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# INJECTION IN BOUNDARY LAYER AND ITS INFLUENCE ON HEAT TRANSFER

BY

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## ABSTRACT:

An experimental investigation was performed to examine the effect of film cooling from different shape holes at the leading edge of a flat plate. The interaction of a heated jet with a deflecting flow has been performed. The secondary flow is introduced at different angles to the mainstream flow direction with single row of holes. Visualization studies using yarn tufts are reported. The influences of hole geometry; mainstream boundary layer thickness are described significant improvements in the film cooling effectiveness are observed by having the coolant and passages widened before the exit of the secondary fluid. "Normal-inclined" injection gives superior results.

## NOMENCLATURE:

- A : Cross sectional area of the injection tube $cm^2$.
- D : Diameter of injection tube cm.
- h : Local heattransfer coefficient with injection, $q/(T_{w2} - T_2)$. W/°K. $cm^2$.
- $h_o$ : Local heat transfer coefficient without injection, $q/(T_w - T_\infty)$. W/°K. $cm^2$.
- I : Electrical current Amper.
- M : Blowing rate or blowing parameter.
- q : Wall heat flux per unit area; $W/cm^2$.
- $Q_2$ : Secondary air discharge $m^3/sec$.

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$Re_D$ : Injection tube Reynolds number; $Re_D = \frac{u_\infty D}{\nu_\infty}$

$t_{ad}$ : Adiabatic wall temperature °C

$t_w$ : Surface temperature without injection °C

$t_{w2}$ : Surface temperature with injection °C

$t_2$ : Temperature of secondary air °C

$t$ : Mainstream temperature °C

$u_2$ : Air velocity through injection tubes m/sec.

$u_\infty$ : Mainstream velocity m/sec.

V : Voltage drop; Volts

x : Distance downstream of injection hole cm

$x^{\bullet}$ : " " " the leading edge of the extension hole cm.

w : Jet width cm.

y : Distance normal to test surface cm.

z : Lateral distance from injection hole cm.

$\nu_2$ : Kinematic viscosity of secondary air $m/sec^2$

$\nu_\infty$ : Kinematic viscosity of mainstream $m/sec^2$

$\eta$ : Film heating (cooling) effectivness; $(T_{w2} - T_\infty / T_2 - T_\infty)$ Dimensionless.

$\rho_2$ : Density of secondary air $Kg/m^3$

$\rho_\infty$ : " " mainstream $Kg/m^3$

$\alpha$ : Flow rate coefficient Dimensionless

$\delta$ : Porosity of holes in row; $\pi$.D/4P Dimensionless.

$\beta$ : Injection angle Degree

$\xi$ : Correlation parameter.

## 1. INTRODUCTION

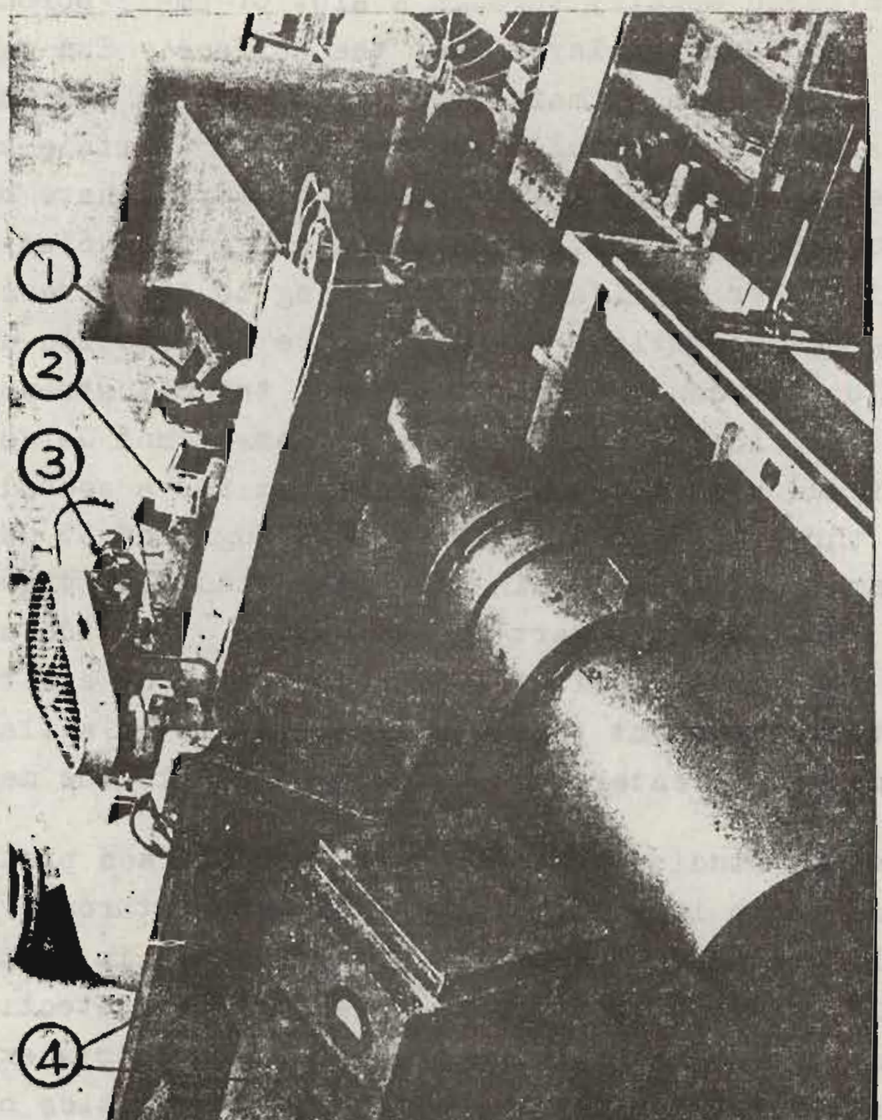
Modern gas turbine engines with ever increasing turbine inlet temperature require a large percentage of the engine air flow to cool the turbine airfoils. In future engines, with design goals of reduced size and weight and improved specific fuel consumption, cycle temperatures and pressures will be much higher with correspondingly larger cooling requirments which leads to improve the engine thermodynamic efficiency. Another applications are in furnaces of steel industry and the dispersion of the hot gases from chimney stacks by using the injection in the boundary layer of the hot gases.

To protect the engineering surfaces from hot air streams flowing over them with film cooling method, a secondary cooled air is injected usually through a slot or small porous section, into the air boundary layer over the surface. The injected fluid is swept down by main flow and or by its own momentum. It serves as an isolating layer between the surface and the free stream. Continuous slot or porous strips have been used in various applications. Rows of openings (or holes)are perferable in other applications according to the stress or manufacturing consideration. A qualitative description of the interaction between the secondary gas, the mainstream and the shape of the flow field, is given by Ramsey and Goldstein[1]. They designed a qualitative flow diagram for a secondary flow entering through a circular tube at an augle of 35 deg to the mainstream. Keffer and Baines[2] reported flow visualization studies. Goldstein, Eckert and Ramsey [3] provide study on the film cooling effectivness with injection of air through a holes into a turbulent boundary layer of air on a flat plate. The secondary air enters at an angle of 35° to the mainstream.

Previous studies indicate that less surface protection is obtained with injection through holesthan through a continuous slot. The intent of the present study is to investigate the possible means for improving the surface protection with injection through holes. The present work reports experimental investigations on the injection characteristics of inclined and perpendicular holes located near the leading edge of an adiabatic plate. It is included that the flow rate characteristics of the injection holes depend on the hole diameter and the hole position.

## 2. APPARATUS AND INSTRUMENTATION:

The tunnel used in this study with the heat flux source are shown in Fig.(1). A backalite plate was used as a carcass for the test plate as in Fig.(2). The test plate with 24




1- Test section 2- Thermosteerer

3- Compressor 4- Rheostat

Fig. 1 Wind Tunnel With Test Section

1- Test plate
2- Stainless steel heater foils
3- Steel frame 4- Driving wheel
5- Injection plate
6- Scale
7- Moving wheel
8- Adjusting screw
9- Total pressure tube
10- Alumel-chromel wire
11- Pressure-temperature probe
12- Static pressure tab
13- Balancing spring
14- 3 Volt Globe

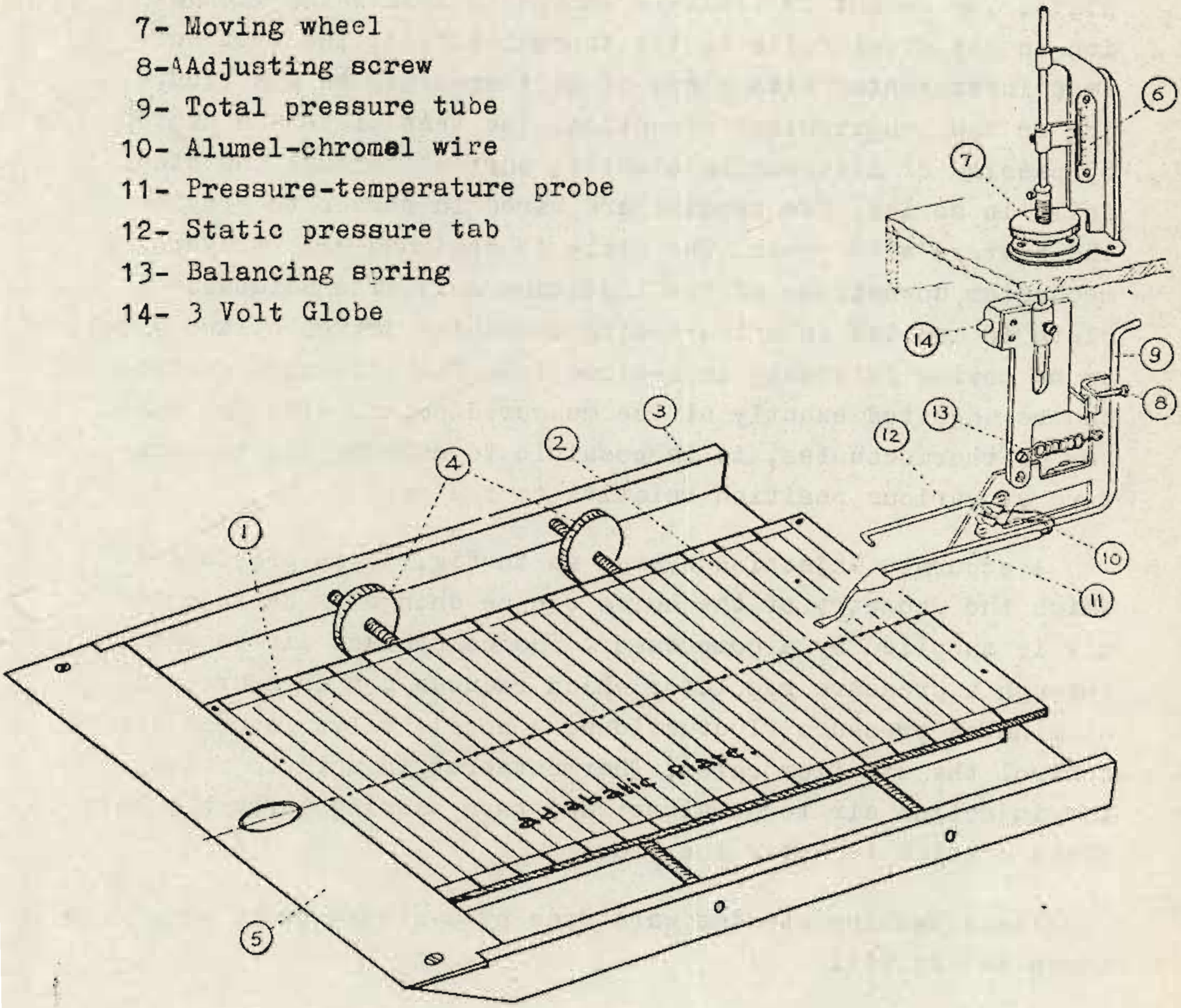



Fig. 2 Test Plate

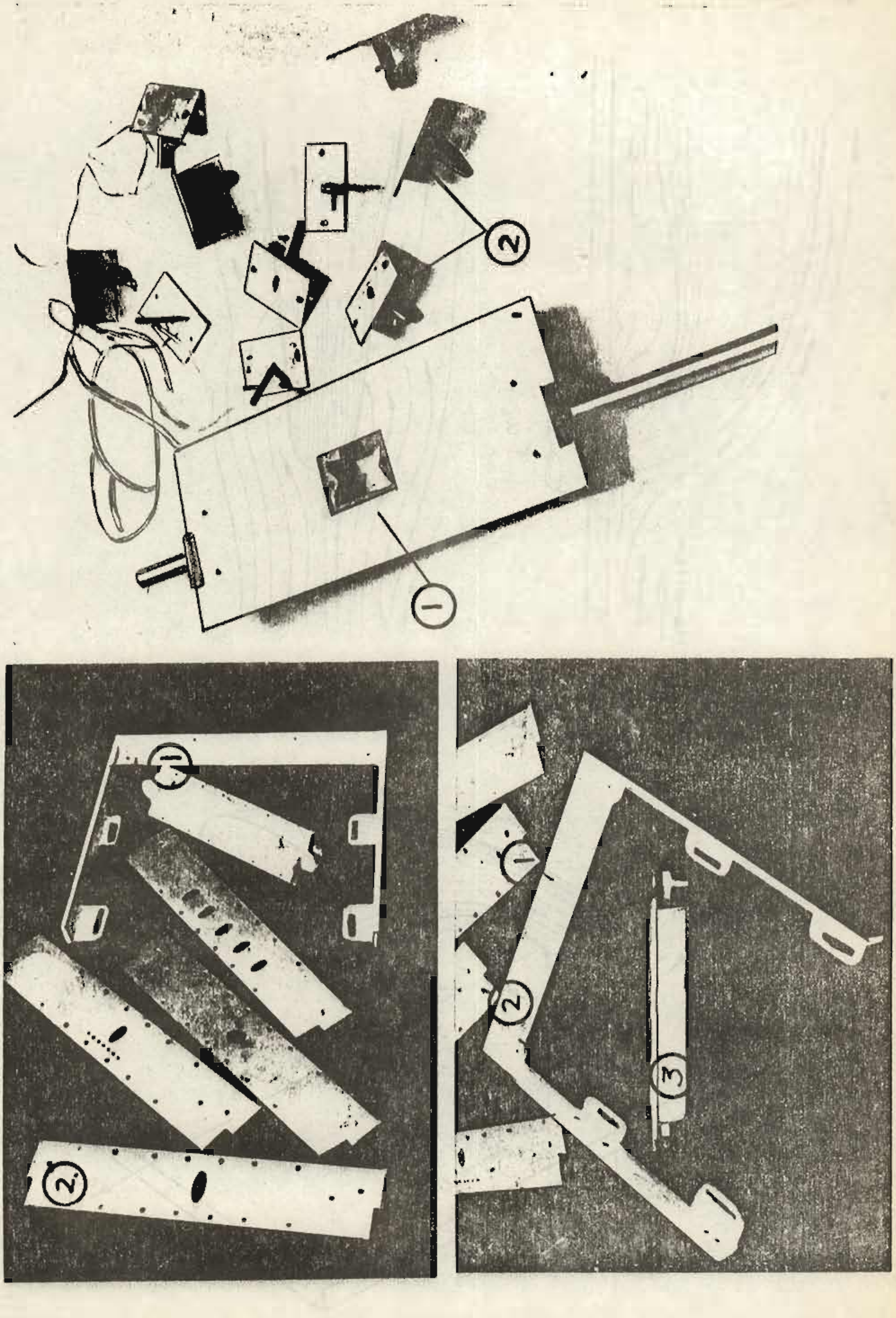
stainless steel electrical heater foils are cemented to the backalite plate with Araldite AV 129 with hardner HV 953 B used for cementing the thermocouples and the foils with test plate. The cement is flexible enough to absorb the elongation in the steel foils to the thermal effect. The test surface instrumented with a row of 24 thermocouples distributing in the longitudinal direction. The test plate was heated by passing of alternating electric current through the steel foils in series. Two reostat are wired in series to provide the heaters with power. The plate is designed with traversing mechanism downstream of the injection unit. The adiabatic plate is mounted on a traversing mechanism driven by two wheels to be moving laterally in z-direction. The adiabatic surface can be adjusted exactly at the measured point. With the same row of thermocouples, it is possible to measure the temperature at various position relative to the jet.

A separate injection system as in Fig.(3) is provided in which the geometry of the holes can be changed. The injected air is supplied by a compressor. The compressed air passes through a pressure regulator which reduces the pressure and eliminates pressure fluctuations. A needle valve is used to control the air flow rates. Thermosteerer is used to raise the injection air temperature; and then passing through a thin plate orifice to meter the flow.

Visualization studies were made by a simple probe as shown in Fig.(4).

## 3. RESULTS AND DISCUSSIONS:

The results obtained from experiments of the present work are reported as follows:



(1) Injection Frame (2) Injection Plates (3) Injection Tube

Fig. 3 Injection Units

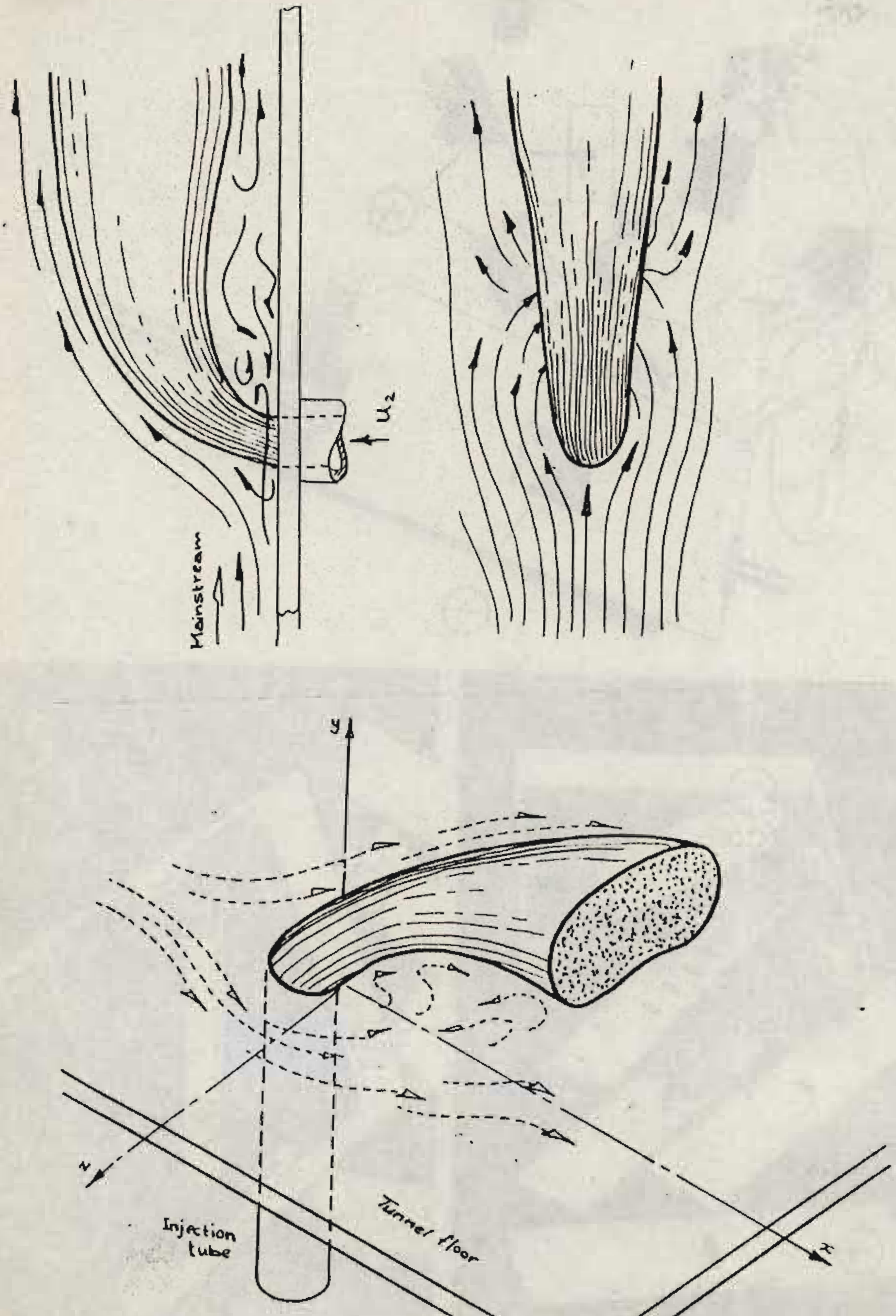



Fig. 4 Sketch Of Perpendicular Jet Based On Tuft Study

### 3.1. Effect of Free Stream Velocity and Injection Tube Diameter on Surface Temperature:

Adiabatic wall temperatures are determined by operating the tunnel with injection of heated secondary air and no heat flux from the test surface.

The combined effect of both free stream velocity and injection tube diameter at a fixed value of the Reynolds number, $U_{\infty} . D / \nu_{\infty}$ , can be observed in Fig.(5).

As indicated a low injection velocity with a large hole diameter is perfrable to a high velocity with small diameter. Although the effect on surface temperature is small for normal injection, it is more pronounced for tangential injection, as illustrated in Fig.(6).

### 3.2. Effect of Hole Geometry on Surface Temperature :

Fig.(7) shows the flow of the secondary air, for the same flow rate. The jet from the shaped hole lies much closer to the surface through which it enters while the jet from the cylindrical channel penetrates far from the wall.

The fact that the jet leaving the shaped hole stay closer to the surface indicates that the film heating performance of this geometry should be better particulary at moderate and high blowing rates.

The above reasoning is verified by the results presented in Fig.(8). The figure shows the surface temperature downstream of the injection bore.

For the shaped holes, the center-line temperature profiles for 35° injection Fig.(9) also the surface temperature at all blowing rates studies is considerably higher than with cylinderical holes.

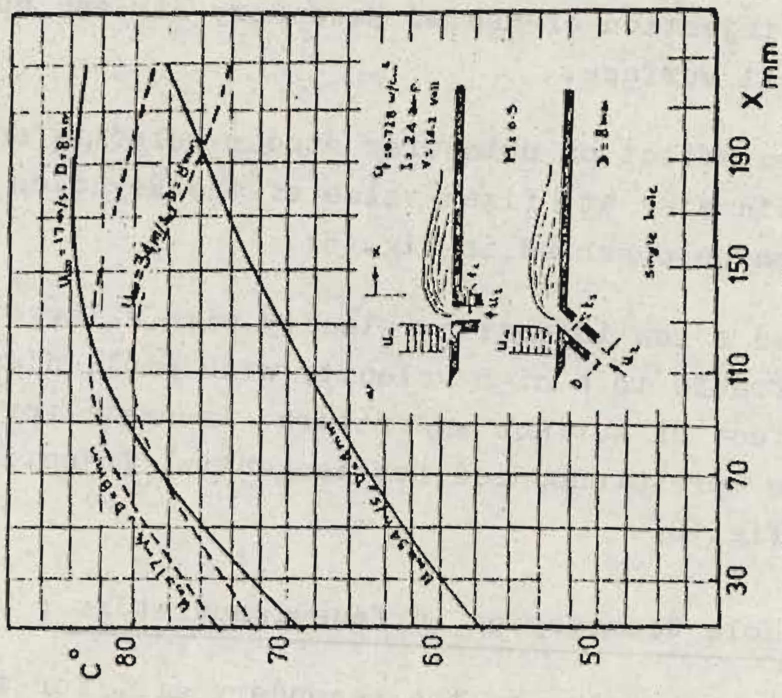



Fig.6 Surface Temperatures With Heated Operation And Injection

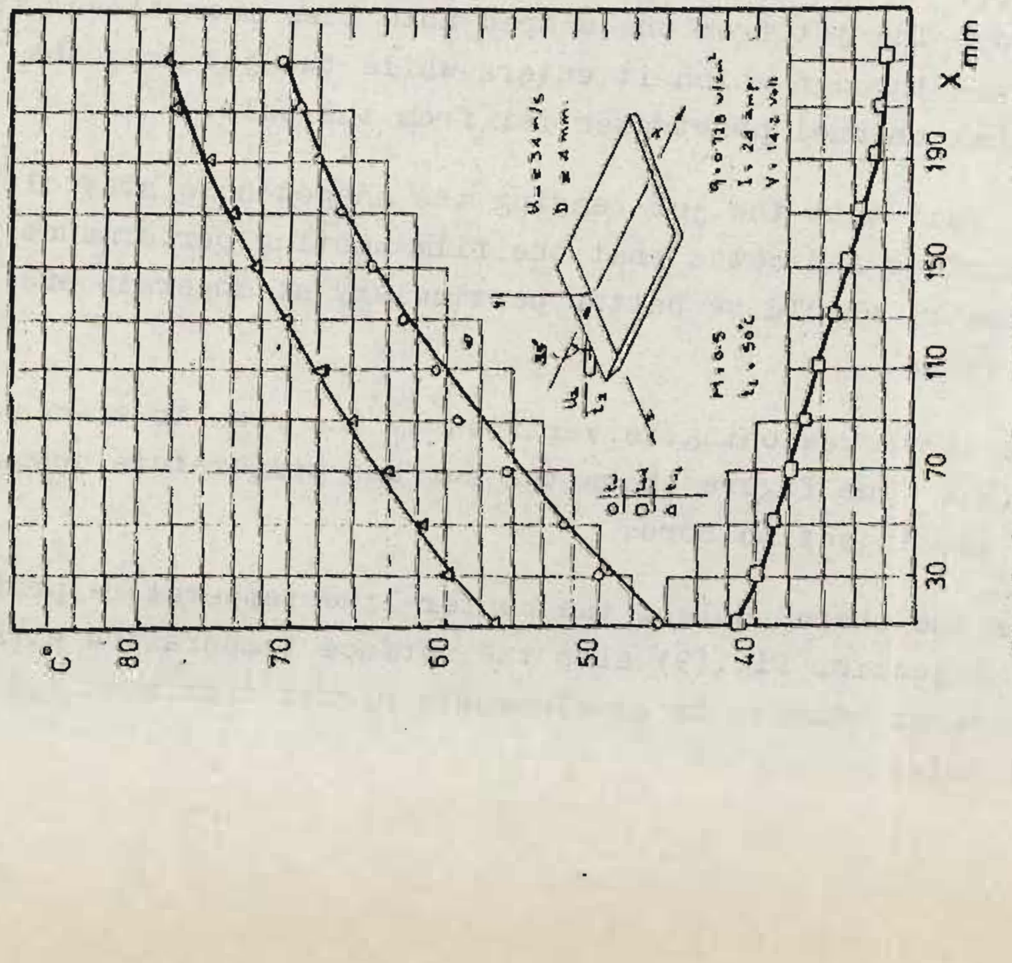



Fig. 5 Surface Temperatures With Adiabatic And With Heated Operation

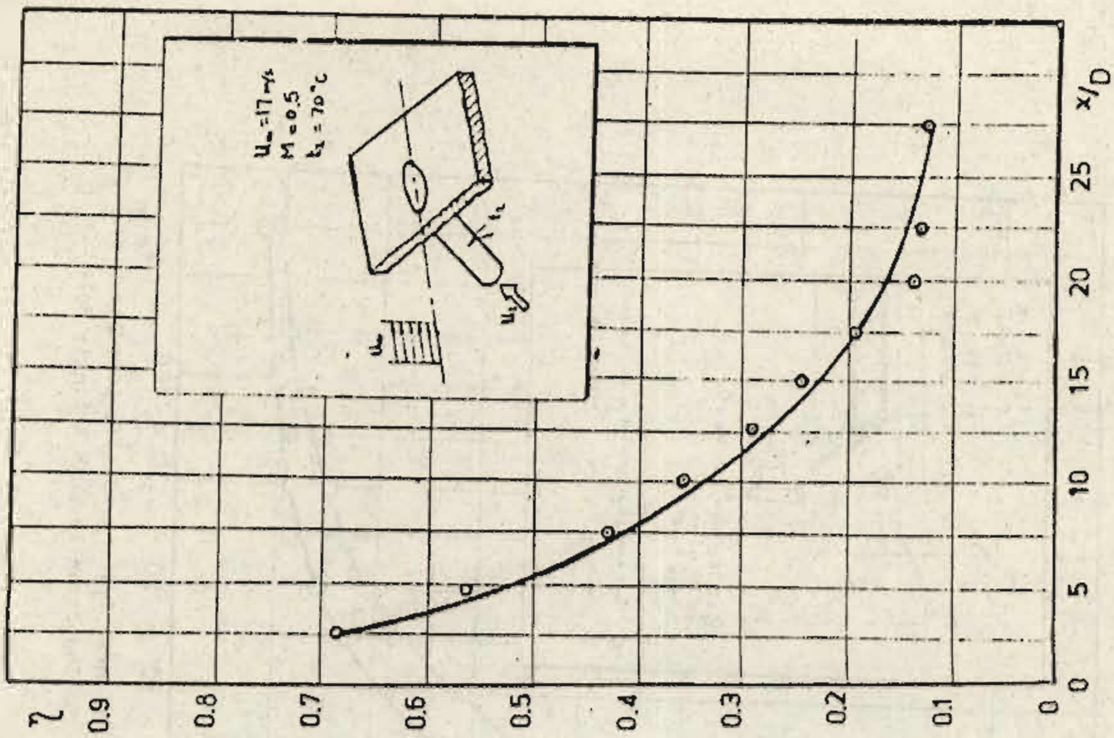



Fig. 8 Film Heating Effectiveness

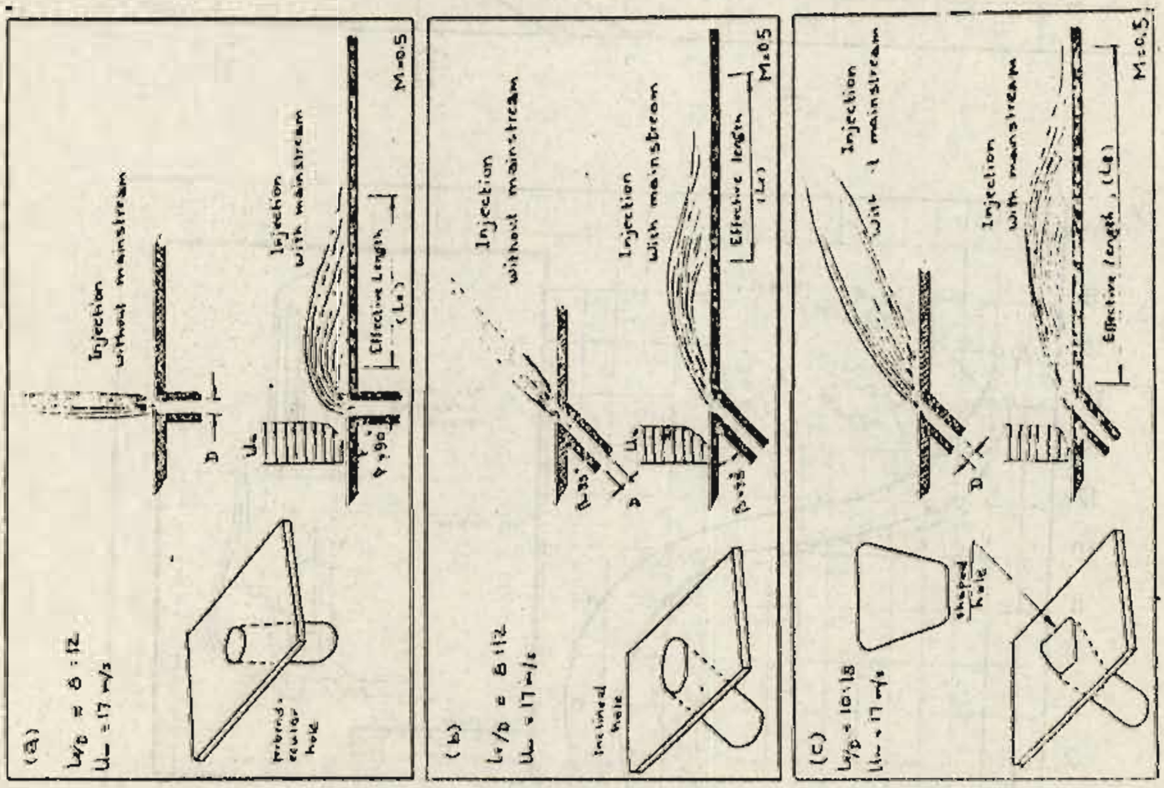



Fig. 7 Approximate Injectant Effective Lengths According To Tuft Visualisation

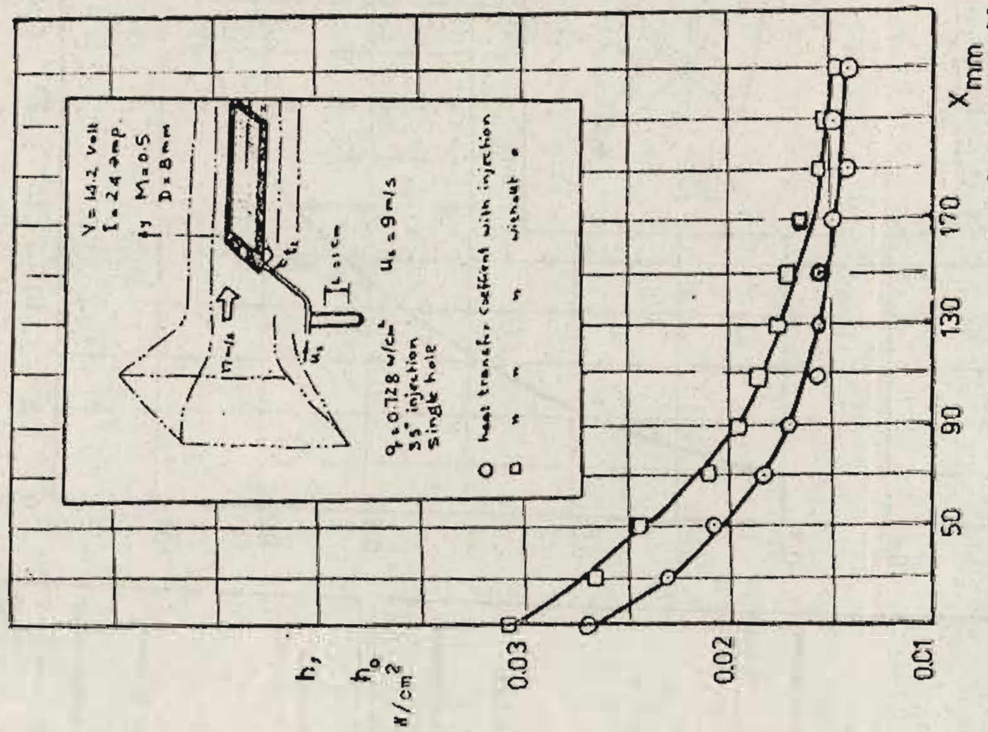



Fig.10 Heat Transfer Coefficient Downstream Of Injection Through A Single Hole

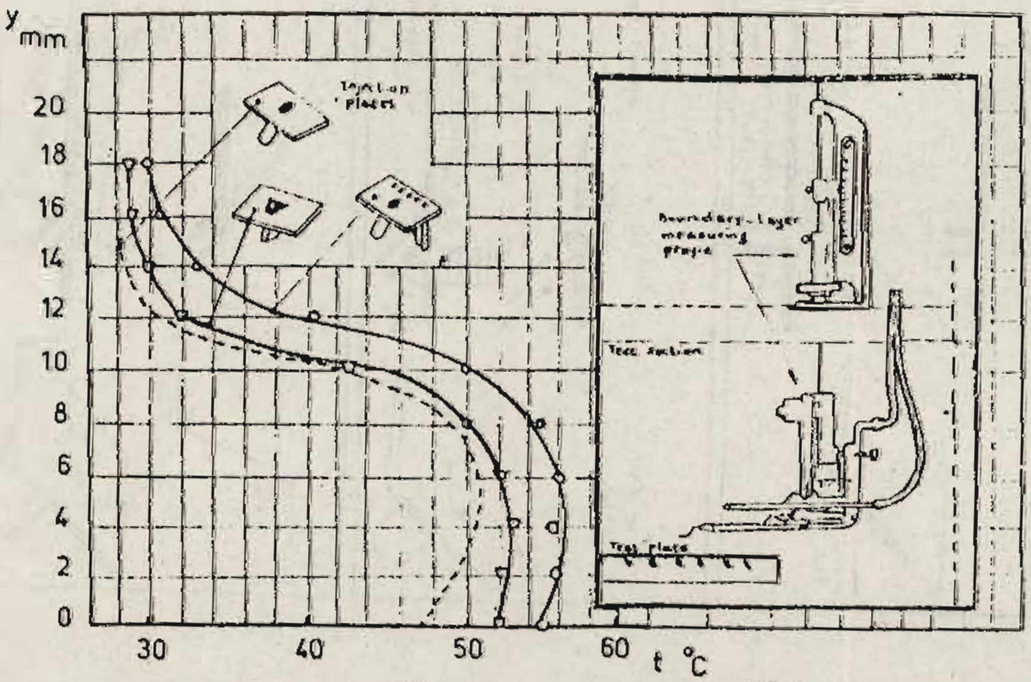



Fig. 9 Center-line Temperature Profiles For 35° Injection

On explanation of increased surface temperature with shaped holes is that the mean velocity on the secondary flow is decreased with the large exit area. This causes the jet to stay closer to the wall rather than penetrating into the mainstream.

3.3. Heat Transfer Coefficient:

Heat transfer coefficients are determined with a heated wall and with either heated or unheated air jets, and defined by the following relations

$$q = h(T_{\infty} - T_{ad}) \text{ for unheated plate}$$

and

$$q = h(T_w - T_{\infty}) \text{ for heated}$$

The heat transfer coefficient downstream of a single 35 deg hole is presented on Figs.(10 : 12) for M = 0.5, 1.0 and 1.5. The heat transfer is within approximately 1/10 of the value without injection for all of these injection rates. It is often less than that found without injection especially at the lower injection rates ($M < 0.5$) and far downstream for the higher injection rates. The heat transfer coefficient is increased near the hole where the jet and main flow interact strongly at the higher injection rates.

Results indicate that the heat transfer coefficient for injection through a hole at an angle of 90 deg to the mainflow is lower than the value without injection between x = 0, x = 200 mm for $M < 1$.

The heat transfer coefficient for a hot jet (50 deg C) is less than the unheated jet for the same conditions as shown in Fig.(13).

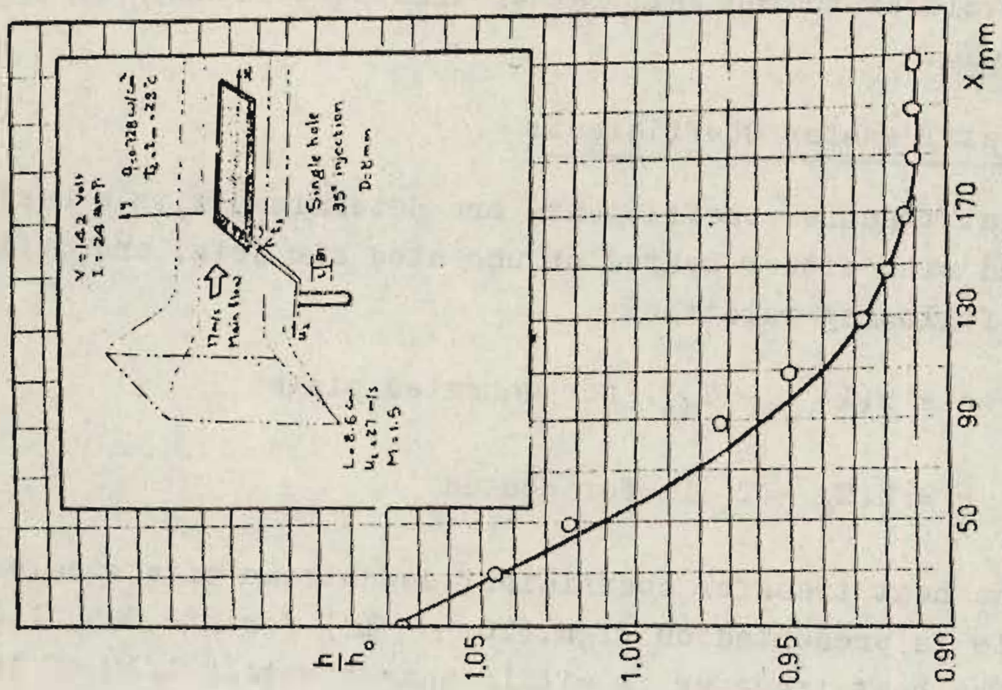



Fig.12 Heat Transfer Coefficient Of Injection Through A Single Hole

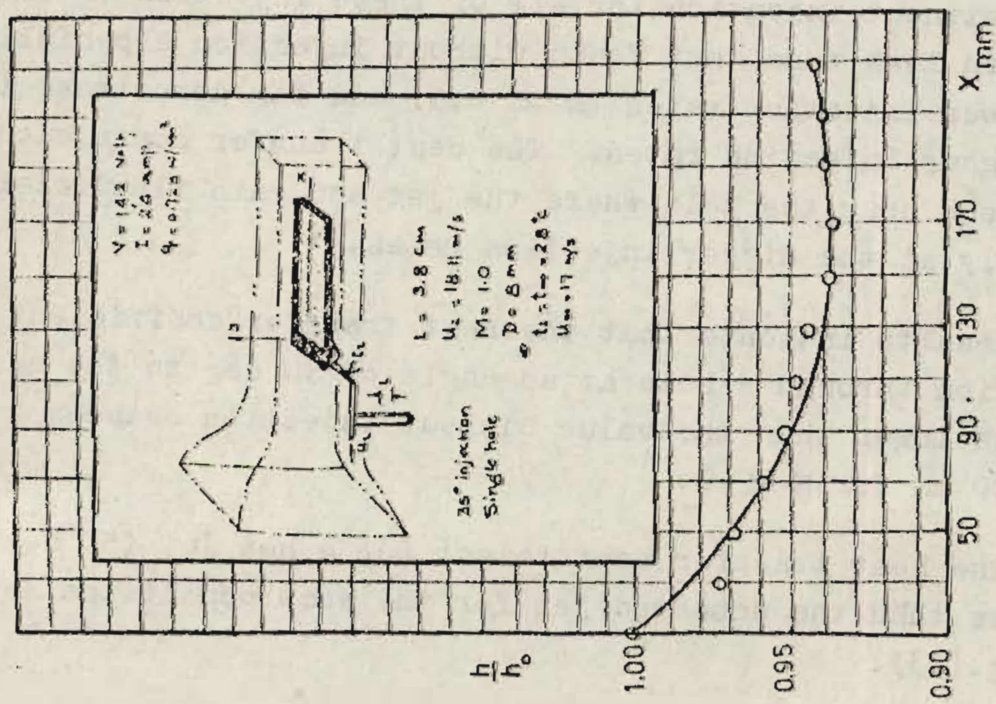



Fig.11 Heat Transfer Coefficient Downstream Of Injection Through A Single Hole

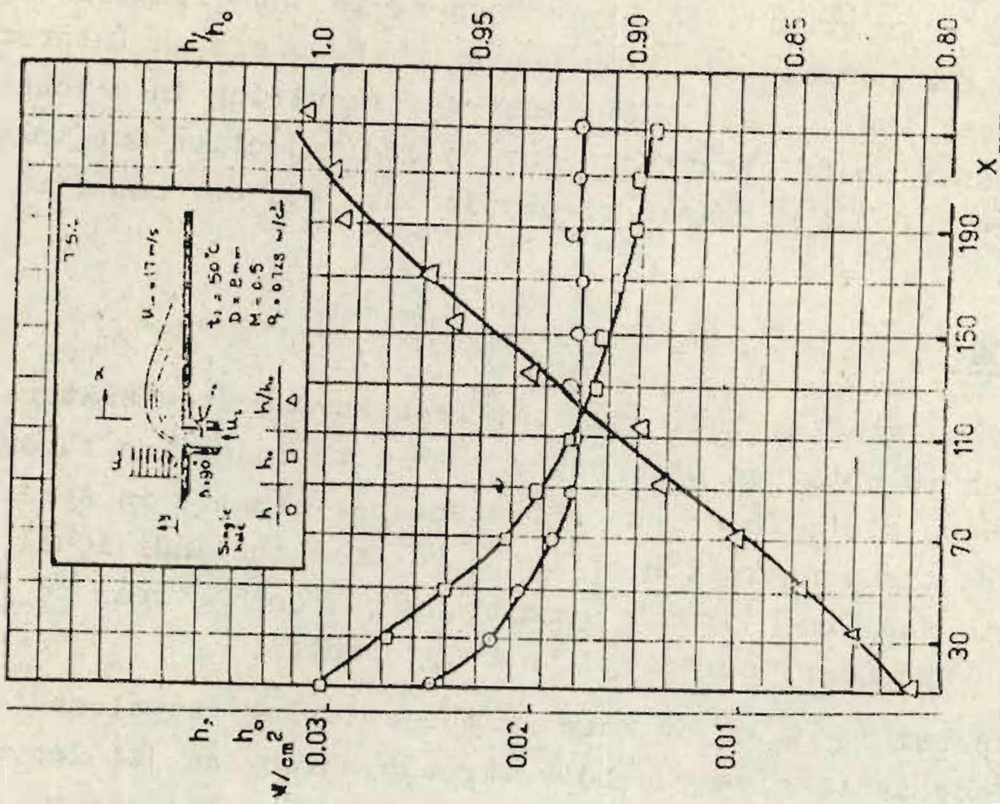



Fig.14 Heat Transfer Coefficients

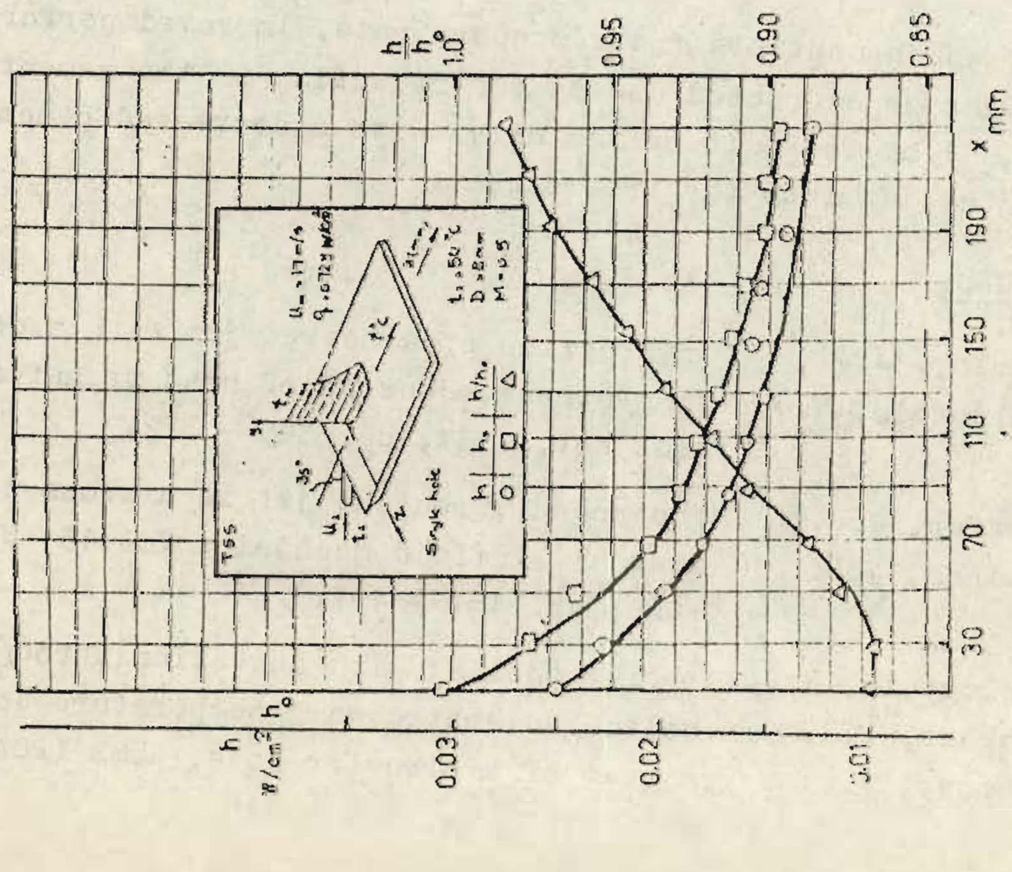



Fig.13 Heat Transfer Coefficients

A jet injected at 35 deg has a velocity component in the direction of the mainflow; a jet injected normal to the mainstream has no initial velocity component in the direction of mainflow. For normal injection there is therefore an interaction between the jet and the mainstream resulting in a lower heat transfer coefficient than for 35 deg injection due to the rapidly bent for the heated perpendicular jet, as shown in Fig.(14).

## CONCLUSION:

Previous studies indicate that less surface temperature or protection is obtained with holes than with injection through a continuous slot. This less efficient performance is apparently due to the penetration of the jets from the individual holes into the free stream, permitting the cold stream to flow under the secondary air close to be protected.

One possible means of keeping the entering jet close to the surface is to give the hole through which the jet leaves the surface a different area and geometry from the metering section, which controls the secondary rate. Improved performance might be exprected due to the reduction in the momentum flux ($\rho_2 u_\infty^2$) at the exit of the holes with a decreased penetration of the jet into the free stream.

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