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"HEAT TRANSFER WITH FILM COOLING NEAR INJECTION SLOTS"

BY

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ABSTRACT

This paper presents a comparison of the experimental results for a flush slot at two angles of inclination. The experimental investigation of heat transfer with film cooling near injection slots were carried out in a wind tunnel. The secondary flow was injected with two angles; 35 and 90 deg to the mainstream flow direction. The experimental objectives were to determine, for each inclination angle, the influences on the film cooling effectiveness and on heat transfer coefficient. Injection through slots gives better results for film cooling compared with that of injection through holes.

NOMENCLATURE

c_p	specific heat at constant pressure, kcal/kg.K
M	mass flux, or blowing ratio
h	heat transfer coefficient, $kcal/m^2.^oC$
k	thermal conductivity $kcal/hr.m.^oC$
l	surface length m
S	slot gap mm
t	temperature ^oC
u	velocity component in x-direction, m/sec
v	" " " y-direction, m/sec
x	distance from slot, measured downstream, mm
y	perpindicular distance from surface mm
β	slot angle, deg
μ	dynamic viscosity, kg/m.sec
ρ	density, kg/m^3

NONDIMENSIONAL QUANTITIES

Pr $= \frac{\mu c_p}{k}$ Prandtl Number

Re	$= \frac{u_\infty l}{\nu_\infty}$	Reynolds Number
S_t	$= \frac{h}{\rho_\infty . u_\infty . c_{p\infty}}$	Stanton Number
	$= \frac{t_{w2} - t_\infty}{t_2 - t_\infty}$	
u'	$= u/u_\infty$	nondimensional x-velocity component
v'	$= v/u_\infty$	" y-velocity "
x'	$= x/l$	" distance
y'	$= y/l$	" "

SUBSCRIPTS

w_2	surface with injection
2	injected flow
∞	mainstream

1- INTRODUCTION

The practicality of film cooling as a method of reducing the operating temperatures of solid surfaces exposed to high temperatures gas streams has been well stablished in recent few years. In this technique a secondary air (fluid) is injected through holes or slots in the surface upstream of the area to be protected.

In typical application to gas turbine engines the secondary air (fluid) is usually compressed air which has bypassed the combustor, and the protected surface may range from the combustion chamber linear to the platforms and trailing edges of stator vanes. Previous experimental works involve information about the development of cooling methods to protect working surfaces by injection of secondary air (fluid) into a turbulent boundary layer. Such experiments are given by[1, 2, 3, 4, 5, 6, 7] indicate that for regions sufficiently far downstream of the injection location, surface heat transfer rates can be adequately predicted. This prediction follows by use of heat transfer coefficient associated with the primary flow in the absence of injection, which gives approximately the same values.

This paper presents the results obtained from experiments carried out on slotted plates. A major objective of the present study is to establish an experimental program of film heating effectiveness and heat transfer coefficient.

The initial results of this program have been obtained for injection through flush angled holes[1, 6, 7] into the boundary layer on heated surface.

2- APPARATUS AND PROCEDURE

The experimental study is followed in a small wind tunnel has an axial blower which induces the main flow air. Fig.1 shows the experimental arrangement used in the investigation of heat transfer with film cooling near injection slots. The discharge of the mainstream is measured by an orifice meter according to ASME standards. The film-flow air is provided by an air compressor system and is heated through thermosteerer. The heated film air is supplied to the injection system with a slot which spans the entire plate. This flow is also metered by an orfice installation. A sketch showing the experimental slotted parts, the test plate and the test arrangement with leading edge arrangement is given in Fig.2. The test plate downstream of the injection location contains thermocouples for measuring wall-temperature distribution downstream of the injection. The total pressure-temperature distribution inner the boundary layer is measured by the special probe illustrated in the same figure.

The moveable slotted plates, Fig.3, for injection angles 35 and 90 deg are machined from steel and aluminium plates. The plates have thickness b = 3 mm and the slot gap S = 3 mm.

3- BASIC PARAMETERS

To derive the nondimensional parameters, convenient for correlating and comparing the experimental results, the simplified Navier-Stokes-, continuity-, and energy-equations are considered in the following form:

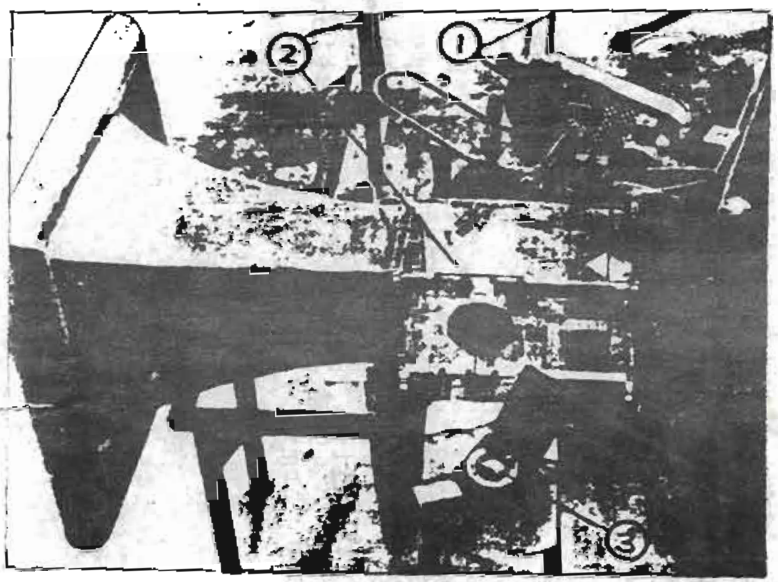


Fig.1 The Experimental Arrangement

1. The Compressor Unit
2. Test Section
3. Thermostimeter

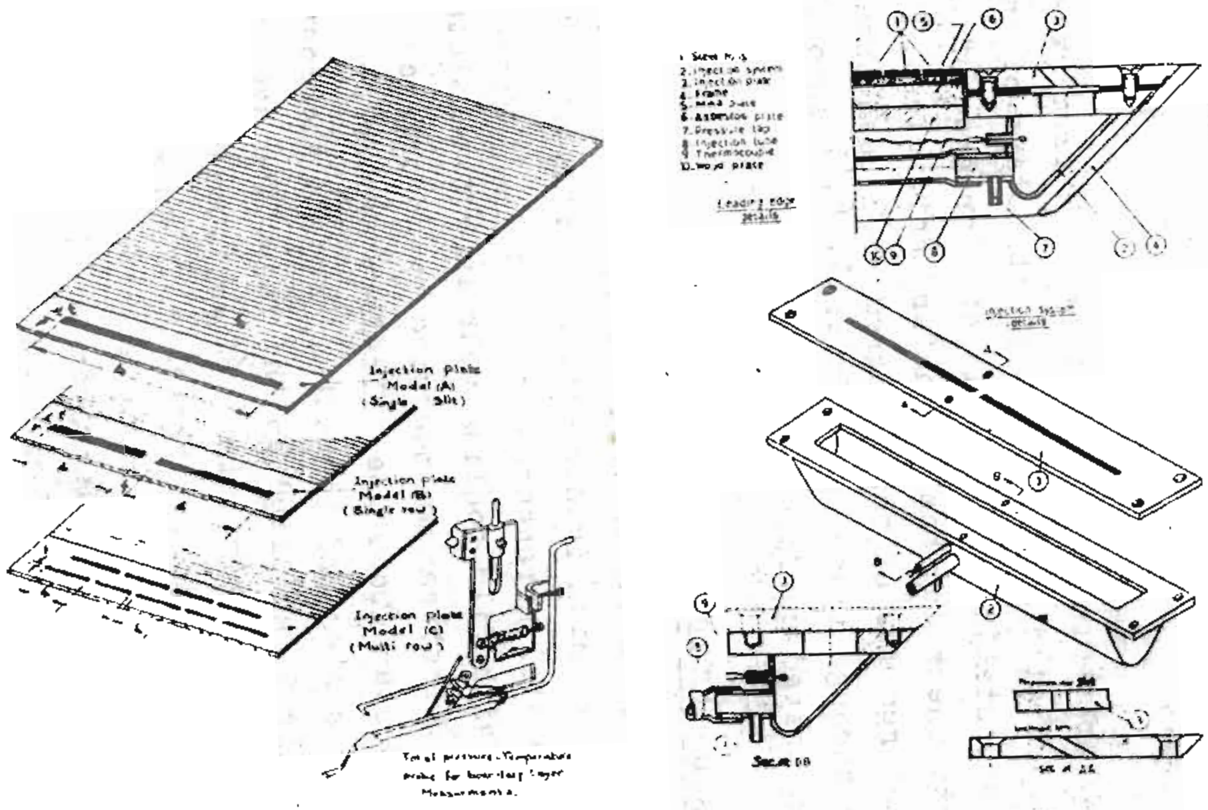


Fig.2 The Test Plate and The Test Arrangement With Leading Edge Details

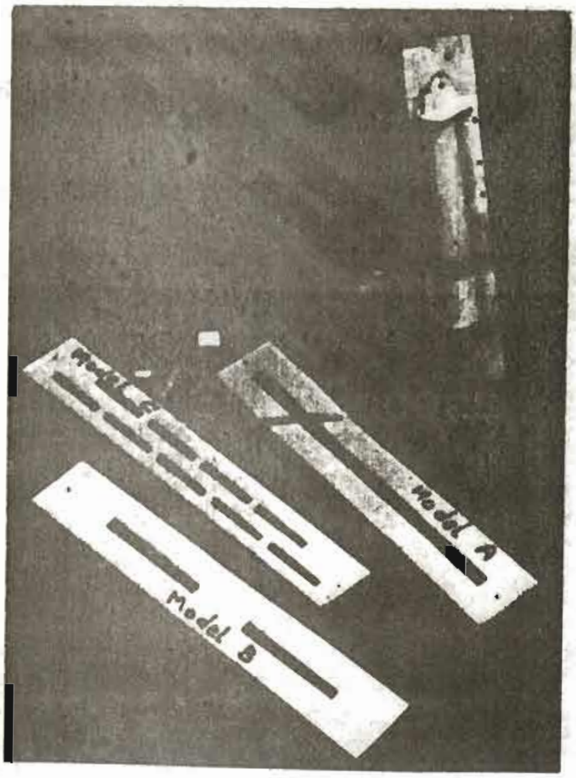


Fig.(3) Different Slot Shapes

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \nu \frac{\partial^2 u}{\partial y^2} \quad (1)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

$$u \frac{\partial t}{\partial x} + v \frac{\partial t}{\partial y} = \frac{k}{\rho . c_p} \frac{\partial^2 t}{\partial y^2} \quad (3)$$

Equation (1) and (2) represent the fluid dynamic and Eq.(3) the heat transfer adjacent to the heat surface.
The x-coordinate is measured parallel to the plate in the direction of flow, and y is measured normal to the plate.
These equations are normalized by using

$x' = x/l \qquad y' = y/l$

$u' = u/u \qquad v' = v/u$

$\eta = (t_w - t_\infty)/(t - t_\infty)$

l, u_∞, and t_∞ being appropriate reference quantities. Thus, l would be the length of the plate, u_∞ and t_∞ are velocity and temperature in the free stream remote from the plate. Equation 1 to 3 yields

$$Re\left(u' \frac{\partial u'}{\partial x'} + v' \frac{\partial u'}{\partial y'}\right) = \frac{\partial^2 u'}{\partial y'^2} \qquad (4)$$

$$\frac{\partial u'}{\partial x'} + \frac{\partial v'}{\partial y'} = 0 \qquad (5)$$

$$Re.Pr\left(u' \frac{\partial \eta}{\partial x'} + v' \frac{\partial \eta}{\partial y'}\right) = \frac{\partial^2 \eta}{\partial y'^2} \qquad (6)$$

The normalized boundary conditions are:

Velocties:

At	$x' = 0$	$u' = u_2/u_\infty$	$0 \leq y' \leq S/l$
		$u' = 1$	$y' \geq S/l$
		$v' = 0$	
At	$y' = 0$	$u' = v' = 0$	

Temperatures:

At	$x' = 0$	$t = t_2$	
		$\eta = (t_w - t_\infty)/(t_2 - t_\infty)$	
			$0 \leq y' \leq S/l$
	$t = t_\infty$	$\eta = 0$	$y' \geq S/l$
At	$y' = 0$	$\eta = 1$	

Inspection of the nondimensional equations and boundary conditions reveals the dependance of the heat transfer behaviour on the following parameter: Re, Pr, u_2/u_∞, η, and S/l. Those controling parameters are investigated and represented in different figures for correlating and comparing the experimental results.

4- EXPERIMENTAL RESULTS

The previous technique has been used to obtain the effects of η, M, 1/S, Re, and β on film cooling performance.

Fig.(4) indicates the adiabatic temperature distribution T_{ad} which obtained from the effect of the injected air with T_2 on the flat plate. The aidabatic temperature for the normal injection is more preferable in the regions near the injection slots than inclined one, as represented by curves A and B. In the regions far from the injection slots, it is observable that the inclined injection gives better results as illustrated by curve B. The same figure shows the surface temperature distribution as the heat flux of the surface is taken into consideration for the flow of electric current ($q = 0.728\ W/cm^2$).

Curve C in the figure belongs to the normal injection but D describes the effect of 35 deg angle of inclination.

Fig.(5) illustrates the relationship between the film cooling effectiveness and the longitudinal distance over the plate for both normal and inclined injection. The best results for the film cooling effectiveness is obtained by normal injection slots for the regions near to injection slots. For regions far from injection slots, the inclined injection is more preferable. The effectiveness is defined by

$$\eta = (T_{w2} - T_{\infty})/(T_2 - T_{\infty})$$

The slope of the curve of normal injection is greater than for normal injection.

The results obtained for heat transfer coefficient h/h_o as a function of x is illustrated in Fig.(6). Both values of h and h_o are defined per unit area of the plate in the following form:

$$h = \frac{q}{t_{w2} - t_{ad}}$$; h is the heat transfer coefficient in the presence of the injected air.

and

$$h_o = \frac{q}{t_w - t_{\infty}}$$; h_o is the heat transfer coefficient without injection.

One may conclude from this illustration that the heat transfer coefficient for 35 deg angle of inclination is smaller than that for 90 deg.

A comparison between the present work, which indicates the effect of injection through slots, and that for holes, is shown in Fig.(7). It is observable that injection through slots gives better results than that through holes. The injection through slots has a smaller heat transfer coefficient, i.e., it minimizes the surface temperature. But the only disadvantgeous for injection through slots is that it reduces the modulus of the structure. Moreover, it is difficult in manufacturing for practical use as in the case of gas turbine blades. Fig.(7) indicate the relation between the surface temperature in the presence of secondary air and the heat transfer ratios against the longitudinal distance x.

Finally, the results can be correlated as h/h_o versus $\left[(1/\eta).M^{0.6}(1/S)^{0.5}\right]$ and this is represented in Fig.(5). A best-fit straight line through these data is represented by the equations:

$$h/h_o = 0.25 + 0.114\left[(1/\eta).M^{0.6}.(1/S)^{0.5}\right] \quad \text{for} \quad = 35^{o}$$

and

$$h/h_o = 0.5 + 0.08\left[(1/\eta).M^{0.6}.(1/S)^{0.5}\right] \quad \text{For} \quad = 90^{o}$$

In the test results, $M = (u_2/u_\infty).(\rho_2/\rho_\infty)$ is changed by changing the velocity ratio (u_2/u_∞). Since for small temperature differences used in the test program the densities of the main and film flows are nearly equal.

The relation between the surface temperature and the lateral distance "z" for the different types of injection slots are given in Fig.(9). The different curves are the results obtained for the different slot types as follows:

Curve "A" for continuous slot
Curve "B" for noncontinuous slot
Curve "C" for the multi staggard slots
The model "C" is more effective compared with the "A" and "B" models, from the manufacturing point of view and heat transfer process.

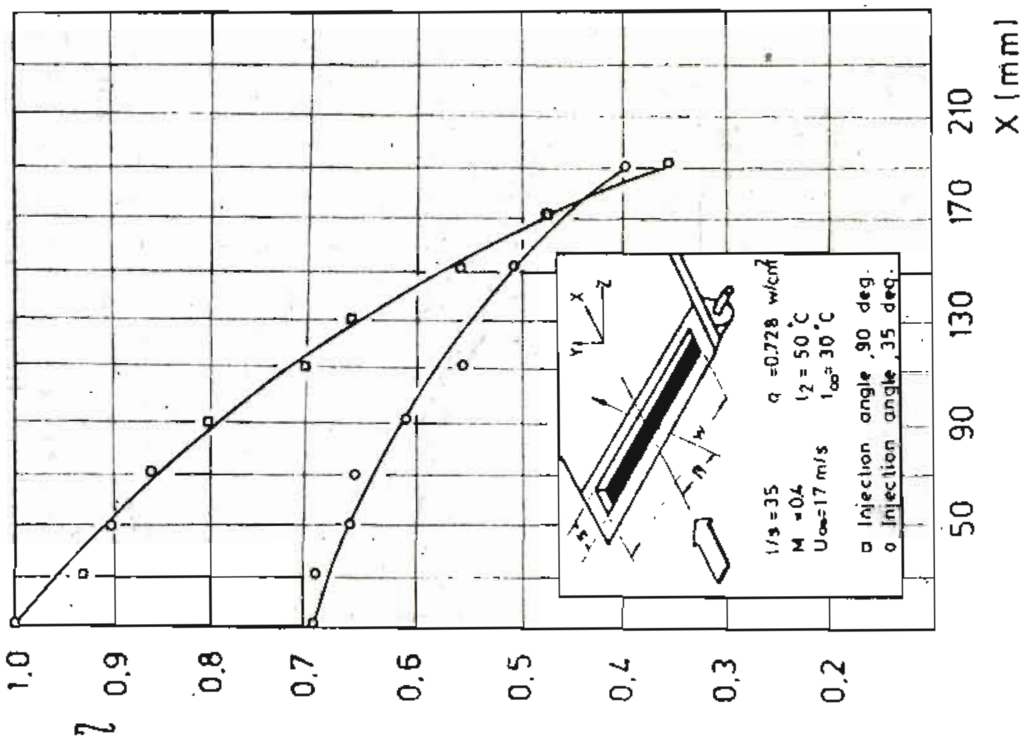
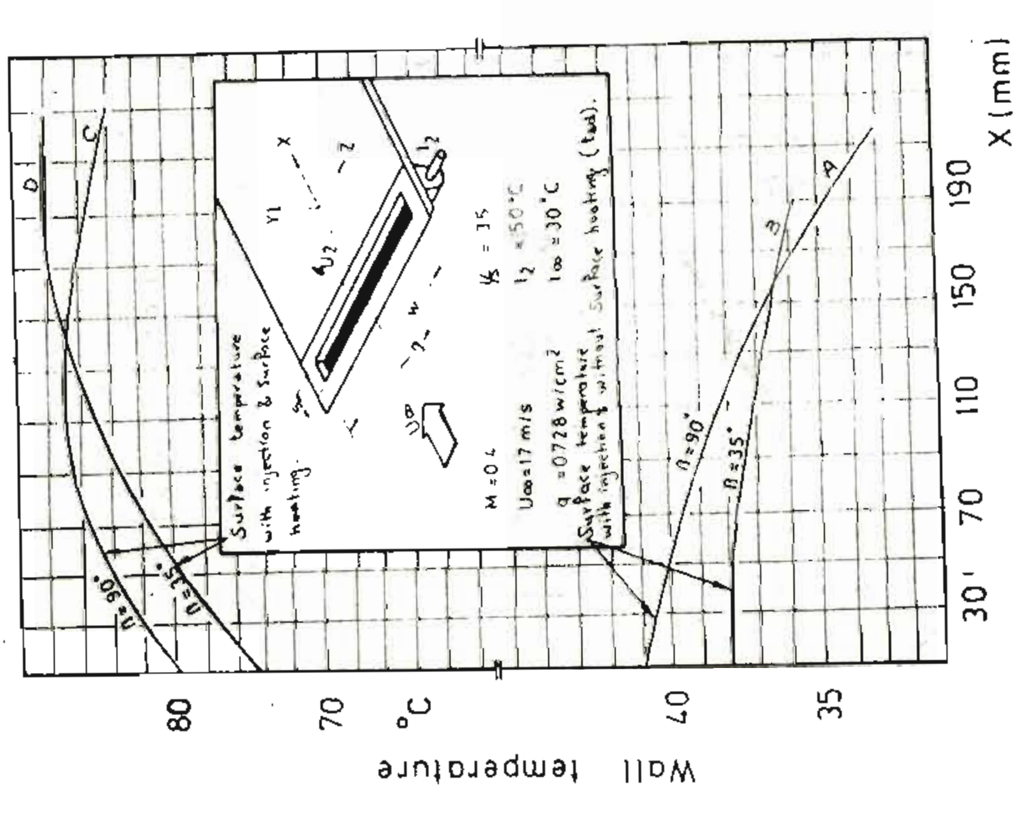
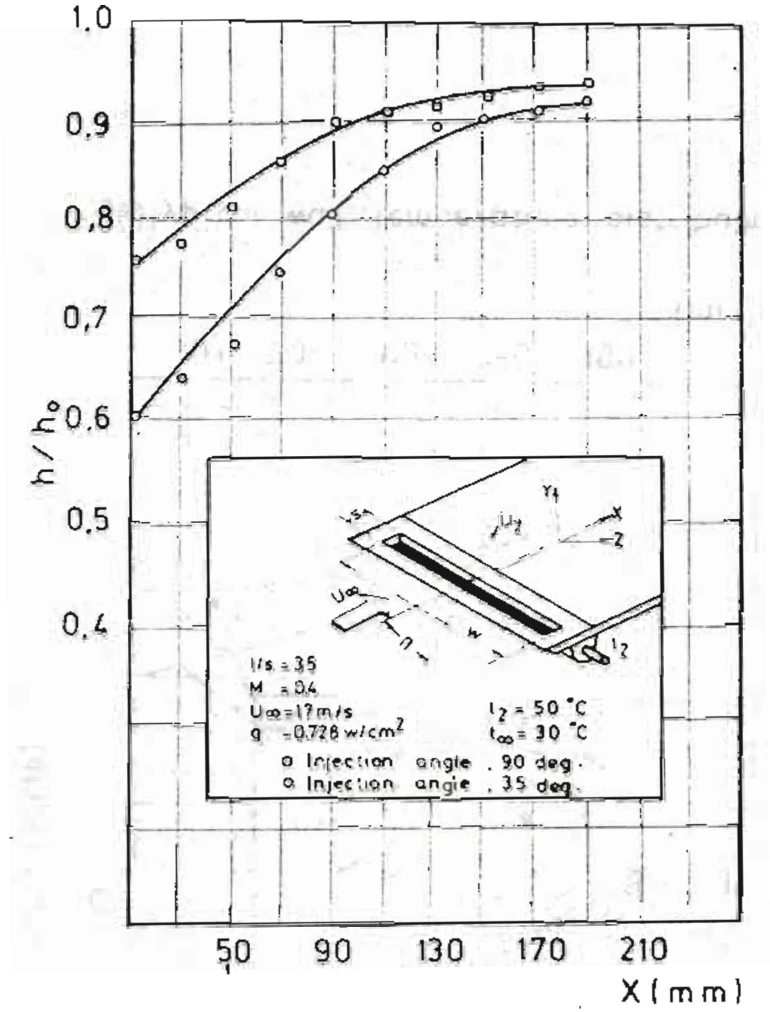


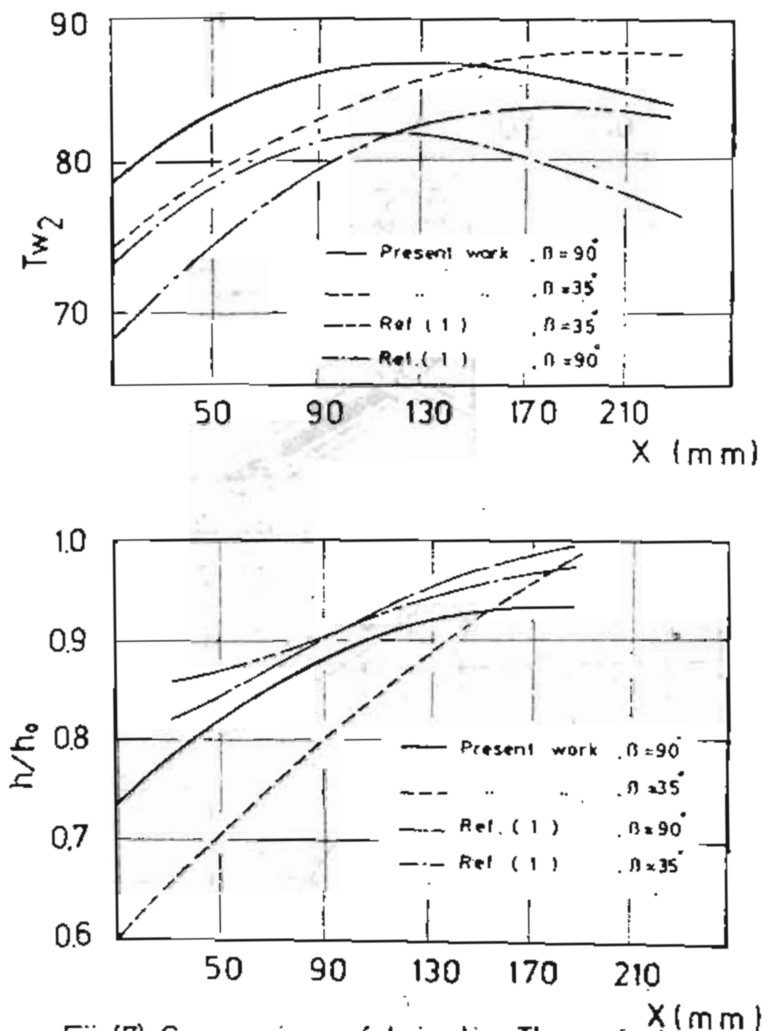
Fig.(5) Film cooling effectivness



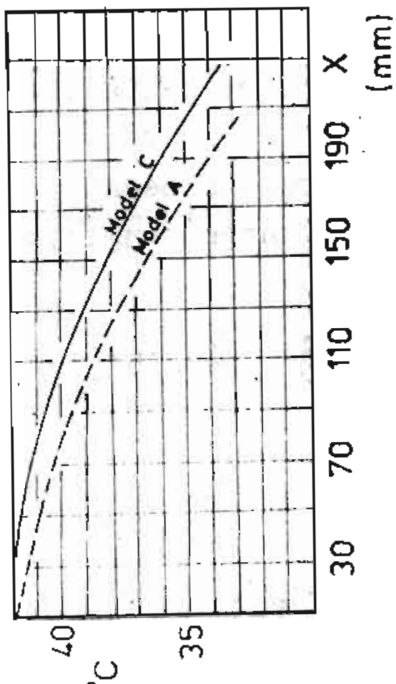
Fig(4)Typical wall temperature distribution



Fig(6) Heat transfer coefficient down of injection.
[slot l/s = 35]



Fig(7) Comparison of Injection Through Slots And That Through Holes



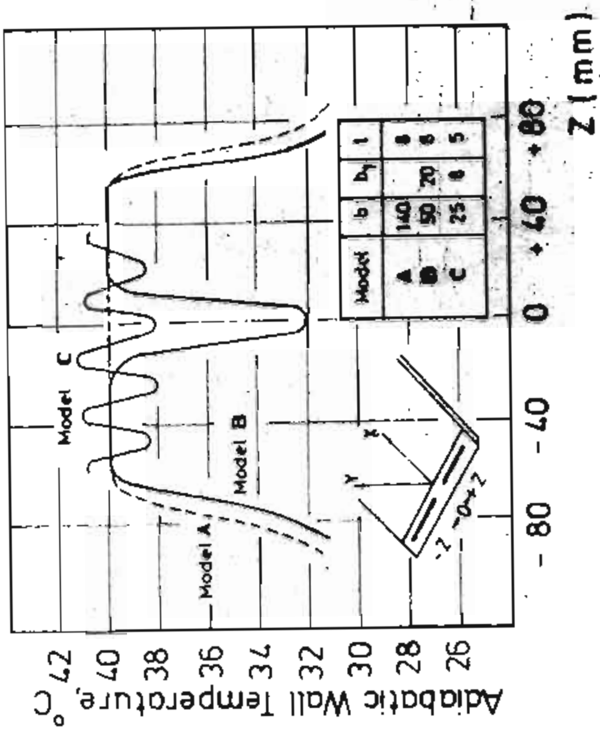


Fig.(9) Adiabatic Wall Temperature Distribution at x = 50 mm

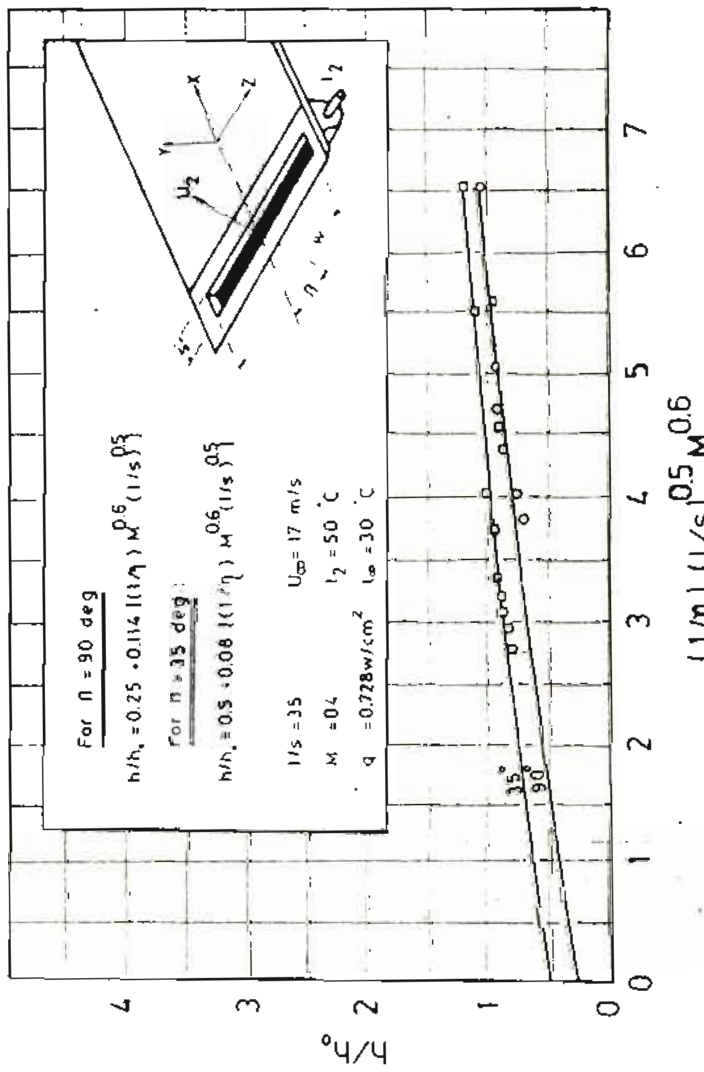


Fig.(8) Coorelated effect for Ω = 90, 35 deg.

CONCLUSIONS

The principal conclusions of the present work are summarized as follows:

1- Secondary injection through flush, angled slots has been studied. The effects of the injected film thickness, angle, temperature and flow rate can be represented by

$$h/h_o = 0.25 + 0.114 \left[(1/\eta).M^{0.6}.(1/S)^{0.5}\right] \quad \beta = 35^o$$

and

$$h/h_o = 0.5 + 0.08 \left[(1/\eta).M^{0.6}.(1/S)^{0.5}\right] \quad \beta = 90^o$$

2- The multi staggard slots is more effective, compared with continuous and noncontinuous slots from the manufacturing point of view and heat transfer process.

3- Injection through slots improves surface cooling efficiency when compared with the case of holes.

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