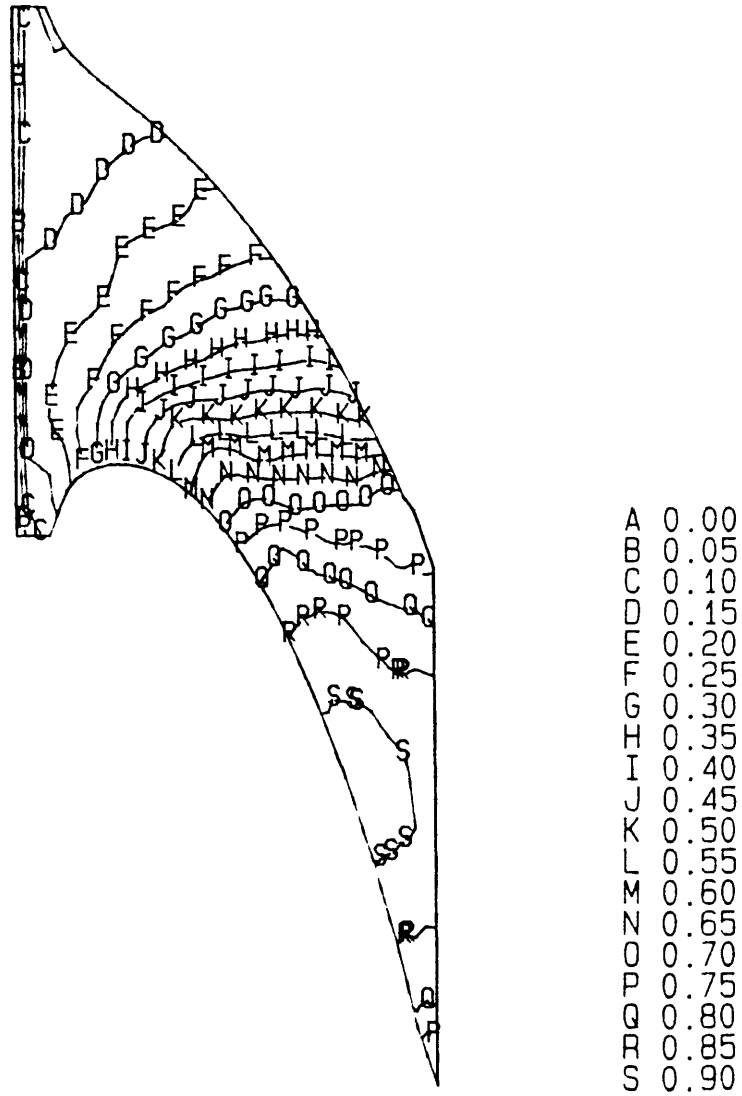


Fig. 7.6 Experimental Mach number distribution without cooling.

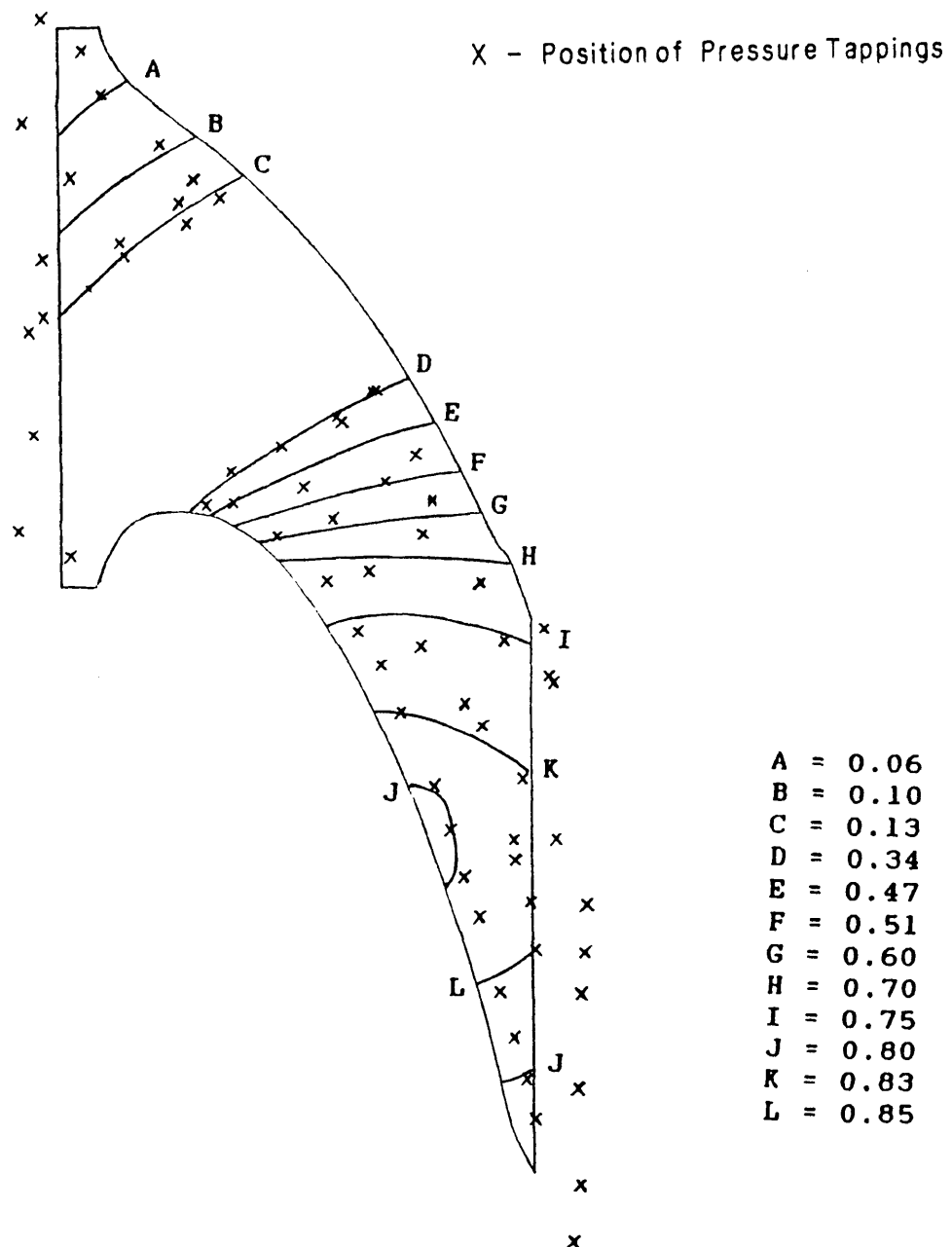


Fig. 7.7 Experimental Mach number distribution with cooling.

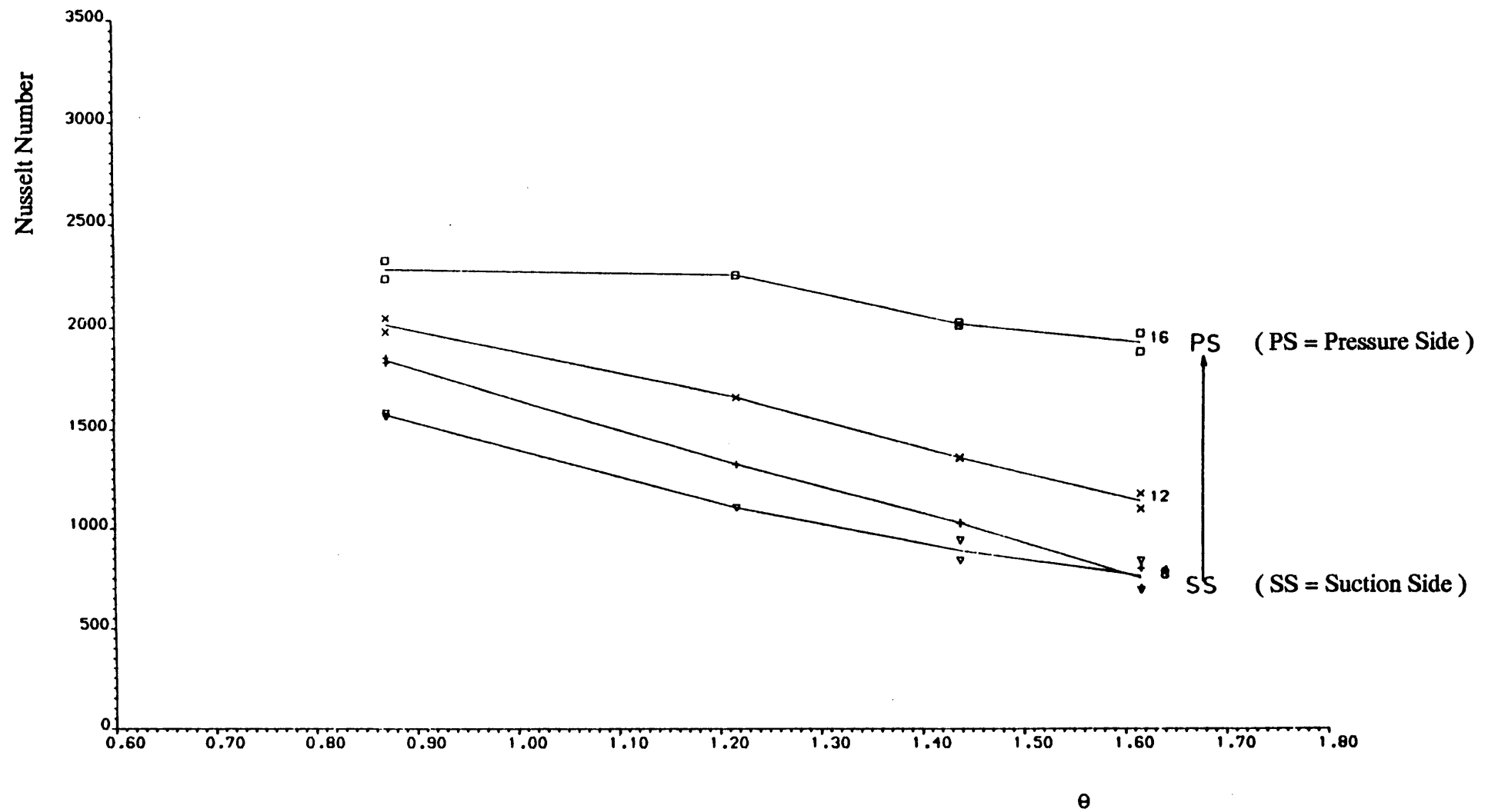


Fig. 7.8 Variation of Nu with Θ at $G=1.11$ and $s/c_t=0.4$.

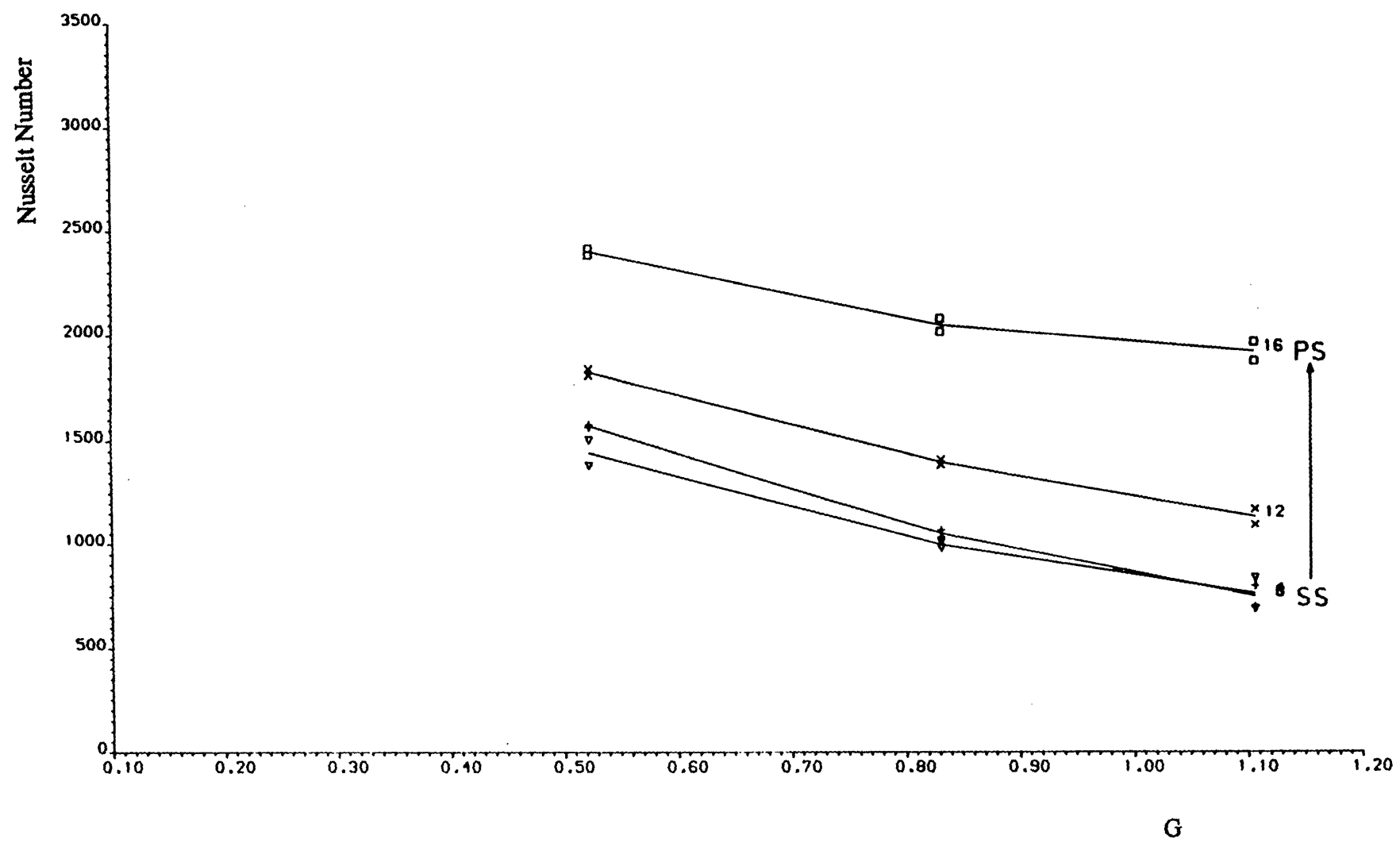


Fig. 7.9 Variation of Nu with G at $\Theta=1.62$ and $s/c_t=0.4$.

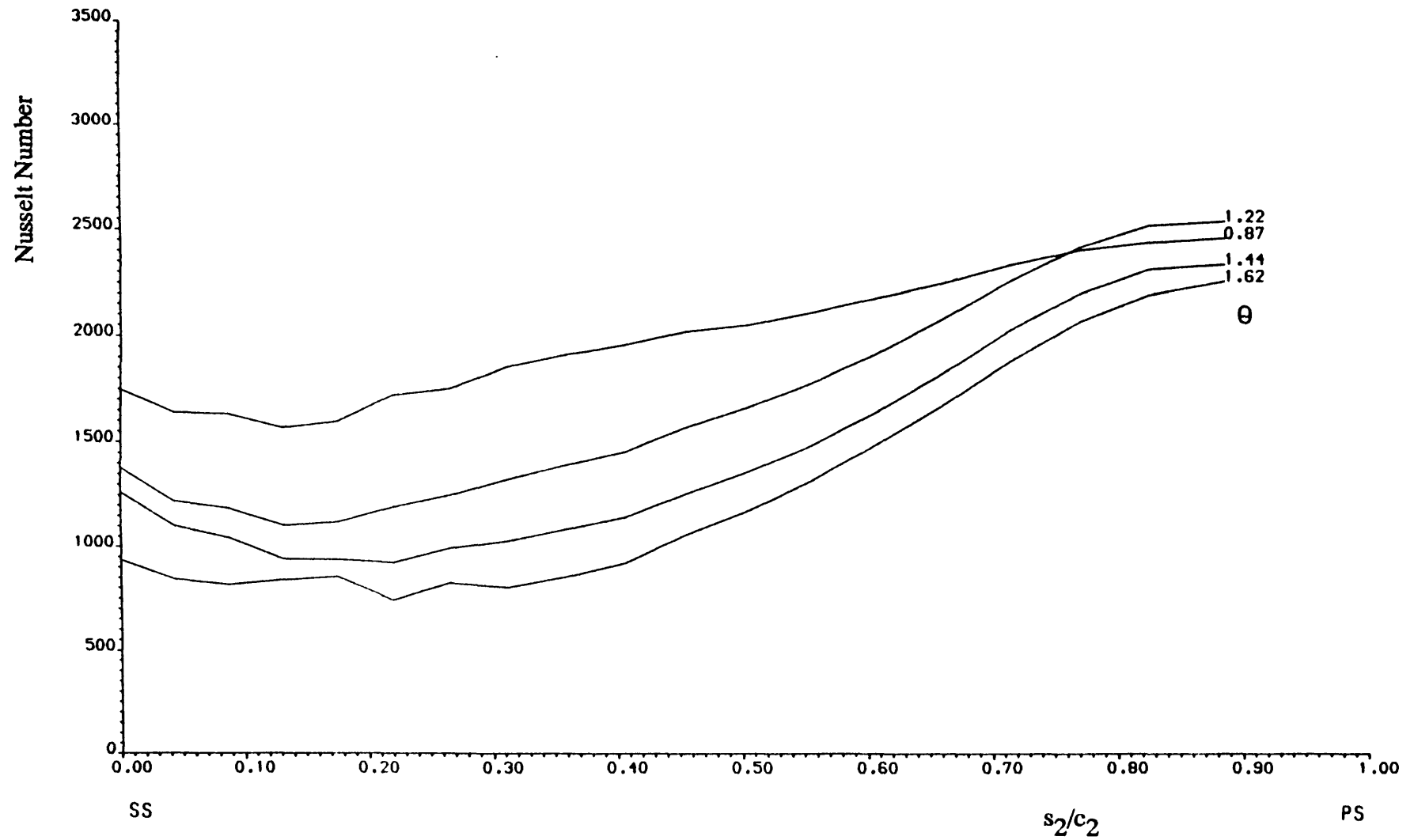


Fig. 7.10 Variation of Nu with distance across the endwall at $s/c_1=0.4$

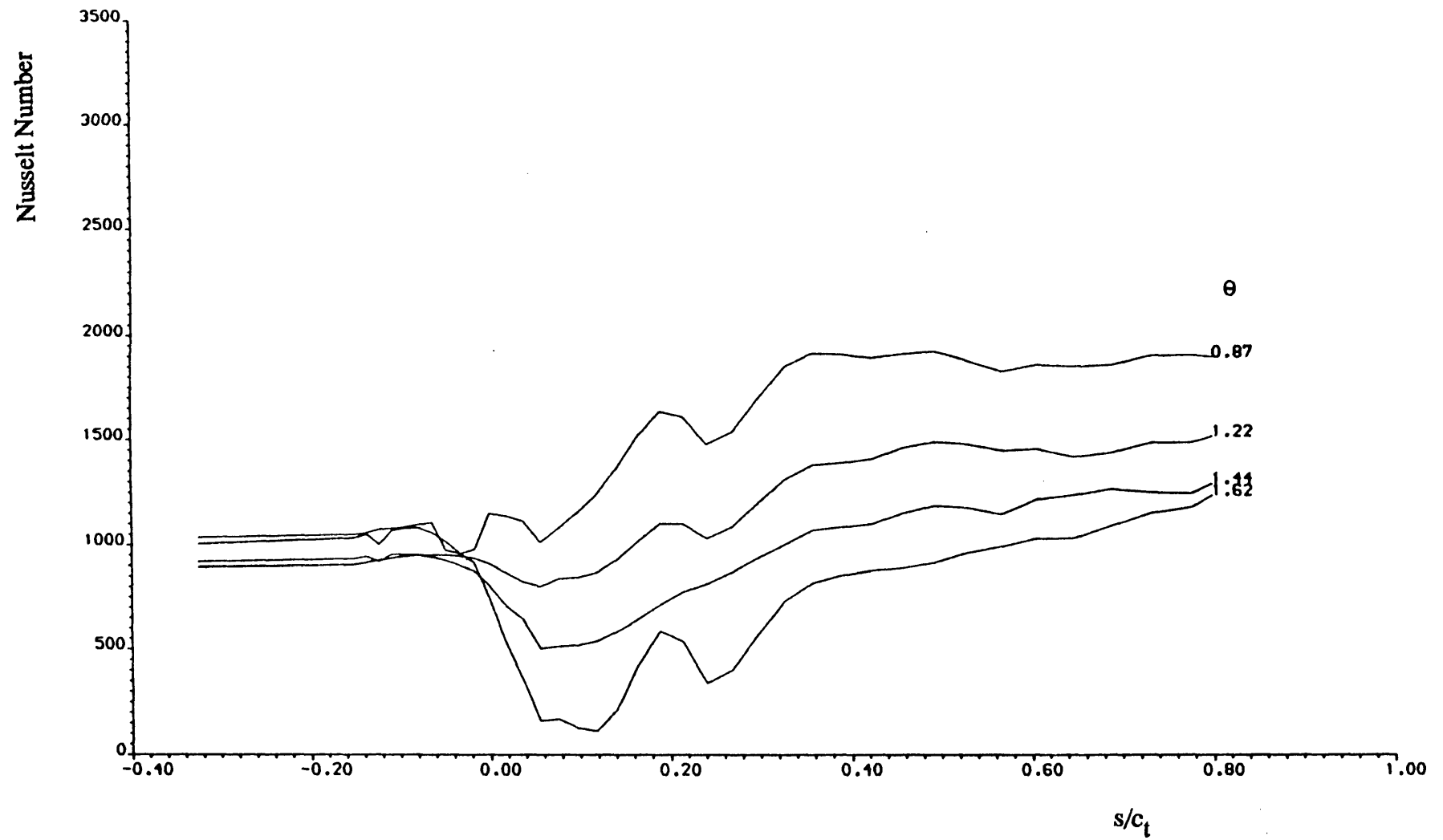


Fig. 7.11 Variation of Nu with distance along the endwall at the mid-passage location

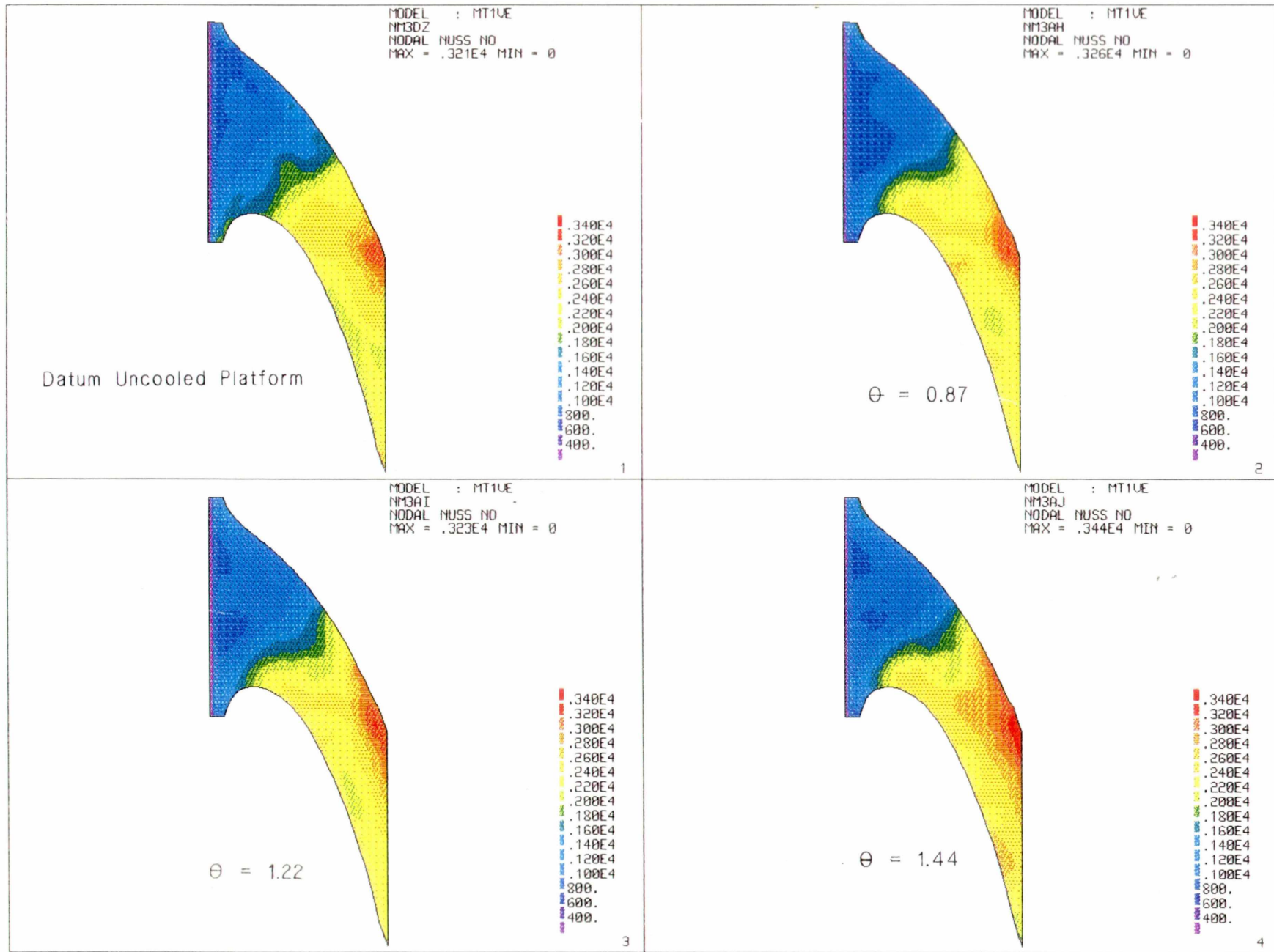


Fig. 7.12 Comparison of endwall Nu between the uncooled case and three values of θ at $G=0.37$.

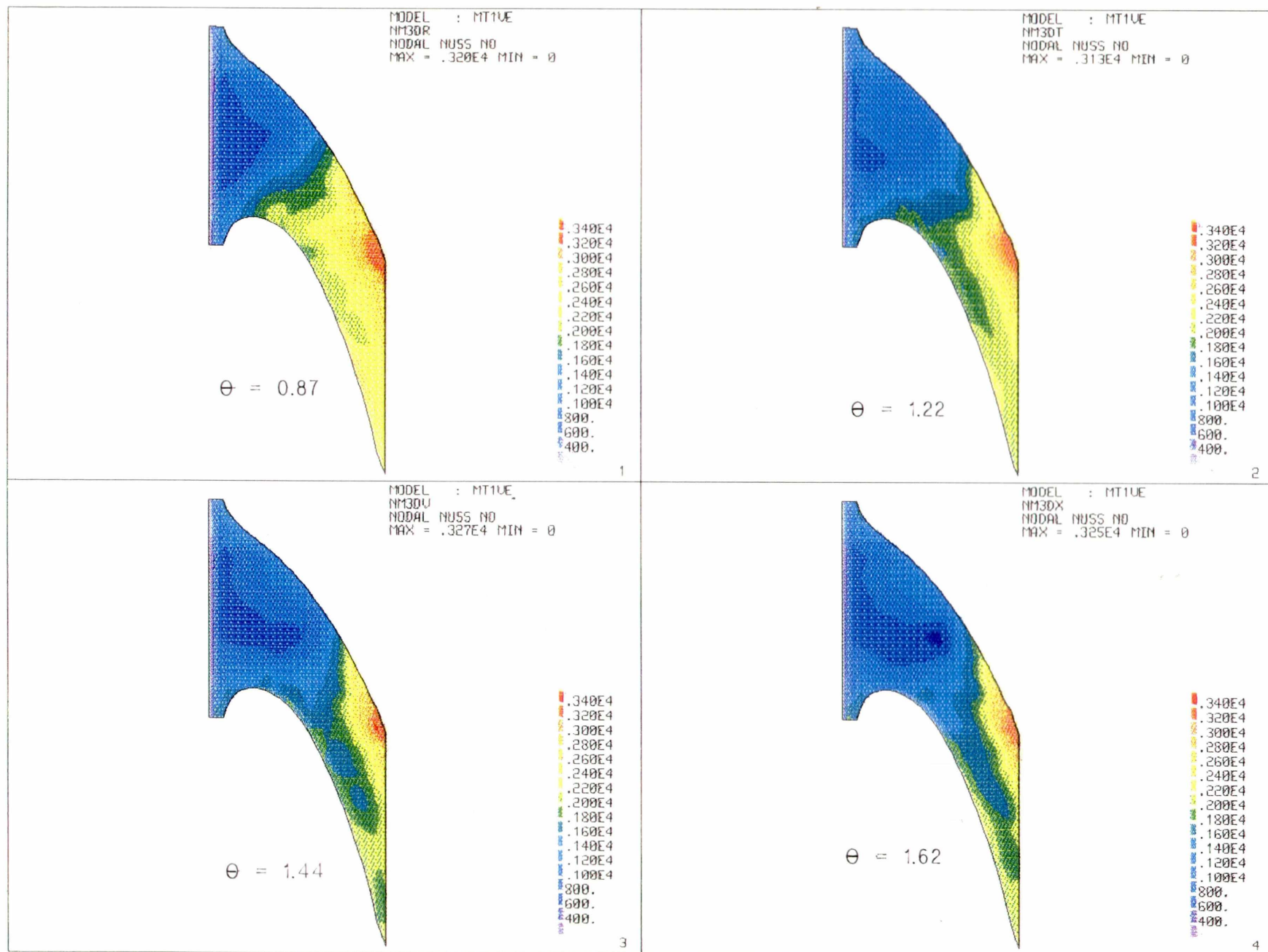


Fig. 7.13 Comparison of endwall Nu for four values of θ at $G=0.52$.

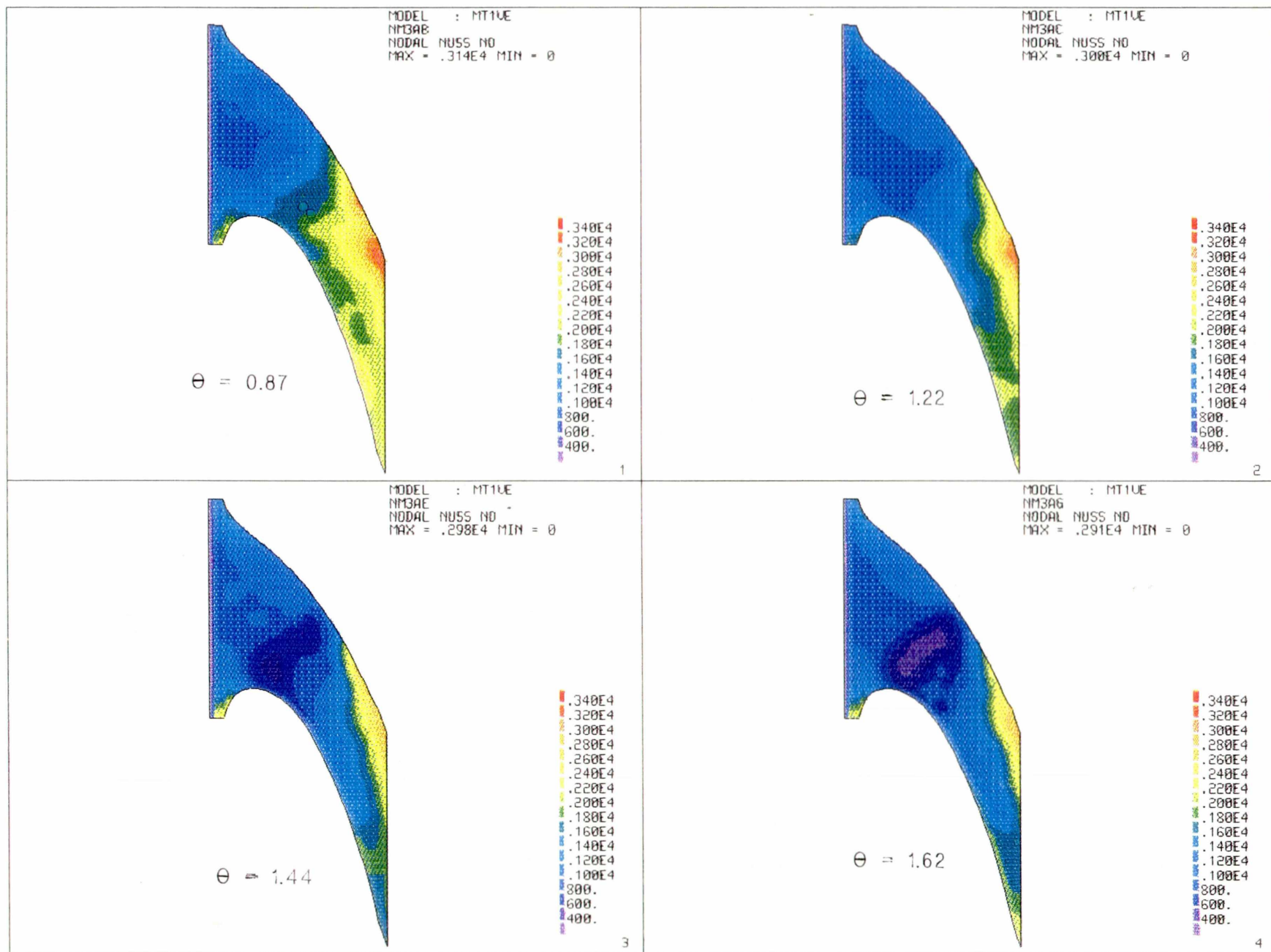


Fig. 7.14 Comparison of endwall Nu for four values of θ at $G=0.83$.

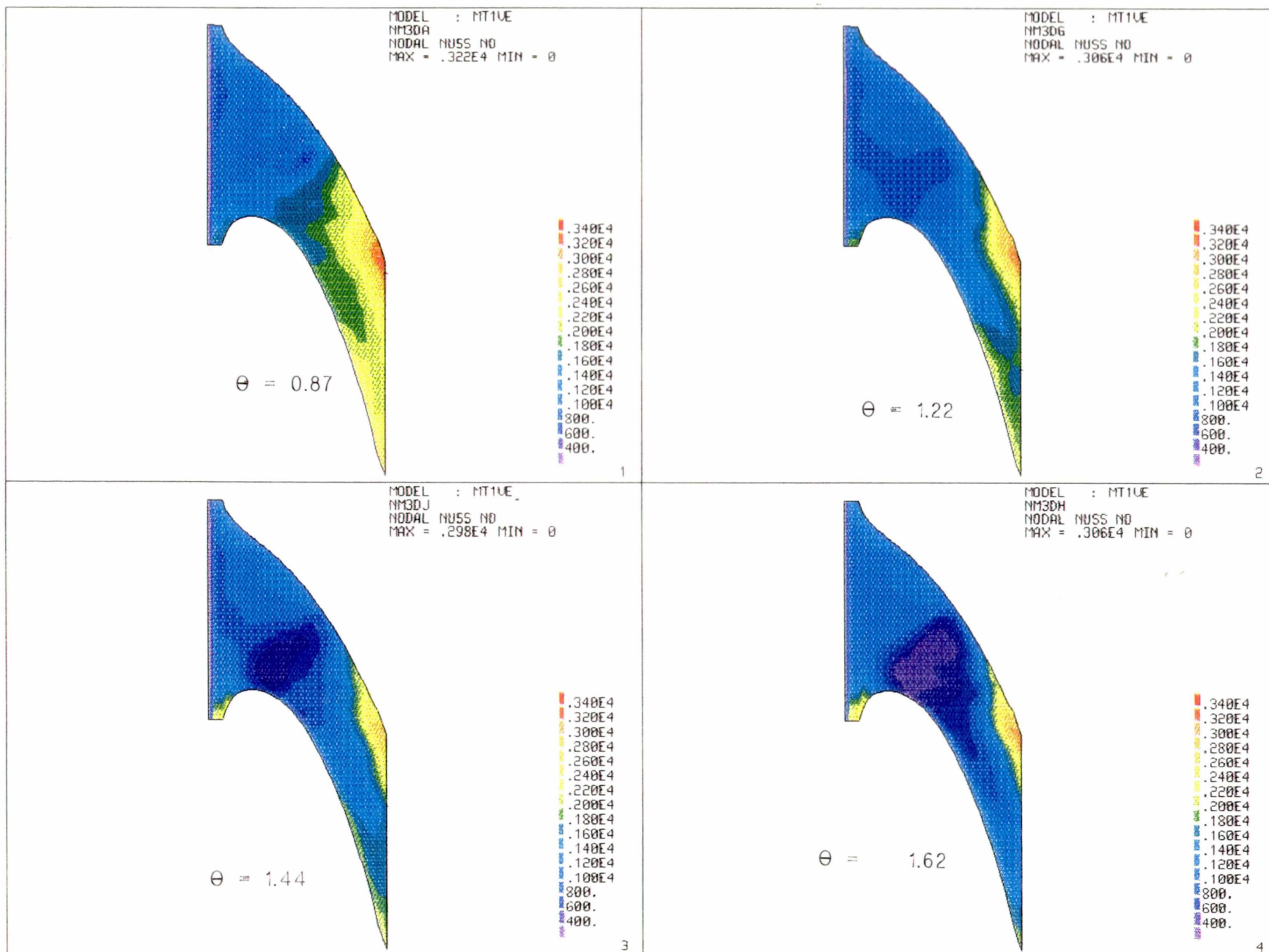


Fig. 7.15 Comparison of endwall Nu for four values of θ at $G=1.11$.

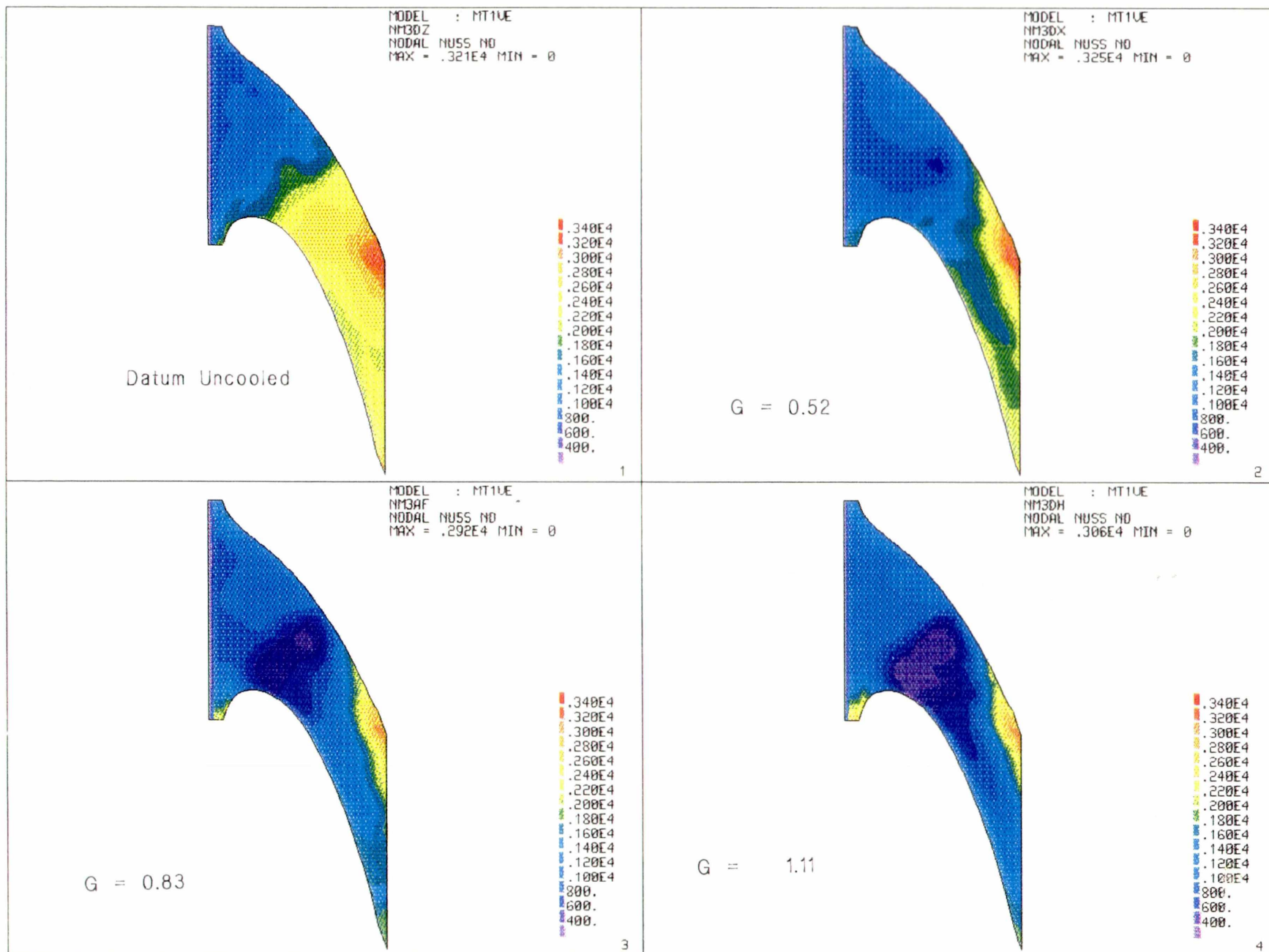
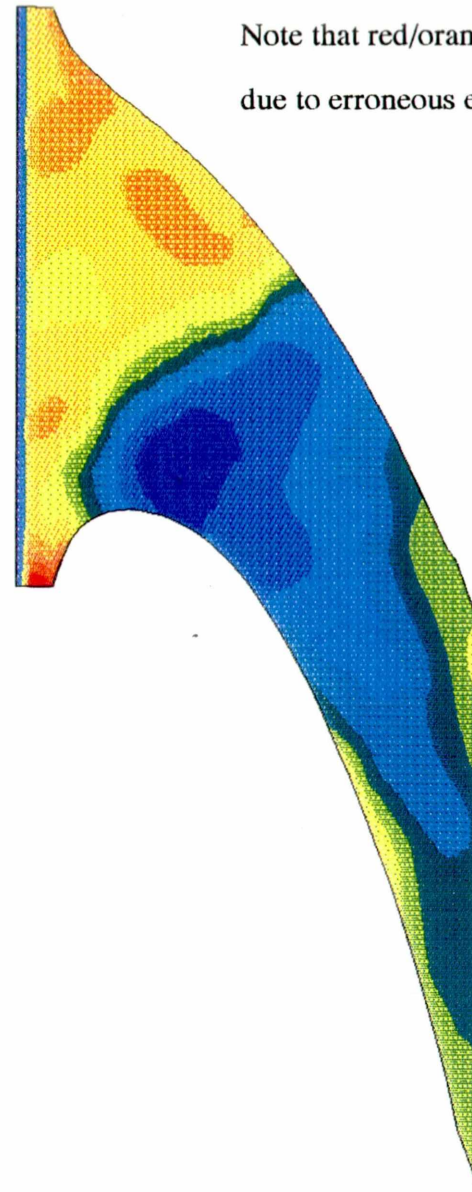


Fig. 7.16 Comparison of endwall Nu between the uncooled case and three blowing rates at $\Theta = 1.62$.



Note that red/orange areas upstream of the cooling holes are due to erroneous extrapolation by the contouring routines.

1.300
1.200
1.100
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100

Y
Z X

Fig. 7.17 Endwall Nu for $G=1.11$, $\Theta=1.62$ non-dimensionalised with uncooled endwall Nu.

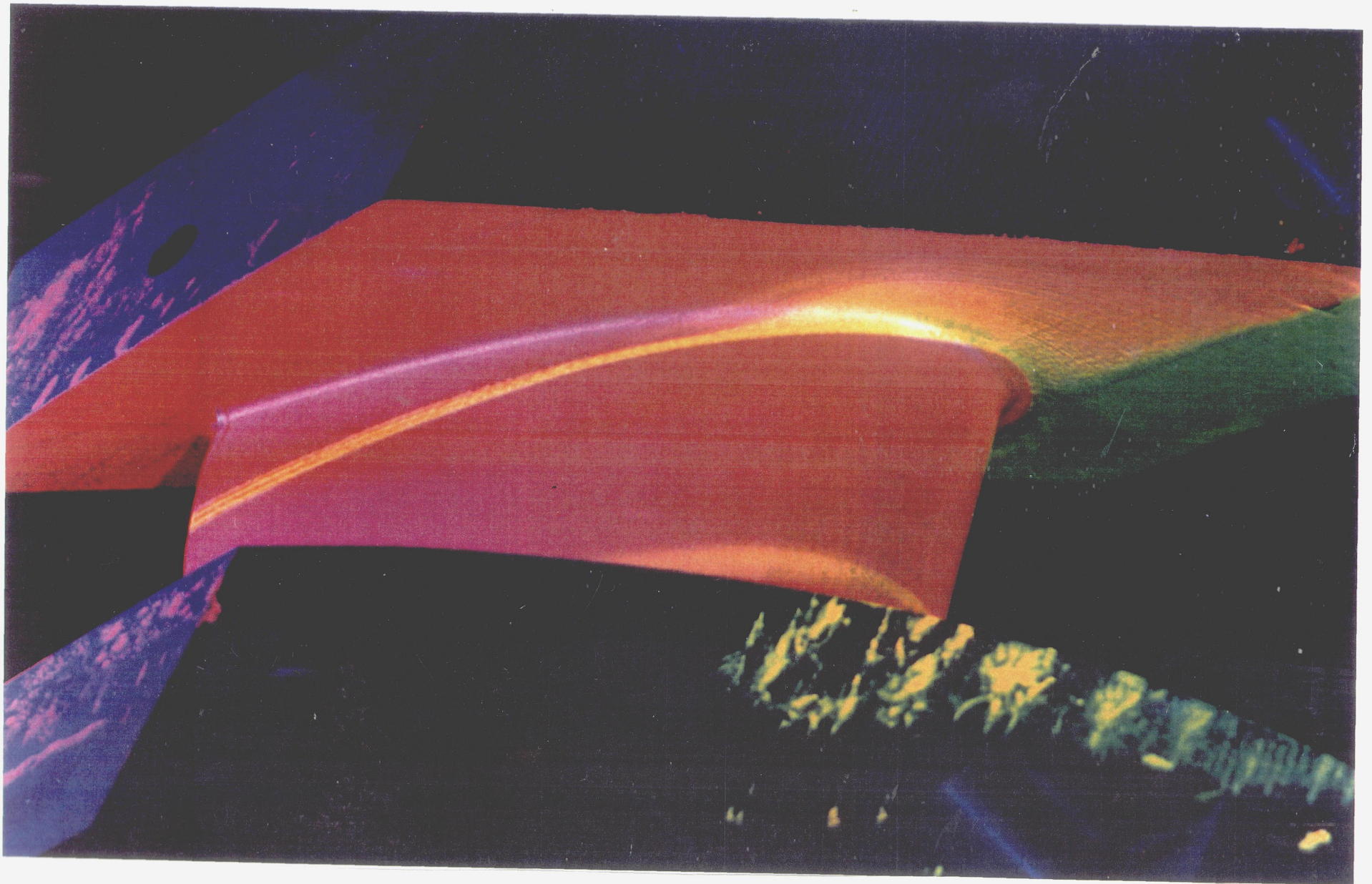


Fig. 7.18 Fluorescent dye flow visualisation of the uncooled platform.

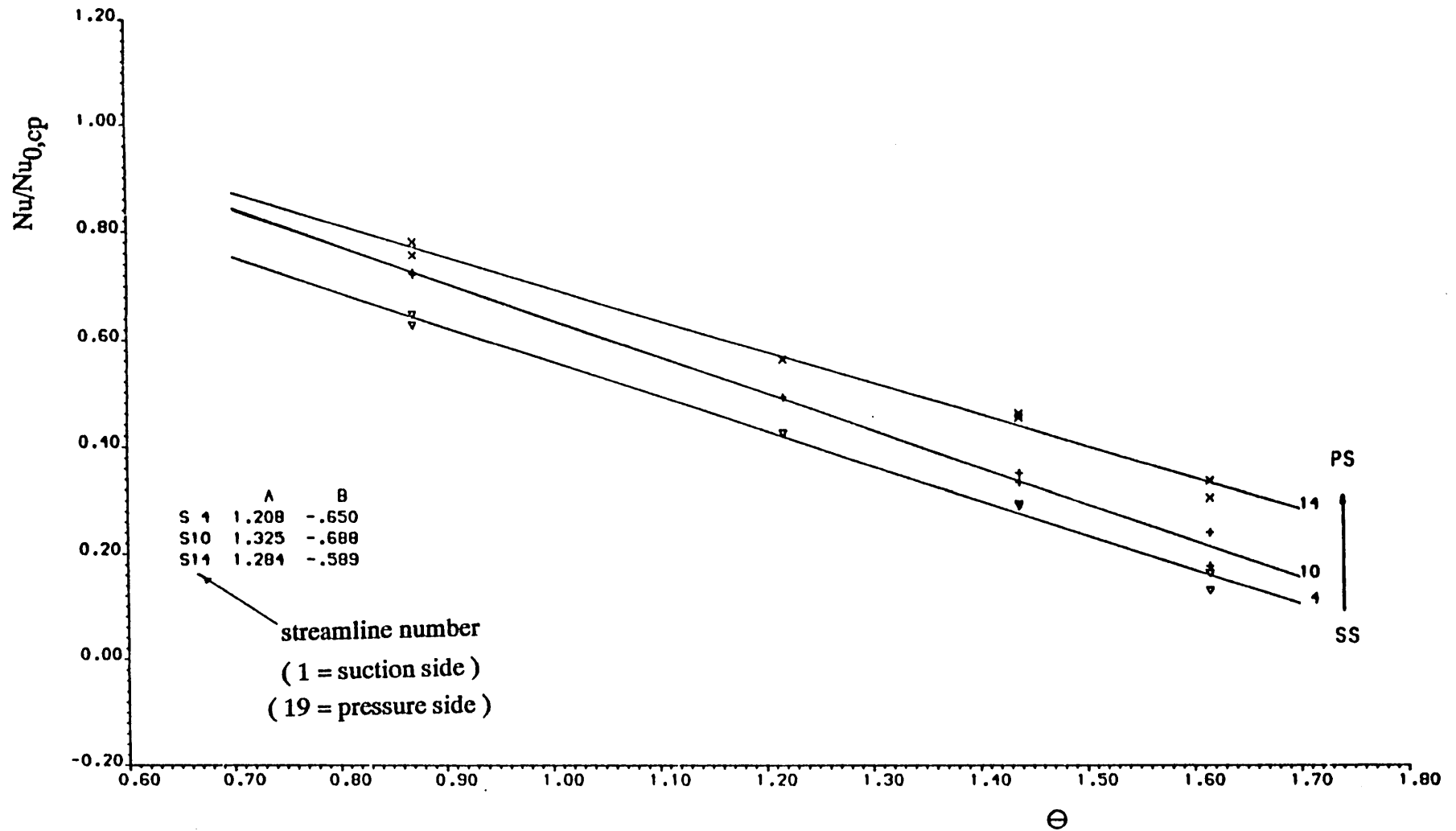


Fig. 8.1 Application of superposition theory to film-cooled data for $G=1.11$, $s/c_t=0.2$.

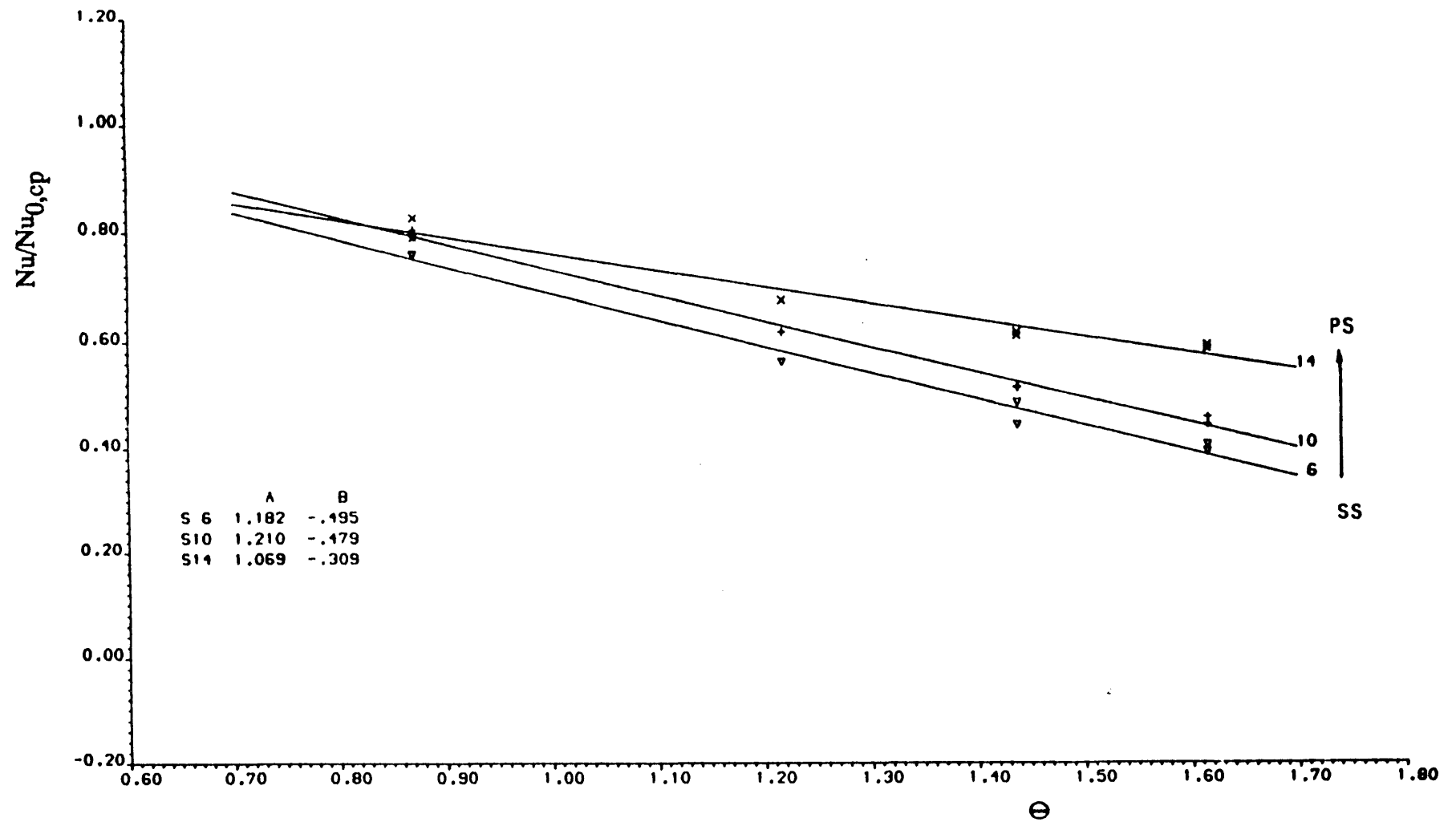


Fig. 8.2 Application of superposition theory to film-cooled data for $G=0.83$, $s/c_t=0.4$.

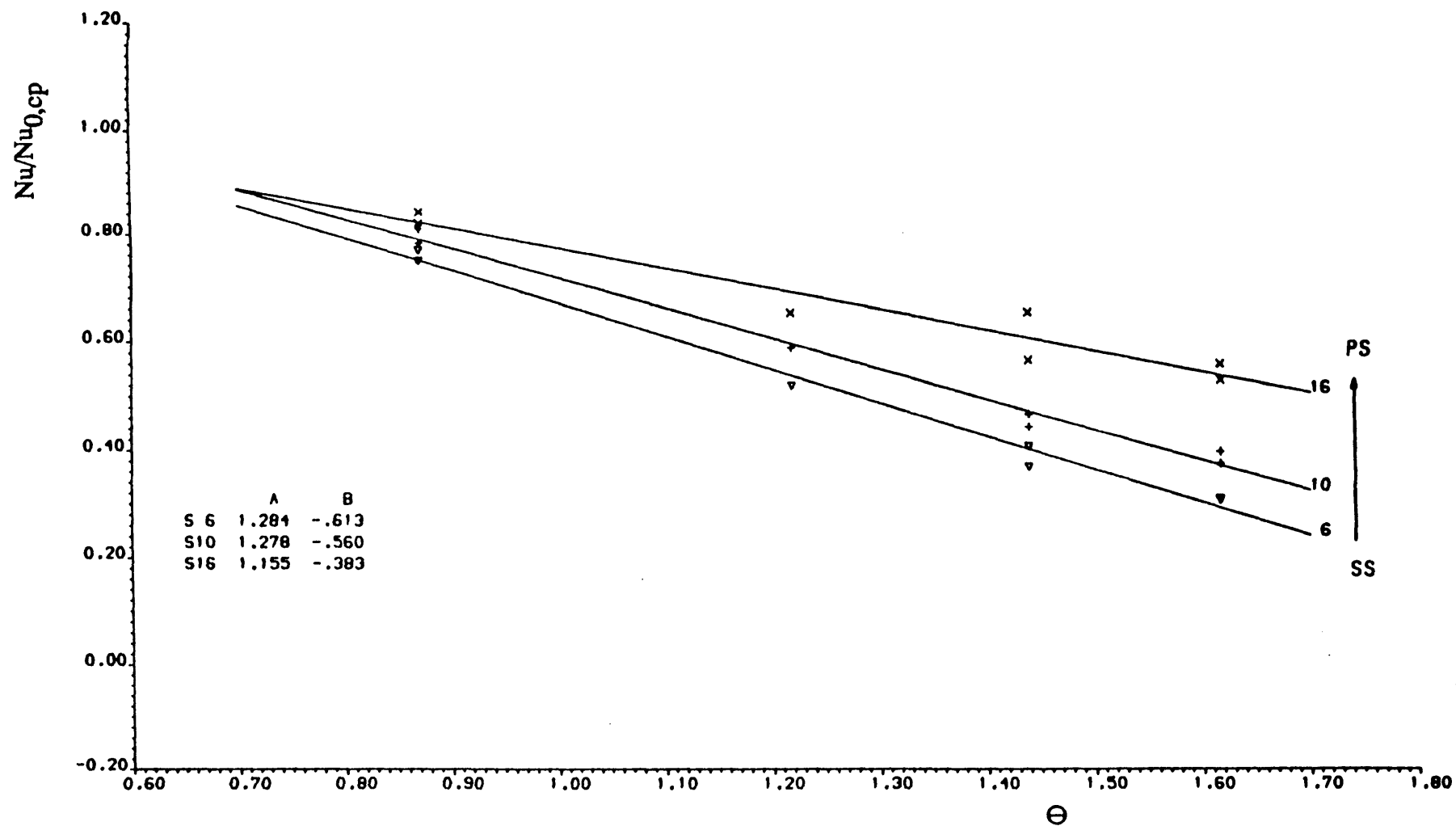


Fig. 8.3 Application of superposition theory to film-cooled data for $G=0.52$, $s/c_t=0.3$.

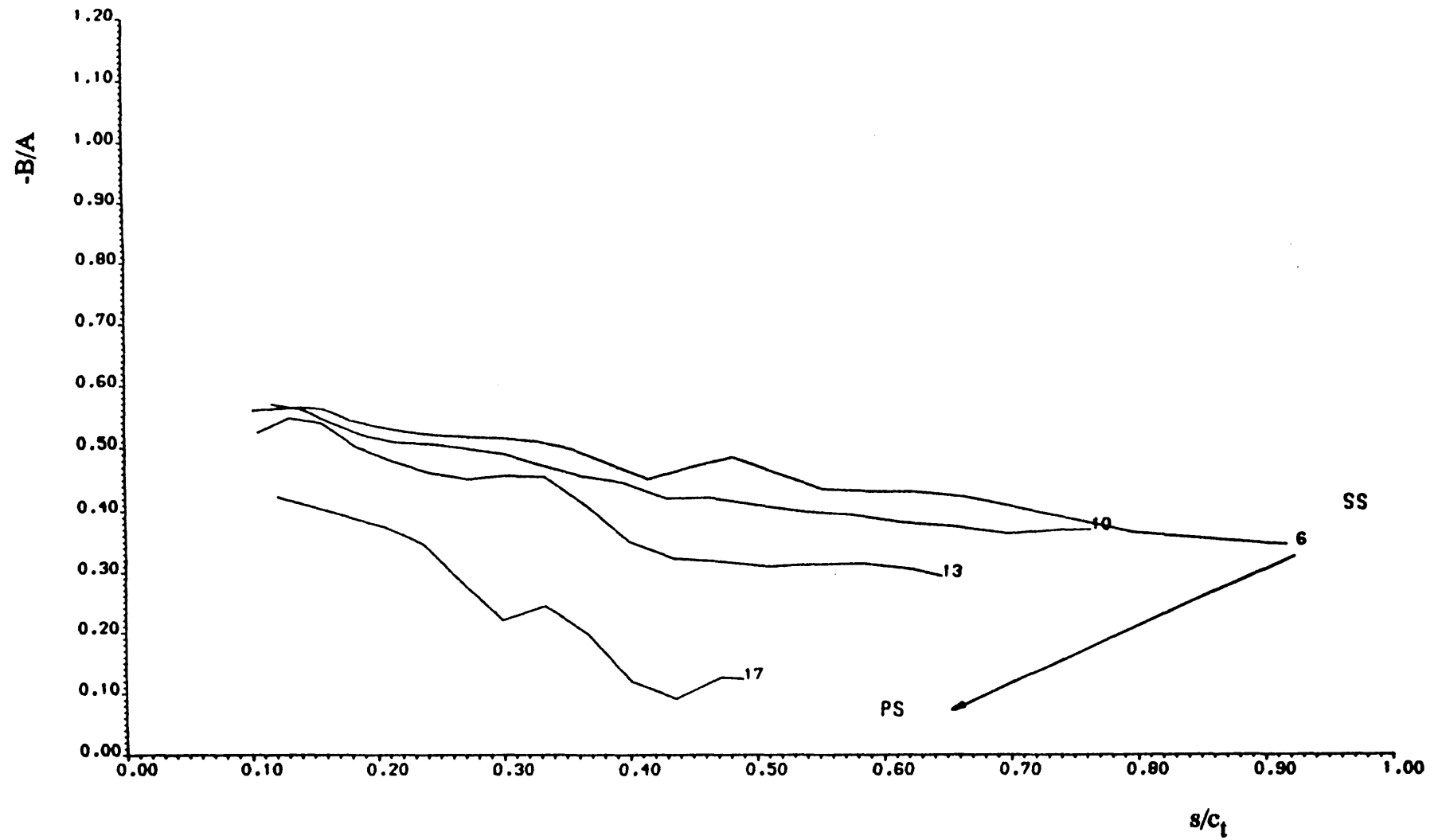


Fig. 8.4 Streamwise variation of film-cooling effectiveness for $G=1.11$.

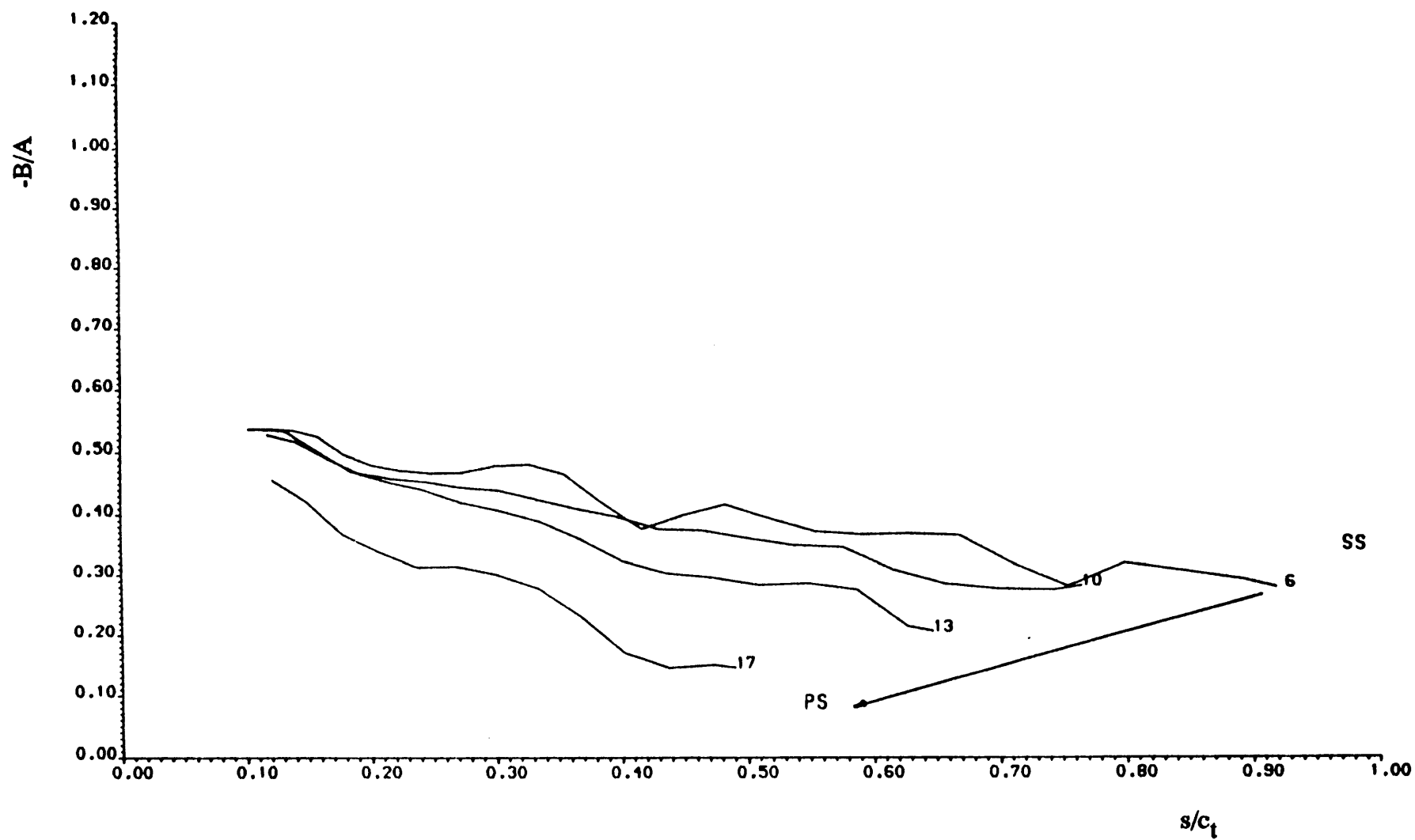


Fig. 8.5 Streamwise variation of film-cooling effectiveness for $G=0.83$.

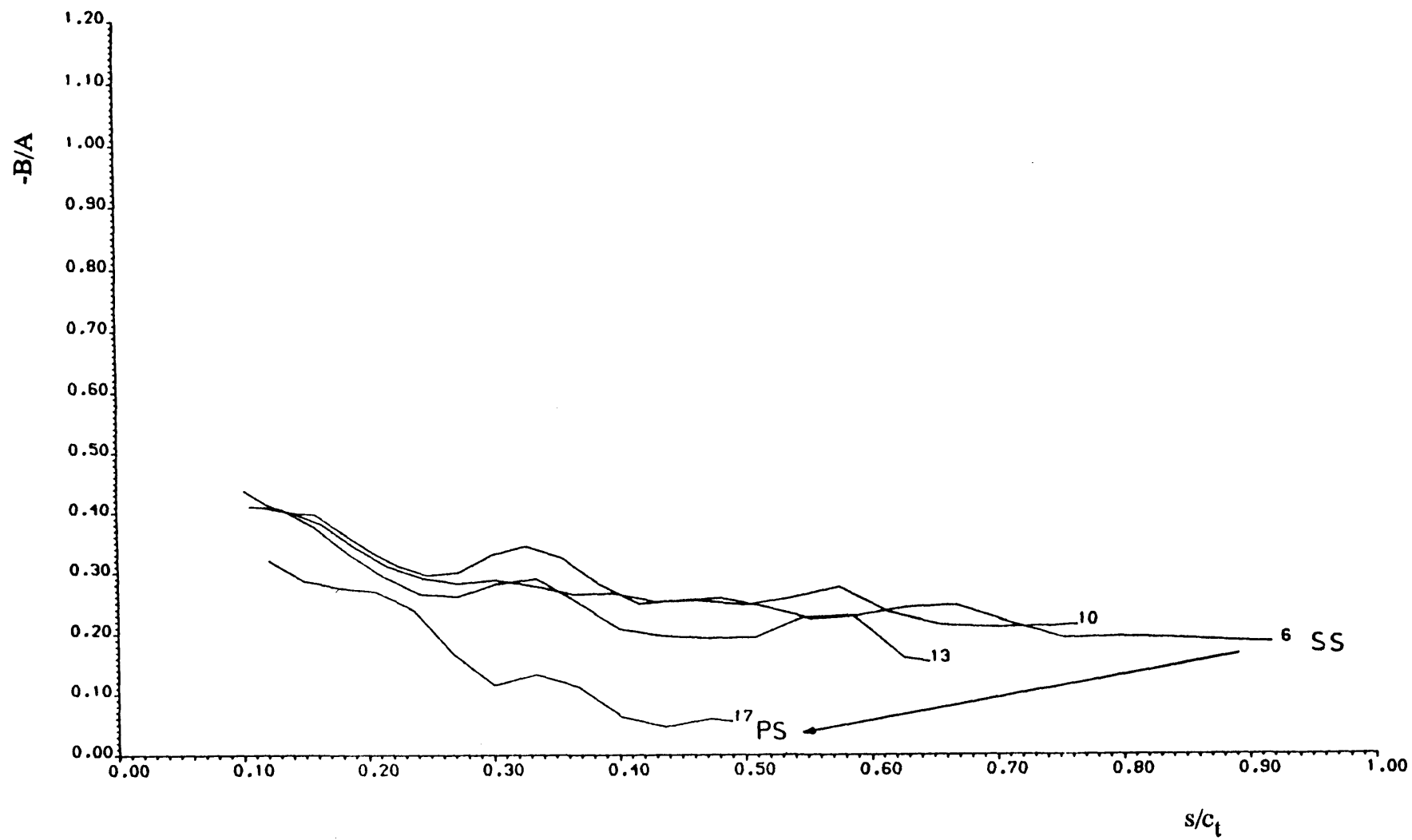


Fig. 8.6 Streamwise variation of film-cooling effectiveness for $G=0.52$.

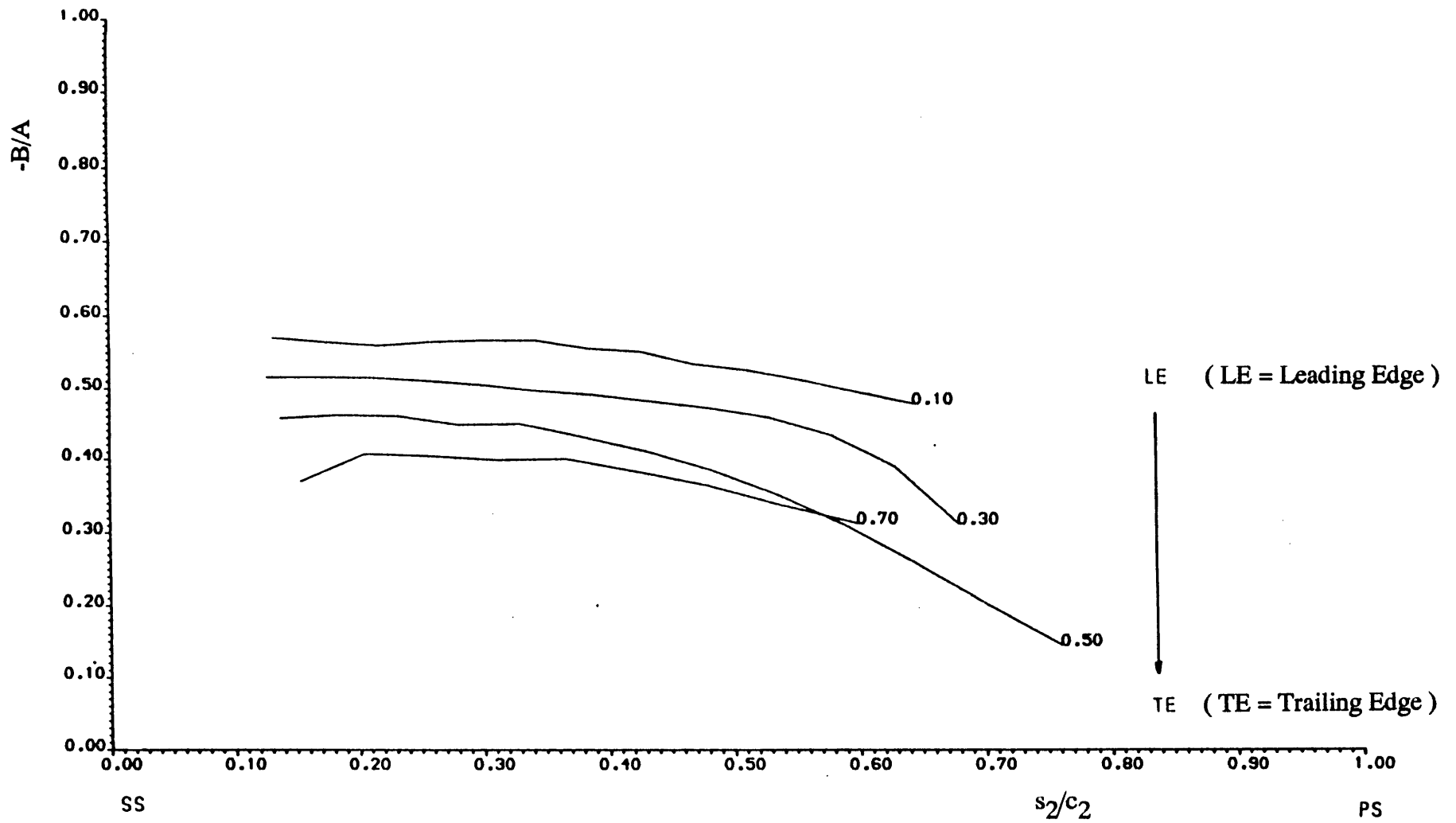


Fig. 8.7 Cross-passage variation of film-cooling effectiveness for $G=1.11$.

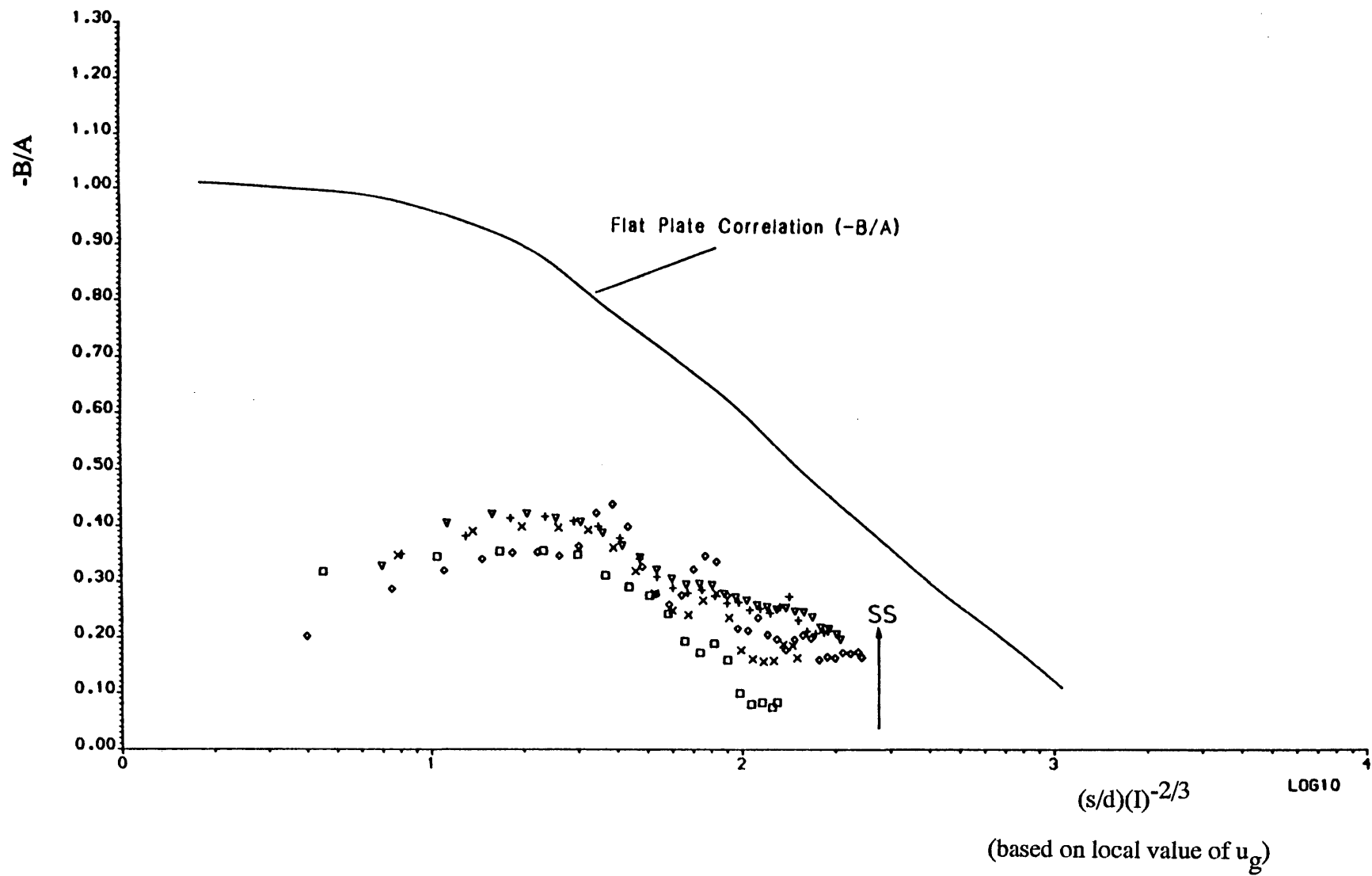


Fig. 8.8 Film-cooling effectiveness against slot wall jet parameter for $G=0.52$.

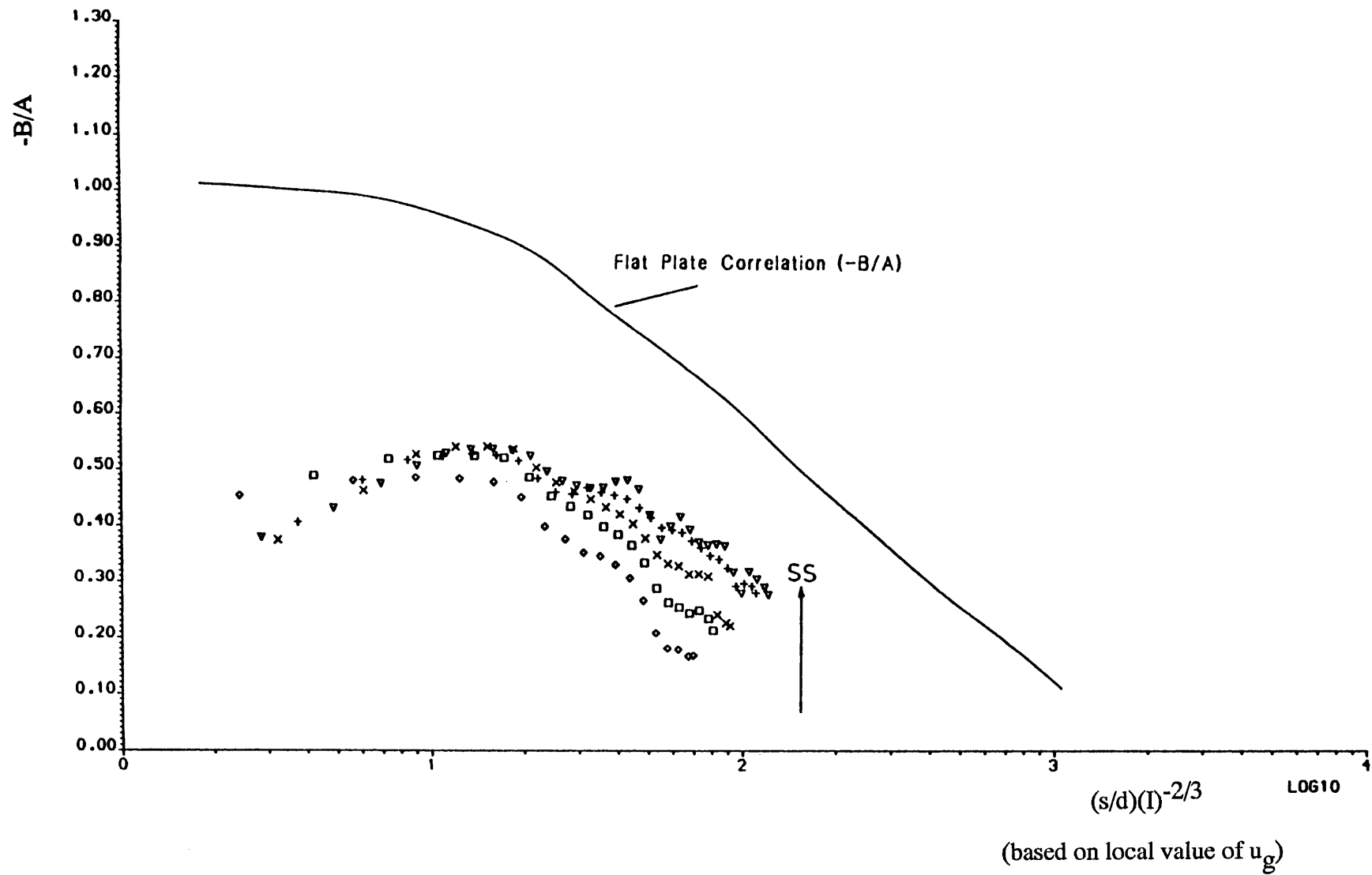


Fig. 8.9 Film-cooling effectiveness against slot wall jet parameter for $G=0.83$.

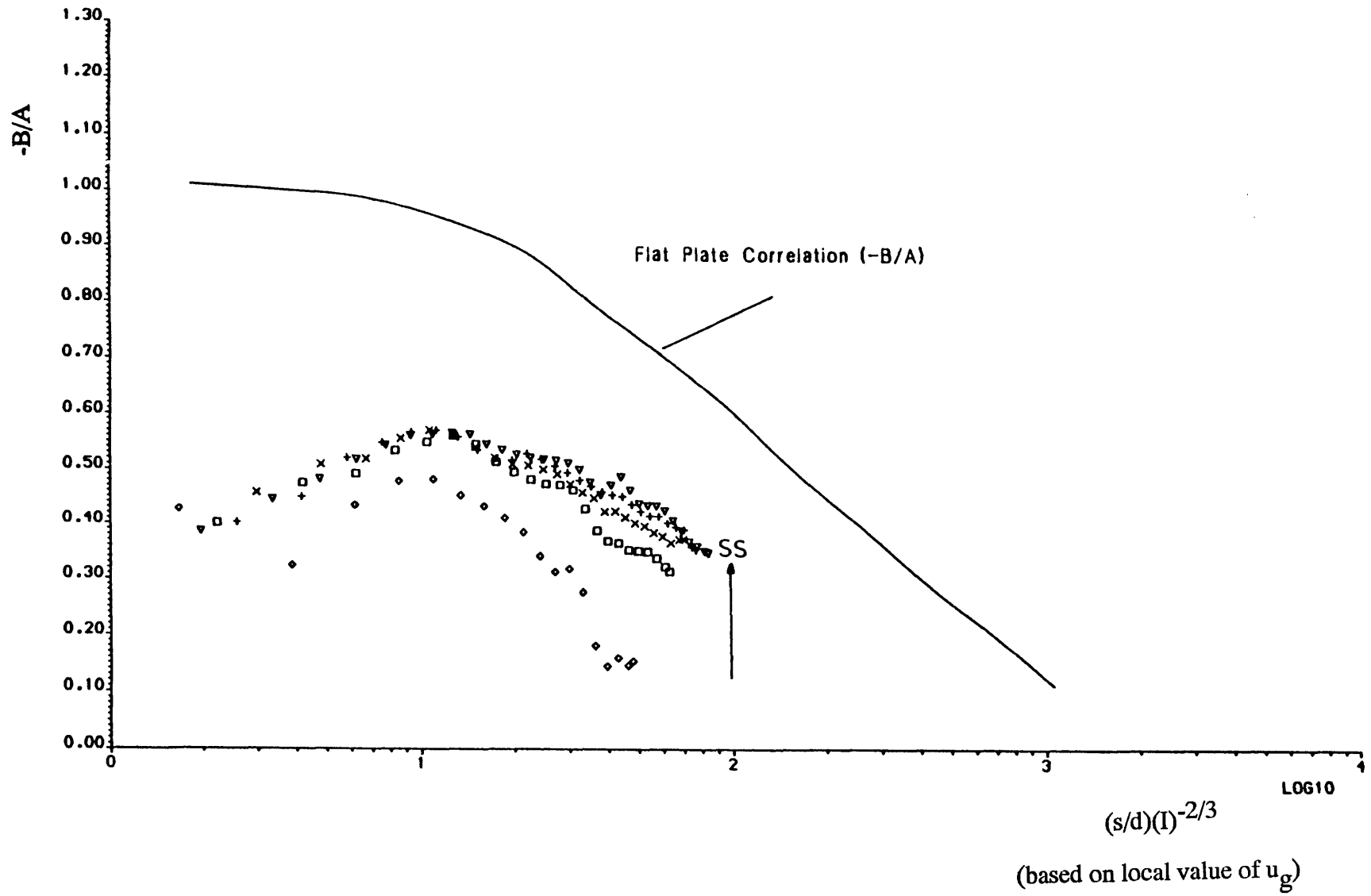


Fig. 8.10 Film-cooling effectiveness against slot wall jet parameter for $G=1.11$.

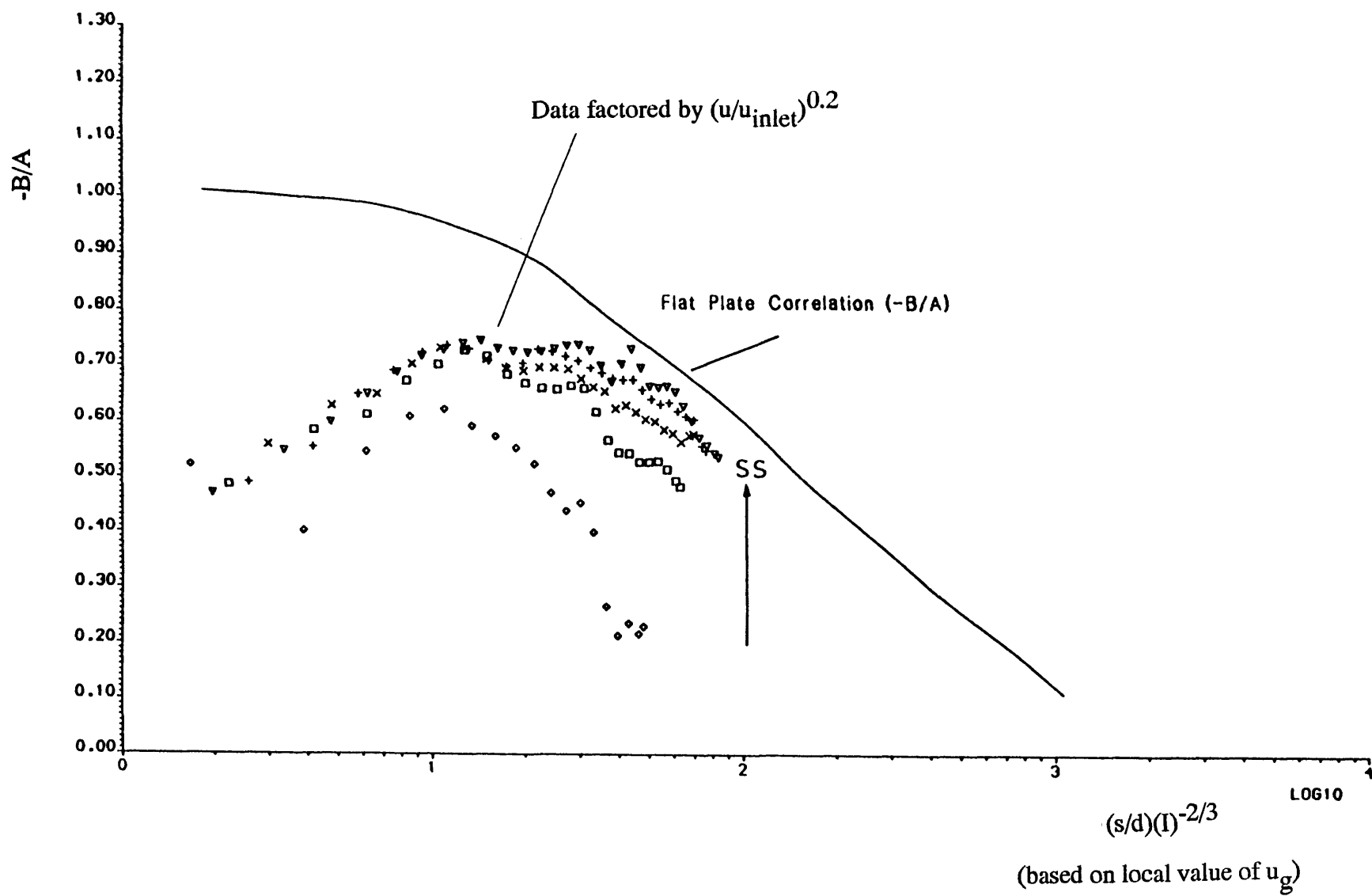


Fig. 8.11 Film-cooling effectiveness with streamwise pressure gradient correction against slot wall jet parameter for $G=1.11$.

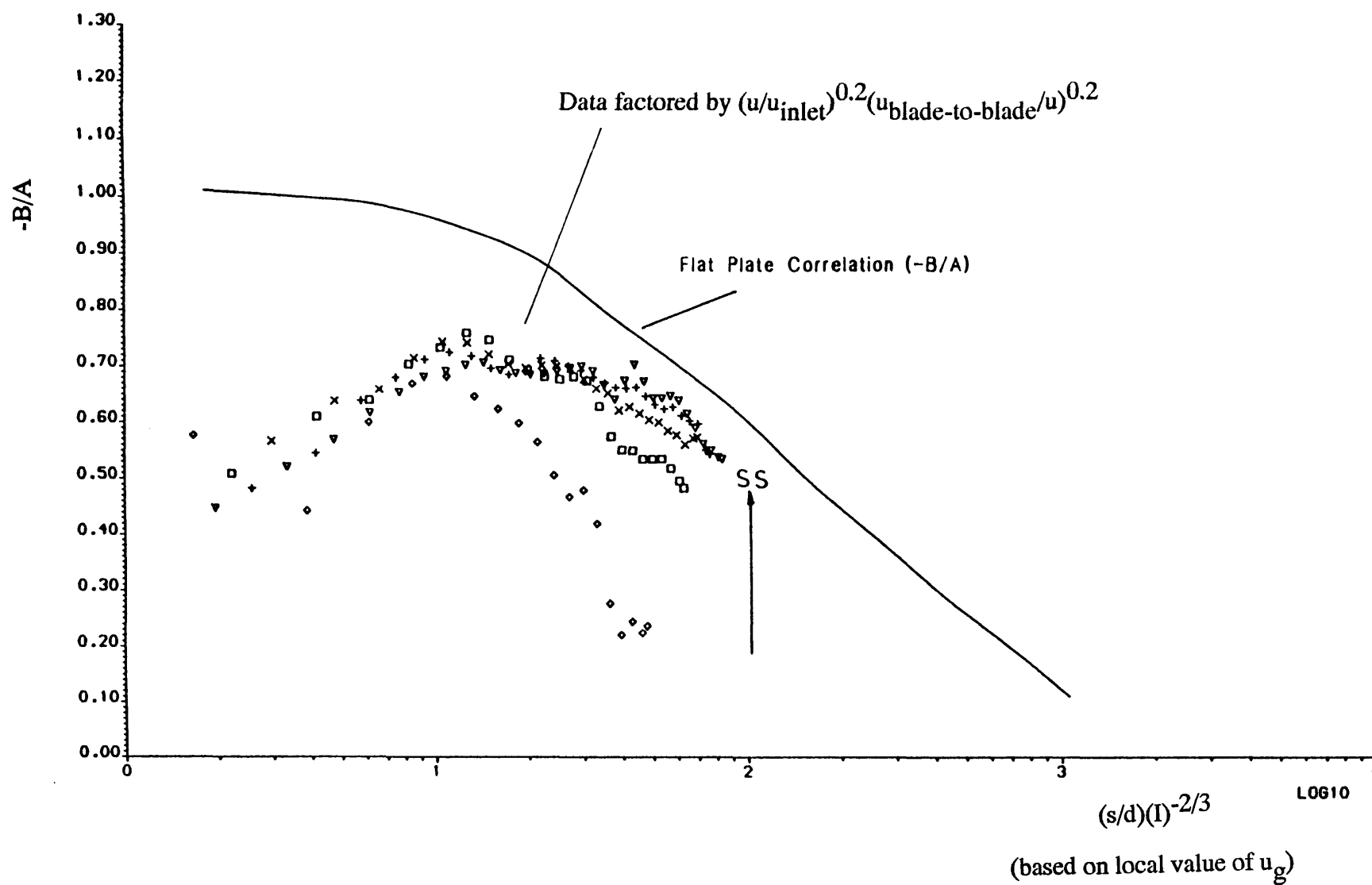


Fig. 8.12 Film-cooling effectiveness with blade-to-blade pressure gradient correction against slot wall jet parameter for $G=1.11$.

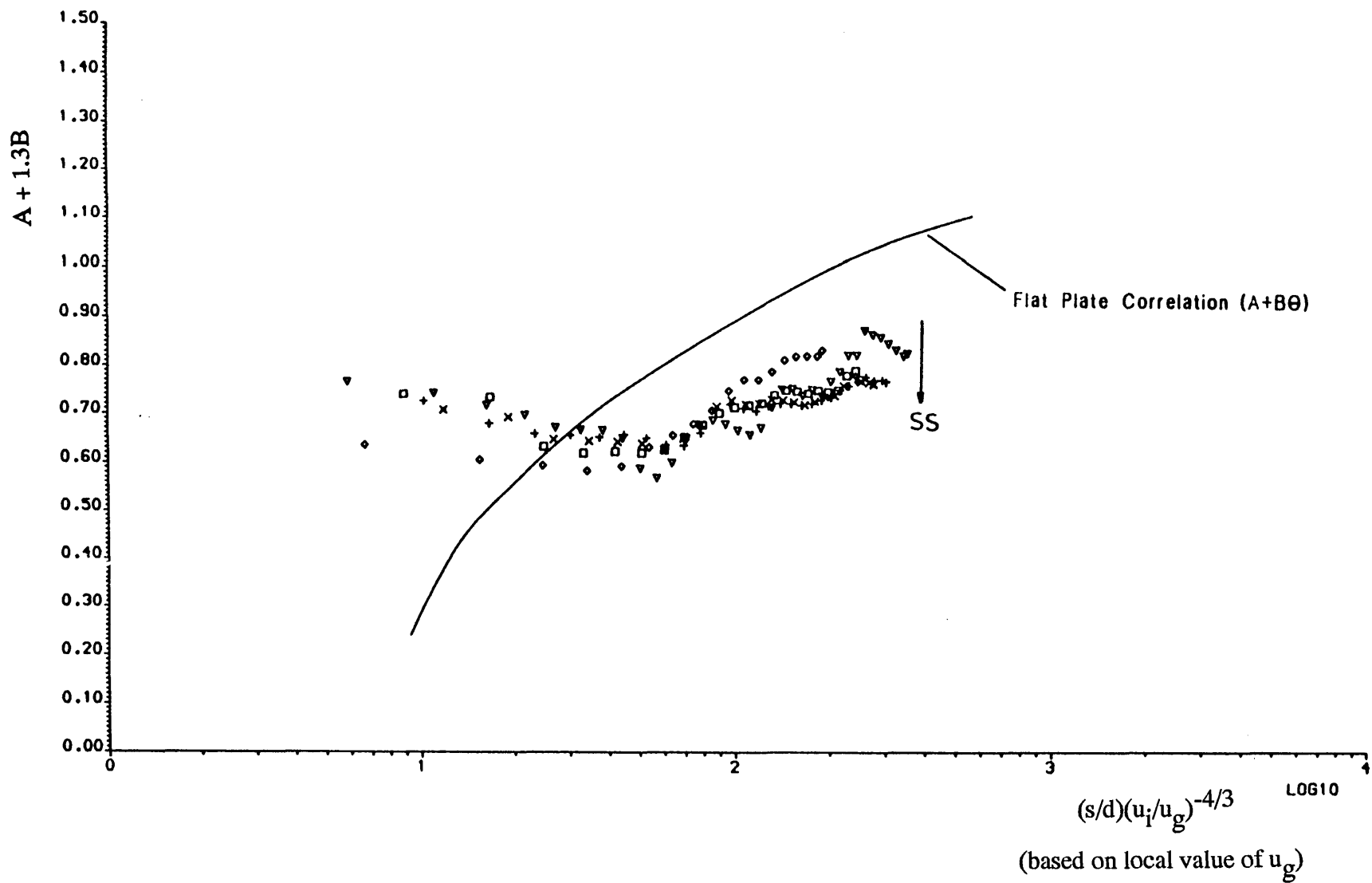


Fig. 8.13 $A + 1.3B$ against slot wall jet parameter modified for strong blowing regime for $G=0.52$.

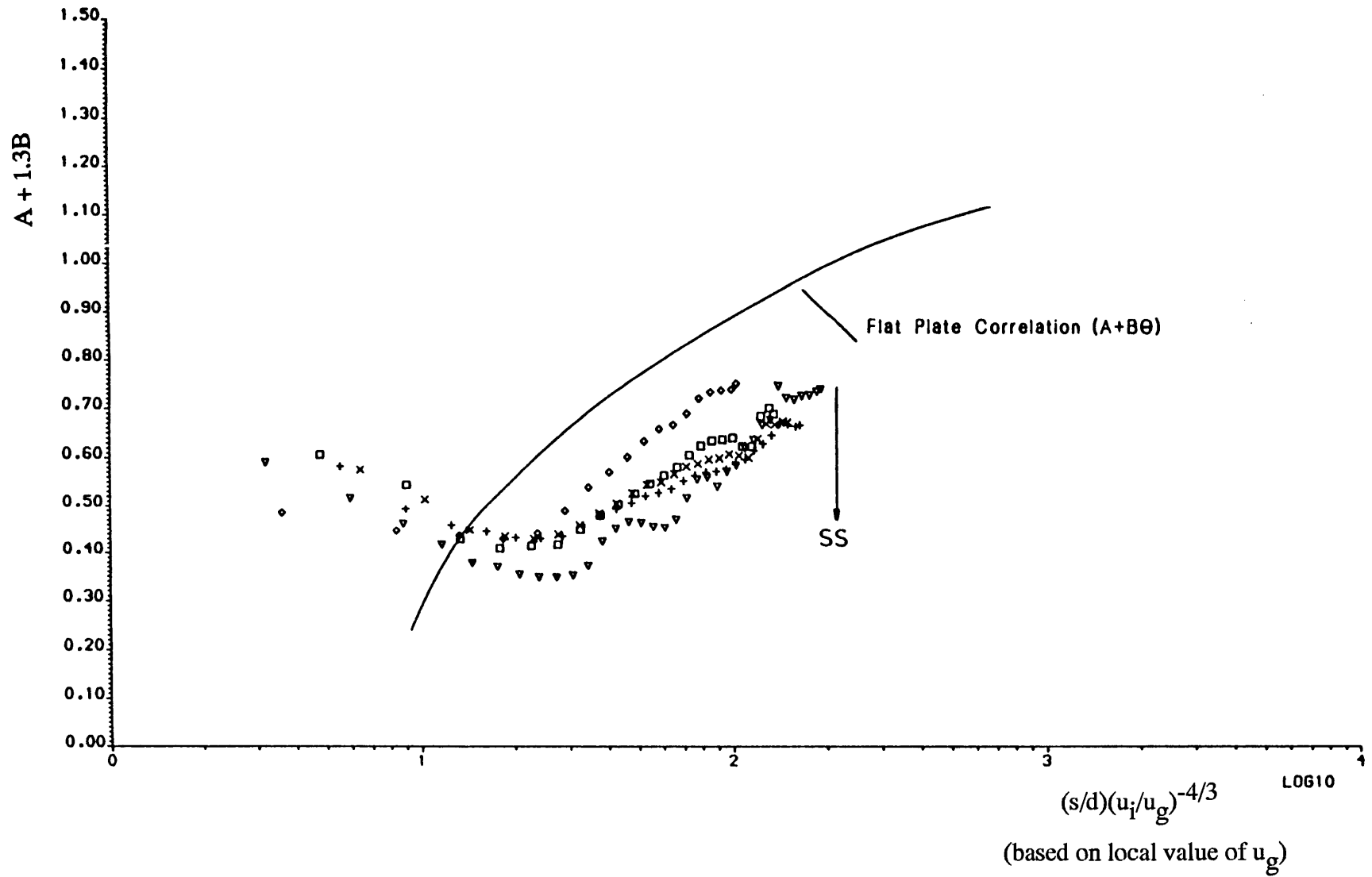


Fig. 8.14 $A + 1.3B$ against slot wall jet parameter modified for strong blowing regime for $G=0.83$.

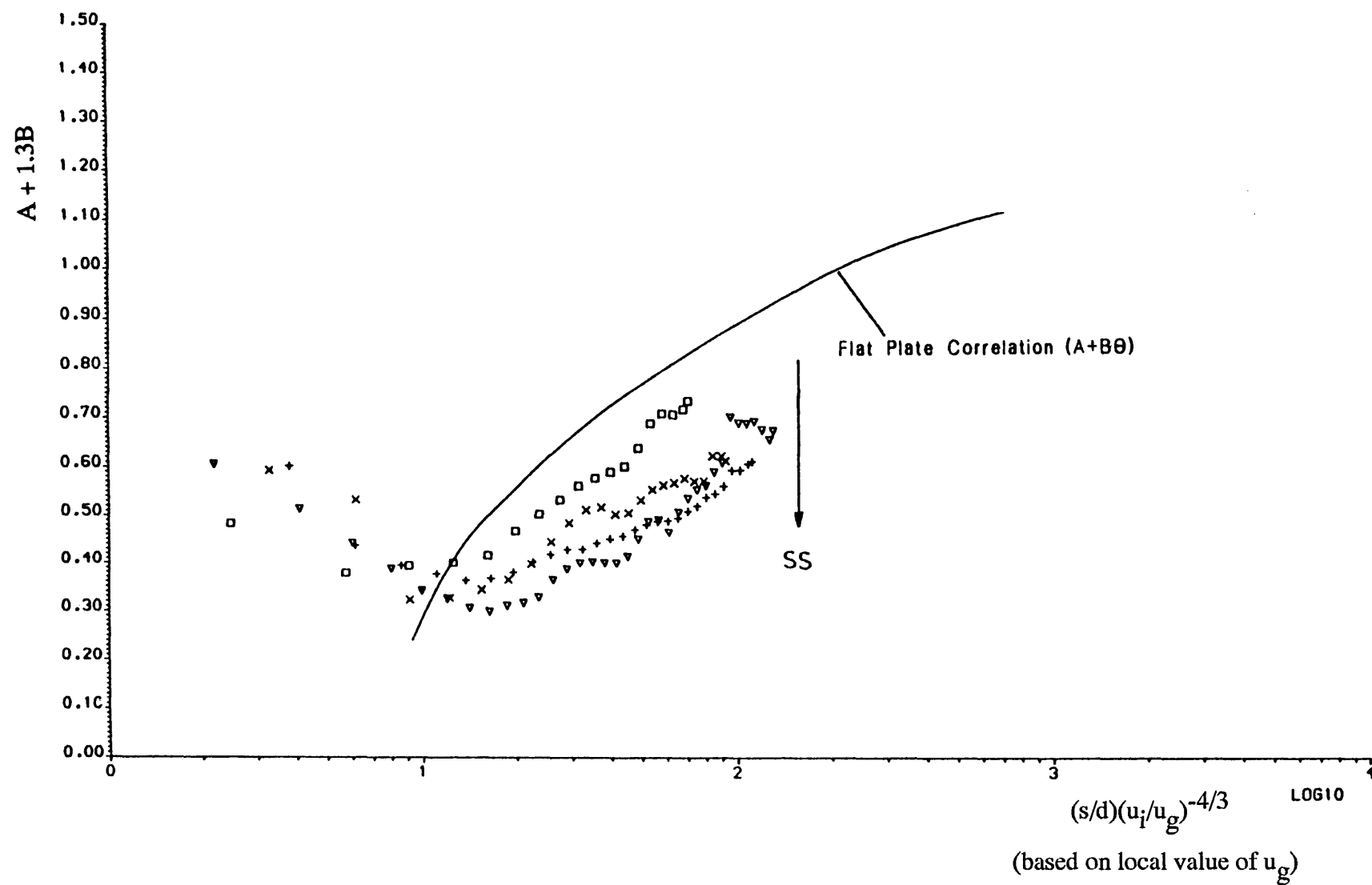


Fig. 8.15 $A + 1.3B$ against slot wall jet parameter modified for strong blowing regime for $G=1.11$.

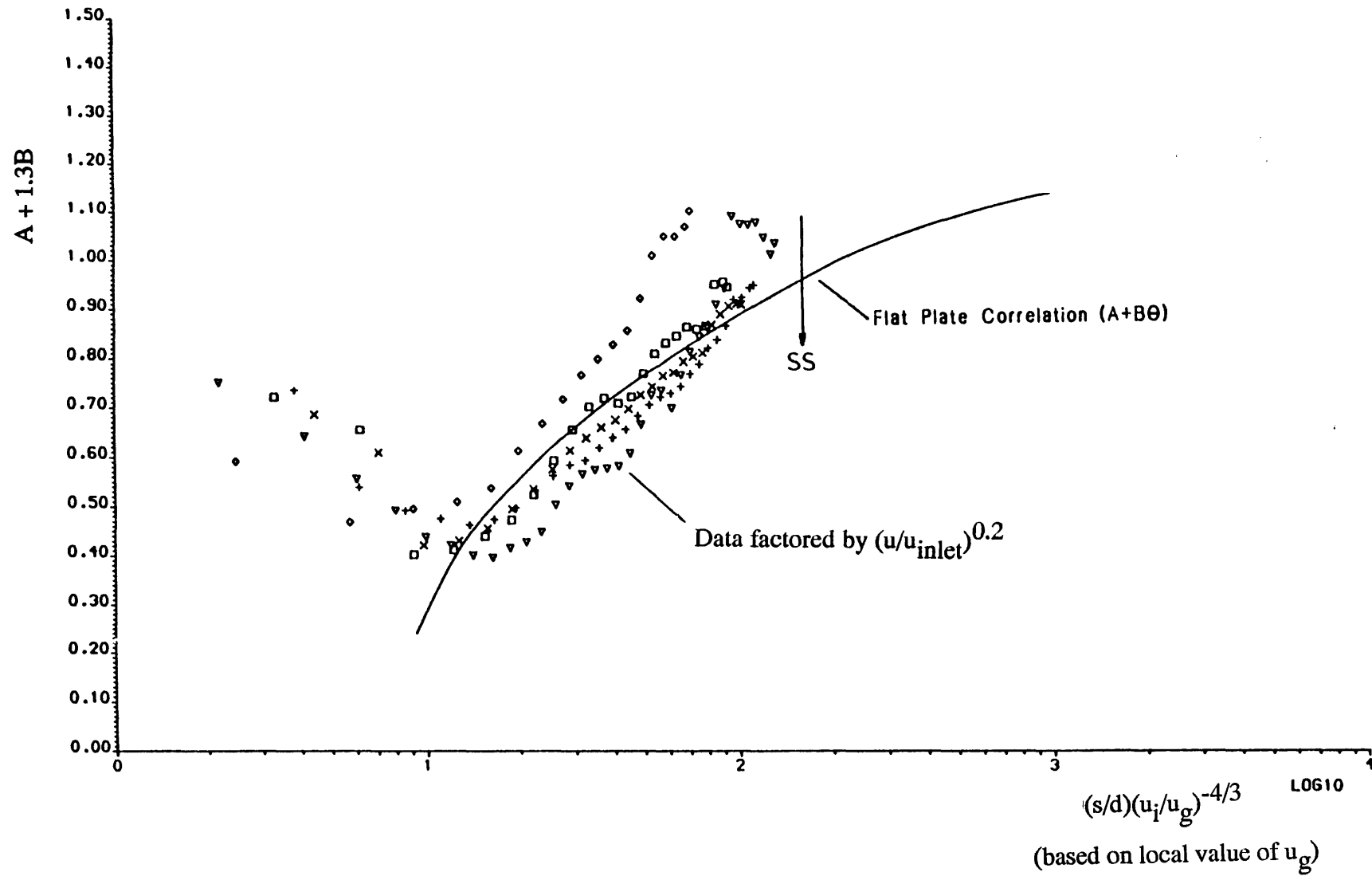


Fig. 8.16 $A + 1.3B$ with streamwise pressure gradient correction against slot wall jet parameter modified for strong blowing regime for $G=1.11$.