

TO

Professor A.H. LEFEBVRE - Mr. E.R. NORSTER

BEST COPY

AVAILABLE

Variable print quality

- بسم الله الرحمن الرحيم -

IN THE NAME OF GOD THE BENEVOLENT AND
THE MOST MERCIFUL

THE COLLEGE OF AERONAUTICS

CRANFIELD

DEPARTMENT OF AIRCRAFT PROPULSION

DISCHARGE COEFFICIENT AND JET DEFLECTION STUDIES

FOR

COMBUSTOR LINER AIR - ENTRY HOLES

BY: K. SH. KADDAH

Thesis submitted for the Diploma of Advanced Engineering

1st JUNE, 1964

ACKNOWLEDGMENTS

The author wishes to express his most sincere thanks to Professor A. H. Lefebvre , Head of the Department of Aircraft Propulsion , and to Mr. E. R. Norster who supervised this work for his helpful advice and assistance.

Thanks are extended also to the Propulsion staff members, and to the College Authorities for providing all facilities to carry out this work.

Thanks are also due to Workshop staff, Mr. F. A. McNeill, Photographic and Library staffs.

The author wishes also to express his thanks to Mrs. Archer for the task of typing this thesis .

Section 1S U M M A R Y

Theoretical and experimental investigations of discharge coefficient , and jet deflection have been made for holes having parallel to the plane of the hole .

In the experimental investigation geometric configurations studied were , circular holes , oval , rectangular , and square slots . The main geometric and flow factors affecting discharge coefficient and jet deflection were studied .

Geometric factors were : Ratio of hole area to approach duct area a^* , ranging from 0.0595 to 0.6040 ; Slot aspect ratio from 1.0 to 8.0 ; Slot major dimension along the flow up to 2.0 inch with duct depth 1.25 inch ; and slot shape .

Flow factors were : Static pressure ratio p_1 / p_j up to 1.12 ; Bleed ratio α ; and approach velocity V_1 up to $130 \frac{\text{ft}}{\text{sec}}$.

The results of these studies have been correlated with the dimensionless flow parameter K incorporating both the geometric and flow factors .

Data are presented in detailed form for direct use with survey and design applications to combustor liners .

Section 2CONTENTSV O L U M E 1SectionPage

Title

Acknowledgments

1	SUMMARY	1	1
2	CONTENTS	2	2
3	NOTATIONS	6	-
3.1	List of symbols	6	5
3.2	Suffix notation	8	6 7
4	INTRODUCTION	9	
5	REVIEW OF PREVIOUS WORK	11	
5.1	Discharge coefficient	11	
5.2	Deflection angle	15	
6	THEORETICAL INVESTIGATION	18	
6.1	Analysis I	19	
6.2	Analysis II	23	
7	EXPERIMENTAL INVESTIGATION	27	
7.1	Rig description and developments	27	
7.2	Test section description and developments	27	
7.3	Test plates	29	
7.4	Instruments and calibrations	32	
7.4.1	Pressure measurements	32	
7.4.1.1	Approach static pressure	32	
7.4.1.2	Jet static pressure	32	

CONTENTS (continued)

<u>Section</u>	<u>Page</u>
7.4.1.3 Total and dynamic pressures	33
7.4.2 Temperature measurements	33
7.4.3 Flow rate measurements	34
7.4.4 Velocity measurements	35
7.5 Deflection angle measurement and jet visulation	36
7.6 Preliminary work	37
7.6.1 Velocity profile	37
7.6.2 Deflection angle	38
7.6.3 Precautions	39
7.7 Test procedure	39
8 PRESENTATION OF RESULTS AND DISCUSSION	42
8.1 Correlation of results	42
8.2 Discussion of theoretical analyses	42
8.2.1 Analysis I	42
8.2.2 Analysis II	44
8.2.2.1 Momentum loss factor	45
8.3 Discussion of experimental results	45
8.3.1 Discharge coefficient and jet deflection for Circular holes	45
8.3.2 Discharge coefficient and jet deflection for Oval slots	47
8.3.3 Discharge coefficient and jet deflection for Rectangular slots	49
8.3.4 Discharge coefficient and jet deflection for various configurations	51

CONTENTS (continued)

<u>Section</u>	<u>Page</u>
8.3.4.1 Holes and slots with equal areas and numbers	51
8.3.4.2 Slots with equal areas, numbers , and aspect ratios	52
8.3.5 Analysis of experimental results	53
8.4 Comparison of experimental results with theory	54
8.4.1 Discharge coefficient	54
8.4.2 Jet deflection	55
8.5 Comparison of experimental results with previous work	55
8.5.1 Discharge coefficient	55
8.5.2 Jet deflection	56
9 USE OF DATA	57
9.1 For survey applications	57
9.2 For design applications	58
10 CONCLUSIONS	60
11 RECOMMENDATIONS FOR FURTHER WORK	62
REFERENCES	63
 <u>APPENDICES</u>	
APPENDIX 1 Flow parameter K	65
APPENDIX 2 Reduction of experimental results	69
A2.1 Method used for calculation of results	69
A2.2 Momentum loss factor	71

CONTENTS (continued)

<u>Section</u>	<u>Page</u>
APPENDIX 3 Calibrations	74
A3.1 Orifice plate characteristics and calibration	74
A3.2 Pitot tube characteristics and calibration	77
APPENDIX 4 Correlation of Gandamihardja's work (Ref. 7)	80
Appendix 5 Jet study	84
TABLES (30 Table)	87

V O L U M E 2

FIGURES (126 figure)

APPENDICES FIGURES (26 figure)

PHOTOGRAPHIC PLATES (24 plate)

SEPARATE DOCUMENT

DESIGN DRAWINGS (10 sheets)

Section 3NOTATIONS3.1 List of symbols

A	Area	sq.ft.
a^*	Area ratio = ratio of holes or slots to approach area	
a	Rectangular slot side normal to flow direction	ft.
a'	Oval slot side normal to flow direction	ft.
b	Rectangular slot side parallel to flow direction	ft.
b'	Oval slot side parallel to flow direction	ft.
b/a	Rectangular slot aspect ratio	
$1 + \frac{b'}{a'}$	Oval slot aspect ratio	
C	Discharge Coefficient	
	= ratio of measured to theoretical flow through hole or slot	
C_{fL}	Flow rate correction factor for temperature effect	
C_{fV}	Velocity correction factor for temperature effect	
C_p	Specific heat of air at constant pressure = 0.24 CHU/lb. ^o k	
C_v	Specific heat of air at constant volume = 0.17 CHU/lb. ^o k	
D	Circular hole diameter	ft.
g	Gravitational acceleration	= 32.2 ft./sec. ²
K	Flow parameter	
	= Ratio of jet dynamic pressure to approach dynamic	
	Pressure = $P_1 - P_j / P_1 - P_1$	
	= V_j^2 / V_1^2 for incompressible flow	
L	Air flow rate	lb./hr.
H	Momentum	lb. _f
n	Number of holes or slots	

NOTATIONS (continued)

P	Absolute total pressure	lb./sq.ft.
p	Absolute static pressure	lb./sq.ft.
T	Absolute temperature	$^{\circ}\text{K}$
V	Air velocity	ft./sec.
Y	Duct horizontal width normal to flow direction	ft.
X	Duct horizontal width parallel to flow direction	ft.
Z	Duct depth vertical to XY plane	ft.
Y/Z	Duct aspect ratio	
α	Bleed ratio = L_j/L_1 = Ratio of actual air flow rate passing through holes or slots to approaching flow rate	
γ	Ratio of specific heat at constant pressure to specific heat at constant volume = 1.4	
ζ	Momentum loss factor	
μ	Ratio of Bleed to area ratio = α/a^*	
ρ	Density	lb./cu.ft.
ϕ	Deflection angle, between jet axis and the downstream plane of the hole	degrees

3.2 Suffix Notation

Atm.	Atmospheric conditions
B	Bleed orifice plate conditions
d	Downstream orifice plate conditions
j	Jet conditions assumed at the vena contracta
O	No cross flow conditions
th	Theoretical flow through holes or slots with $C = 1.0$
U	upstream orifice plate conditions
1	Steady flow conditions approaching holes or slots
1'	Flow conditions opposite to hole centre line
2	Steady flow conditions downstream the holes or slots

Section 4INTRODUCTION

In the simple tubular combustor system for turbojets and ramjets, figure 1, at the primary zone it is required to achieve a high heat release and stable flame. At the dilution zone to have a good air flow distribution (Ref. ¹), and adequate penetration. In both zones these requirements needs to be with the minimum total pressure loss for high overall efficiency, short liner length, and light simple construction (Ref. 2).

The air flow distribution between these two zones is still the main problem of the design engineer. But the flow of annular air to these zones is governed by the geometry of the system, hole geometry and discharge coefficient of these holes. For light construction and adequate penetration, the main governing factor is the deflection angle of the liner jets.

The work presented here is a theoretical and experimental study of the main geometric and flow factors affecting discharge coefficient and deflection angle for the commonly used hole shapes used in combustor liners over a wide practical range of geometry. These are, plain circular holes, flush oval and rectangular slots, geometric details are shown at Section 7.3, slot major dimension with flow direction.

An attempt has been made to correlate discharge coefficient and deflection angle with flow parameter, which is the ratio of jet dynamic pressure to the approach dynamic pressure. This work can be applied for both survey and design applications up to static pressure ratio of

1.12 across the holes. This is most suitable for low pressure loss combustors and can allow up to pressure loss factor of 10%.

Although these data corresponds to flow parallel to the plane of the hole with zero internal flow case in the combustor, (Refs. 3 and 4) showed that such data can be satisfactorily applied to both internal and external flows, since the jet velocity is greater than the internal flow velocity and the correct jet static pressure is used. Also (Refs. 5 and 6) showed that the effect of wall inclination and curvature on discharge coefficient is negligible, and (Ref. 7) showed the same negligible effects on deflection angle.

Theoretical analysis based on incompressible flow gives good agreement with experimental results within the range of the experiment.

Although some authors measured discharge coefficient with parallel flow, i.e. Dittrich and Graves (Refs. 5 and 6) for circular holes and rectangular slots; Fielding (Ref. 8) for circular holes over a wide practical range; Callaghan (Ref. 3) for circular holes, square and elliptical slots with normal flow into still and moving streams. No one however has measured the discharge coefficient for oval slots, and only Gandamihardja (Ref. 7) measured the deflection angle. Gandamihardja's work covers a small range of circular holes and have been correlated into a more practical form Appendix 4.

For special applications such as liners designed with high annular air velocity and low overall pressure loss, the work by Dittrich and Graves (Ref. 6) covered discharge coefficient for most of these shapes such as thumbnail scoops, step louvers and scoops over circular holes.

Section 5

REVIEW OF PREVIOUS WORK

5.1 Discharge Coefficient

Dittrich and Graves, (Ref. 5) measured discharge coefficient for combustor liner air-entry holes having parallel flow using 2.23 x 2.23 inch test section, with different duct aspect ratios and test hole thickness from 0.04 to 0.5 inch, and at air temperature of 75 °F. They found that discharge coefficient decreases with increasing approach velocity up to $V_1 = 500$ ft./sec., and increases with increasing static pressure ratio across the hole up to $p_1/p_j = 1.32$.

For no cross flow they showed that discharge coefficient increases with a decrease of the ratio of hole area to duct area up to $a^* = 0.6$, and increase also with either the increase of wall thickness at the hole or a decrease of hole diameter, so that the ratio of hole diameter to wall thickness is less than 6.0. In their study they showed that the effect of wall thickness and hole diameter were found to be small, effects of duct height, boundary layer thickness and static pressure level were negligible.

A good correlation had been made between discharge coefficient and flow parameter, but at high pressure ratios a pressure ratio correction factor was introduced. This is the ratio of actual discharge coefficient to discharge coefficient corrected for pressure ratio effect. The introduction of this parameter forms a common curve for various approach velocities.

Provided the external flow passage walls are parallel with flow direction, jet velocity greater than the internal parallel flow velocity and jet static pressure assumed equal to static pressure in the liner at the considered point. The corrected coefficient C_p from Figure 2 is multiplied by appropriate value of C/C_p from Figure 3 to obtain the coefficient to be used.

The same authors, (Ref. 6) measured the discharge coefficient for other various configurations of liner wall with approximately the same conditions as used with (Ref. 5). For rectangular flush slots with major dimension parallel to flow direction, they found that the discharge coefficient is slightly higher than those of circular holes and square slots. And the increase in slot aspect ratio increases discharge coefficient slightly throughout the range of flow parameter. The main factors affecting discharge coefficient are static pressure ratio across the hole and duct stream velocity.

The addition of a scoop to a flush hole increases discharge coefficient with flow range extension at low values of flow parameter less than 1.0 (due to ram pressure effect). But it decreases discharge coefficient at high values with scoop face areas less than 1.4 times hole area, Figure 4. The effect of scoops or louvers is to increase discharge coefficient and make flow range wider at low values of flow parameter depending on scoop height which makes them essential in upstream region of combustor liners, having low pressure difference across openings.

The authors also showed that the effect of boundary layer

displacement thickness is to reduce scoop face area. Thus to correlate discharge coefficient in this case with flow parameter, boundary layer correction factor was taken into consideration.

For calculations based on effective scoop area together with static pressure ratio effect discussed before, the corrected discharge coefficient for both boundary layer and static pressure ratio effects can be read from curve, Figure 5. This being selected on the basis of geometric similarity (both shape and size). This coefficient must then be reduced to the corrected discharge coefficient for static pressure ratio alone, by multiplying the ratio of effective scoop area (estimated from pressure profile measured at scoop face) to scoop face area as follows

$$C_p = C_{p,\zeta^*} \frac{A_f^*}{A_f} = C_{p,\zeta} * \left(1 - \frac{b\zeta^*}{A_f}\right)$$

The desired discharge coefficient can be calculated as for circular holes using Figure 3.

$$C = C_p \left(\frac{C}{C_p}\right)$$

where

- | | | |
|-----------------|---|------------------|
| A_f | = face area of scoop | ft. ² |
| A_f^* | = effective scoop face area | ft. ² |
| b | = width of opening | ft. |
| C | = discharge coefficient | |
| C_p | = discharge coefficient corrected for pressure ratio effect | |
| C_{p,ζ^*} | = discharge coefficient corrected for both static pressure ratio and boundary layer effects | |
| ζ^* | = boundary layer displacement thickness. | |

In many combustor designs, the liner walls and outer shell are not parallel. The same authors (Ref. 6) showed that for flush holes and step louvers mounted in walls of convergent duct walls, inclinations up to 20° had little effect on discharge coefficient, with static pressure ratio $(p_1 + q_1 \sin \Theta)/p_j$ instead of p_1/p_j for parallel holes. Where Θ is the angle between direction of flow and hole plane in degrees, and q_1 is the dynamic pressure of approach stream, Figure 6.

Also they showed that multiple flush hole arrangements both in the longitudinal direction range from 1.5 to 5 hole diameter (centre to centre) and transverse direction from 2 to 4 hole diameter spacing has no significant effect on discharge coefficient, Figures 7 and 8.

D. H. Fielding, (Ref.8) made a detailed investigation of discharge coefficient for plain circular holes, 0.064 inch thickness, using 1 x 5 inch test section. He studied effects of bleed, area ratio up to $a^* = 1.2$, pressure loss coefficient, aspect ratio of approach duct up to 10/1, and jet Mach number up to 1.0, on discharge coefficient. He found that for a given area ratio, discharge coefficient increases as the bleed increases, till the flow in the approach duct forms a vortex into the hole, causing decrease of discharge coefficient. But in general it decreases with increase of area ratio for any value of bleed. For the effect of approach duct aspect ratio, he showed that for an aspect ratio 2.5/1, discharge coefficient increases continuously with bleed for area ratio range of 0.1 to 1.2. And with aspect ratio 5.0/1, discharge coefficient

behaves as above case up to area ratio 0.14, above which, sudden decrease in discharge coefficient occurs between bleed of 0.8 and 0.9 due to vortex formation in the hole flow, Figure 9. At aspect ratio 10/1, sudden decrease in discharge coefficient occurs between bleed values of 0.45 and 0.8 depending on area ratio.

E. Callaghan (Ref. 3) measured discharge coefficient for circular holes up to 0.625 inch diameter, squares and elliptic slots up to aspect ratio of 4/1, with equal areas and 0.064" thickness discharging normally into still and moving air streams. Air jet total temperature was 70 and 400°F. In terms of pressure ratio up to 3.2 and jet Reynolds number up to 64×10^4 , he found that up to chocking, discharge coefficient increases linearly with pressure ratio, with transition region slightly higher than chocking. Then linearly again, Figure 10, the rate of increase is high below chocking than above it. At constant pressure ratio, discharge coefficient decrease with increasing jet Reynolds number, but for the given pressure ratio and jet total temperature, ellipses yields the highest discharge coefficient. The effect of stream velocity on discharge coefficient was neglected provided that proper outlet static pressure was utilised.

5.2 Deflection angle

Candamihardja (Ref. 7 , 1962) measured the deflection angle for circular holes diameter range 0.25 - 1.0 inches with corresponding area ratio of 0.0344 - 0.314 respectively. He used the same rig before modifications, Sections 7.1, 7.2, with the jet issuing into atmosphere. For deflection angle measurement he used carbon coated

plate, Section 7.5. Results of his work showed that with no cross flow, deflection angle Φ is function of area ratio a^* . As a^* increases Φ decreases and the variation in Φ within his range was from 83 degrees for largest holes to 88 degrees for the smallest. With cross flow he found that Φ is a function of bleed ratio ($a^* U^*$) and a^* . Where U^* is the jet velocity component normal to the plane of the holes. Also for a given value of a^* , with increase in bleed Φ increases, and for a given bleed ratio as a^* increases, Φ decreases. Results of his work are shown, Figure 11.

In a trial to correlate Gandamihardja's results Appendix 4 in a more practical form. An empirical equation has been derived from his work results giving Φ as a function of a^* , $a^* U^*$ as follows

(i) with no cross

$$\Phi_0 = 88 - 14.43 a^*$$

(ii) with cross flow

$$\Phi = 88 - a^* \left[\frac{33.43}{(a^* U^*)^{.69}} - .0575 (330)^{a^* U^*} \right]$$

These two equations give good agreement with his work, Figure A4.6, and to the present work for circular holes Figures 112 and 119.

M. Cox (Ref. 9) in his experiments on combustion chamber liner, he estimated the value of $\cos \Phi$ as the ratio of axial approach velocity V_x to jet velocity, which is a good approximation for small values of Φ , and with increasing values of Φ , the axial approach velocity decreases by a factor k obtained from previous tests

so that

$$\cos \phi = k \frac{V_1}{V_j}$$

where $k = (V_x/V_1)$

From examination of previous results Howell (Ref. 9) suggested an empirical correlation for discharge coefficient as

$$C = C_0 \sin^2 \phi$$

where C_0 is the discharge coefficient for no cross flow assumed of constant value.

Section 6

THEORETICAL INVESTIGATION

The analyses of this section deal with discharge coefficient C , and deflection angle ϕ , in terms of the dimensionless factors; area ratio a^* , bleed ratio α , bleed area ratio μ , and flow parameter K (Appendix 1).

Analysis I assumes ideal flow conditions with no change in the axial direction of the approach momentum.

Analysis II deals with directional changes in approach momentum, and needs some experimental work to confirm the effects of flow conditions on discharge coefficient and deflection angle. This was attempted in Appendix 2.2.

The following assumptions have been used in the investigation

- (1) Discharge coefficient is defined as the ratio of jet area at vena contracta normal to jet axis and hole or slot area.
- (2) Two dimensional in-compressible flow, since density changes in the experiment within 8%.
- (3) Total pressure at the jet vena contracta is equal to the total pressure of the approach stream.
- (4) Static pressure opposite the test hole, is uniform and equal to the approach stream static pressure.
- (5) Jet static pressure at vena contracta is equal to the surrounding pressure.
- (6) Uniform flow conditions upstream, downstream and at jet vena contracta.

(2) From Bernoulli's equation

$$p_1 = p_1 + \frac{\rho v_1^2}{2} = p_j + \frac{\rho v_j^2}{2} = p_2 + \frac{\rho v_2^2}{2} \quad (2)$$

$$\text{or } p_1 = p_j + \frac{\rho}{2} (v_j^2 - v_1^2)$$

$$p_2 = p_j + \frac{\rho}{2} (v_j^2 - v_2^2)$$

$$\text{and } p_2 - p_1 = \frac{\rho}{2} (v_1^2 - v_2^2) \quad (2^1)$$

(3) Momentum equation

(i) Axial x direction

$$M_1 - M_2 - M_j \cos \phi = A_1 (p_2 - p_1)$$

$$\rho A_1 (v_1^2 - v_2^2) - \rho C A_h v_j^2 \cos \phi = A_1 (p_2 - p_1) \quad (3)$$

(ii) Vertical z direction

$$A_h (p_1 - p_j) = M_j \sin \phi$$

$$A_h (p_1 - p_j) = \rho C A_h v_j^2 \sin \phi$$

$$\text{or } p_1 - p_j = \rho C v_j^2 \sin \phi \quad (4)$$

From equation (1)

$$\begin{aligned} C &= \frac{A_1}{A_h} \frac{(v_1 - v_2)}{v_j} \\ &= \frac{1}{a^*} \frac{v_1 - v_2}{v_j} \end{aligned} \quad (5)$$

Substituting from equation 2¹ and 1, equation 3 becomes

$$\cos \phi = \frac{v_1 + v_2}{2 v_j} \quad (6)$$

but for incompressible flow using continuity equation

$$L_j = A_1 \rho_1 v_1 - A_2 \rho_2 v_2$$

$$\text{or } \frac{L_j}{A_1 \rho_1 v_1} = 1 - \frac{A_2 \rho_2 v_2}{A_1 \rho_1 v_1}$$

$$\text{since } A_1 = A_2$$

$$\text{or } v_2 = v_1 (1 - \alpha) \quad (7)$$

by using equations (7) and (A1-3) equation (5) becomes

$$C = \frac{\alpha}{a^* \sqrt{K}} = \mu / \sqrt{K} \quad (8)$$

equation (6) becomes

$$\cos \phi = \frac{(2 - \alpha)}{2 \sqrt{K}} \quad (9)$$

substituting from equation (2), (4) becomes

$$\sin \phi = \frac{1}{2C} \frac{K-1}{K} \quad (10)$$

from (9) and (10) by squaring and adding

$$\frac{(2 - \alpha)^2}{4K} + \frac{1}{4C^2} \left(\frac{K-1}{K} \right)^2 = 1$$

or

$$C = \frac{K-1}{\sqrt{K [4K - (2 - \alpha)^2]}} \quad (11)$$

for this to be true, equations (8) and (11) should be equal

$$\text{or } \frac{\alpha}{a^* \sqrt{K}} = \frac{K-1}{\sqrt{K [4K - (2 - \alpha)^2]}}$$

$$\text{or } K^2 - K(2 + 4\mu^2) + \mu^2(2 - \alpha)^2 + 1 = 0 \quad (12)$$

Equation (12) is a quadratic in K which by solving gives

$$K = 1 + 2\mu^2 + \sqrt{4\mu^4 + \mu^2(4\alpha - \alpha^2)} \quad (13)$$

$$K^1 = 1 + 2\mu^2 - \sqrt{4\mu^4 + \mu^2(4\alpha - \alpha^2)} \quad (14)$$

Equation (14) represents the flow limit when $\alpha = 0$, this is true when there is no flow through test holes i.e. $K^1 = 1.0$, so equation (13) is the required solution.

A - Case with no cross flow

i.e. all the approaching flow passes through hole

$$\text{i.e. } \alpha = 1.0, \quad \mu_0 = \frac{1}{a^*} \quad (15)$$

using equations (8) and (9)

$$C_o = \frac{1}{a^* \sqrt{K}} \quad (16)$$

$$\cos \Phi_o = \frac{1}{2\sqrt{K}} \quad (17)$$

Combining (16) and (17)

$$\cos \Phi_o = \frac{a^* C_o}{2} \quad (18)$$

from equations (13) using (15)

$$K = 1 + 2\mu_0^2 + \sqrt{4\mu_0^4 + 3\mu_0^2}$$

or

$$K = 1 + \frac{2}{a^{*2}} + \sqrt{\left(1 + \frac{2}{a^{*2}}\right)^2 - \left(1 + \frac{2}{a^{*2}}\right)} \quad (19)$$

For $.05 \leq a^* \leq 0.8$, Table 1 gives the values of K , C_o and Φ_o .

Various relations between a^* , K , C_o and Φ_o are represented graphically Figures 12 to 15.

It is noted that
Equation (19)
cannot be used

B - Case with cross flow

In this case the approach flow passes partially through holes

$$\text{i.e. } 0 < \alpha < 1.0$$

using equations (8) and (9)

$$C = \frac{\alpha}{a^* \sqrt{K}} = \frac{\mu}{\sqrt{K}}$$

$$\cos \phi = \frac{2 - \alpha}{2 \sqrt{K}}$$

Combining (8) and (9) together we get

$$\cos \phi = \frac{C a^*}{2} \frac{(2 - \alpha)}{\alpha} \quad (20)$$

Tables 2 to 5 show values of K , C and ϕ for bleed ratio range $0.2 \leq \alpha \leq 0.8$, and for values of a^* within $.05 \leq a^* \leq 0.8$.

Various relations between a^* , α , μ , K , C and ϕ are represented graphically Figures 16 to 21, values of K from equation (13) as

$$K = 1 + 2\mu^2 + \sqrt{4\mu^4 + \mu^2(4\alpha - \alpha^2)}$$

Analysis II

With this analysis a broader approach to the problem is attempted,, from the physical behaviour of the approach stream lines. As the approach stream approaches the holes, the stream lines changes its direction from the axial direction of the undisturbed stream to an inclined direction towards the hole as

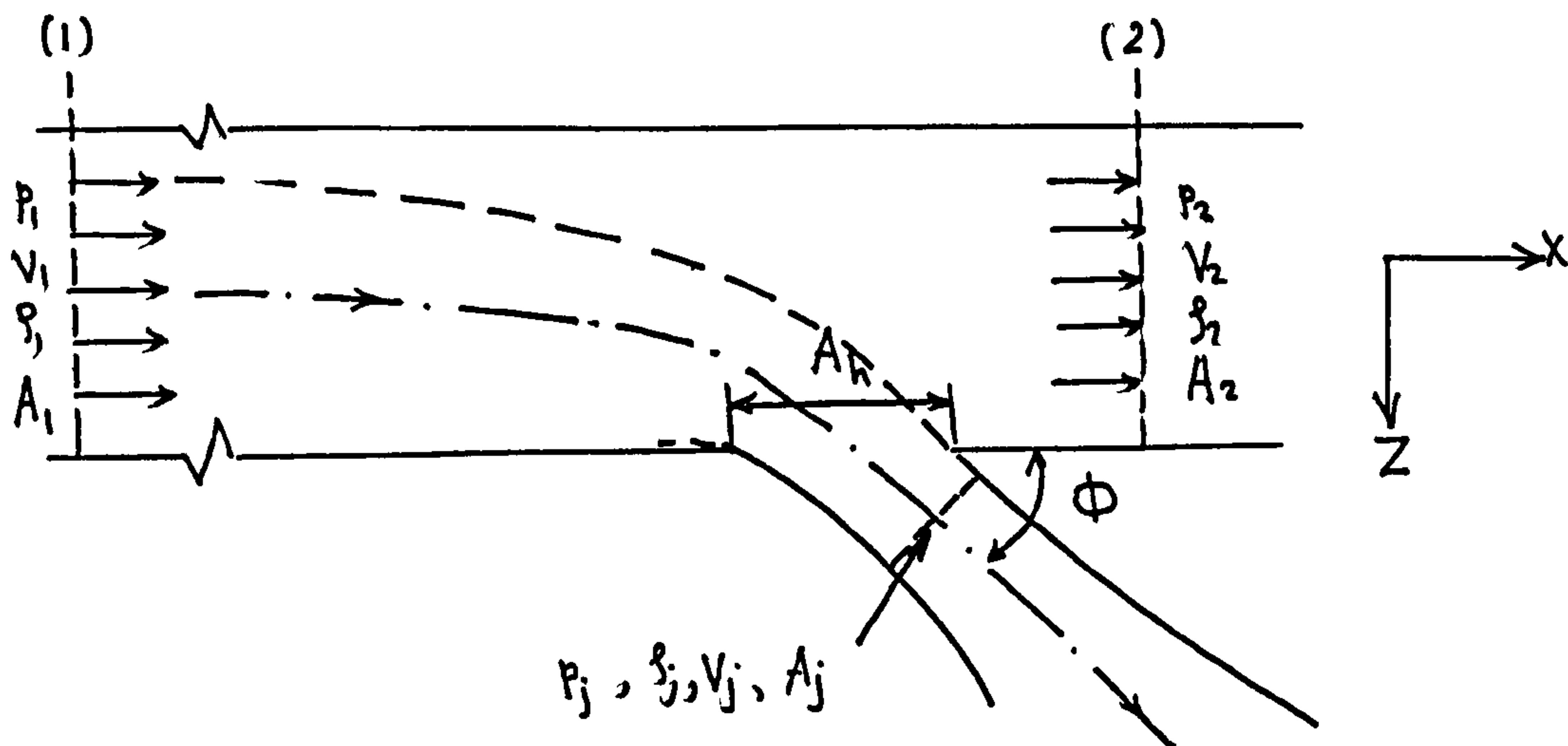


FIG. II.

shown (Figure II). This inclination depends on the flow range through the hole, i.e. on the flow parameter. For very small values of K , the deflection angle approaches zero and the approach stream lines become axial. In this region results of this analysis approaches that of Analysis I.

The effect of the change in axial direction of the approach momentum appears in this analysis in the momentum equation as a factor ζ , which is called the momentum loss factor. This momentum factor affects the value of K for same geometric and flow factors compared with Analysis I, Figure 22, as discussed later. It is clear now the effect of this momentum factor on discharge coefficient and deflection angle, as K is the main factor governing them. Complete analysis of the momentum loss factor is discussed in Appendix 2.2. Equation A2.2.3 shows that the simple form of the momentum equation (4) is written in the form:

$$H_j \sin \Phi = \zeta [A_h (p_1 - p_j)]$$

$$\therefore (p_1 - p_j) = \zeta \left[\frac{1}{2} c v_j^2 \sin \Phi \right] \quad (21)$$

using equation (2)

$$\therefore \sin \Phi = \frac{1}{2 c \zeta} \left(\frac{K-1}{K} \right) \quad (22)$$

from (9) and (25)

$$c = \frac{(K-1)}{\zeta \sqrt{4 \mu^2 - K(2-\alpha)^2}} \quad (23)$$

from equations (11) and (23)

$$K^2 - K(2 + 4\mu^2\zeta^2) + [\mu^2\zeta^2(2-\alpha)^2 + 1] = 0 \quad (24)$$

Solution of equation (24) gives

$$K = 1 + \zeta^2 \left[2\mu^2 \pm \sqrt{4\mu^4 + \frac{\mu^2}{\zeta^2}(4\alpha - \alpha^2)} \right] \quad (25)$$

equation (25) gives the two values of K of which that of positive value is used as discussed before thus

$$K = 1 + \zeta^2 \left[2\mu^2 + \sqrt{4\mu^4 + \frac{\mu^2}{\zeta^2}(4\alpha - \alpha^2)} \right] \quad (26)$$

For no cross flow

$$K = 1 + \zeta^2 \left[\frac{2}{a^{*2}} + \sqrt{\frac{4}{a^{*4}} + \frac{1}{\zeta^2} \frac{1}{a^{*2}}} \right] \quad (27)$$

It was found that the value of ζ depends on flow parameter.

For the configurations studied ζ was varying between 0.75 at high values of flow parameter and 1.0 as the flow parameter approaches 1.0, Figures A2-1 to A2-5.

These figures show that a suitable mean value of $\zeta = 0.8$ is covering most of the flow range for the configurations studied. So substituting by this value of $\zeta = 0.8$ equations 26 and 27 becomes:

With No Cross Flow:

$$K = 1 + \frac{1.28}{a^{*2}} \left[1 + \sqrt{1 + 1.17 a^{*2}} \right] \quad (28)$$

With Cross Flow:

$$K = 1 + 0.64 \left[2 \mu^2 + \sqrt{4 \mu^4 + 1.56 \mu^2 (4\alpha - \alpha^2)} \right] \quad (29)$$

Values of C and Φ can be derived with this new value of K using equations 8 and 9 with cross flow and 16 and 17 with no cross flow.

Results of this analysis are calculated in Tables 6 - 10, represented graphically Figures 12 - 16 and 22 - 25.

Section 7

EXPERIMENTAL INVESTIGATION

7.1 Rig Description and Developments

The rig used for the investigation, Figure 26, Plate 1, was located at Allis Chalmers Compressor Test House, which was mainly a 4.5 inch diameter steel pipe supplied with air from an Allis Chalmers Rotary Vane Compressor. Compressor delivery 3120 cu.ft./min. of air at pressure 7 lb. per sq.in.(g) and running at 412 r.p.m. The test section was inserted along the pipe 13 ft. from feed point horizontally. Air control was made by 4 main valves, Figure 27.

- (i) spill valve (s.v.) at compressor outlet
- (ii) upstream 4.5 inch butterfly valve (U.V.) located
at rig inlet
- (iii) Downstream 4 inch butterfly valve (D.V.) located
8 ft. downstream test section.
- (iv) Bleed 2 inch gate valve (.B.V.) located downstream
test holes.

For rig details see (Ref. 7) Volume II, and the author's design drawings of rig scheme and components. Due to space limitations, the rig was extended towards north direction, raised up to a level of 4.5 ft. from the floor.

7.2 Test Section Description and Developments

The perspex section 1.25 inches high, 8 inches wide and 18 inches long, used for jet deflection study (Ref.7), was slightly modified

for the present investigation as shown in Figure 28, Plate 3.

From static pressure survey along test section, Figure 29a to f due to the large range of slot sizes, it was found that the position of the constant approach static pressure value varies with slot size used. So 12 static tappings 0.02 inch diameter were added to the existing 5 tappings in the longitudinal direction with duct centre line, and distributed from station 12 which was opposite to hole centre line as shown in Figure 28b.

Plenum Chamber

For the necessity of accurate flow measurements through test holes, especially with smaller hole sizes and very low pressure ratios. The upstream and downstream orifice plates are not accurate enough, and so the need of small size bleed orifice downstream test holes gave rise to the design of a perspex plenum chamber 7.25 x 7.25 inches cross sectional area and 12 inches deep, shown on Plate 4. It was made from 0.25 inch thickness perspex sheet with 1 inch thickness flange 8.75 x 10 inches cross section, to fit tightly in the test section instead of the perspex frame Plate 6, which was used for high pressure ratio tests. Also it was used for visualisation study of jet profiles for various hole configurations.

With both the plenum chamber and the frame, test plates were flush with duct floor. Using enough studs and a suitable packing for adequate sealing of the system. The plenum chamber 2 inch I.D. perspex pipe was flexibly connected to the 2 inch diameter bleed pipe ending with the bleed orifice plate and bleed valve exhausting

into atmosphere. The plenum chamber connection with the rig is shown in Figure 26, Plate 2.

7.3 Test Plates

Test plates used for the investigation were made of $\frac{1}{16}$ inch thick aluminium plates (16 s.w.g.), means of fitting test plate flush with duct floor were considered in plenum chamber design. Sealing along its edges was done on plenum chamber side by sealing strips of Bostick 5.

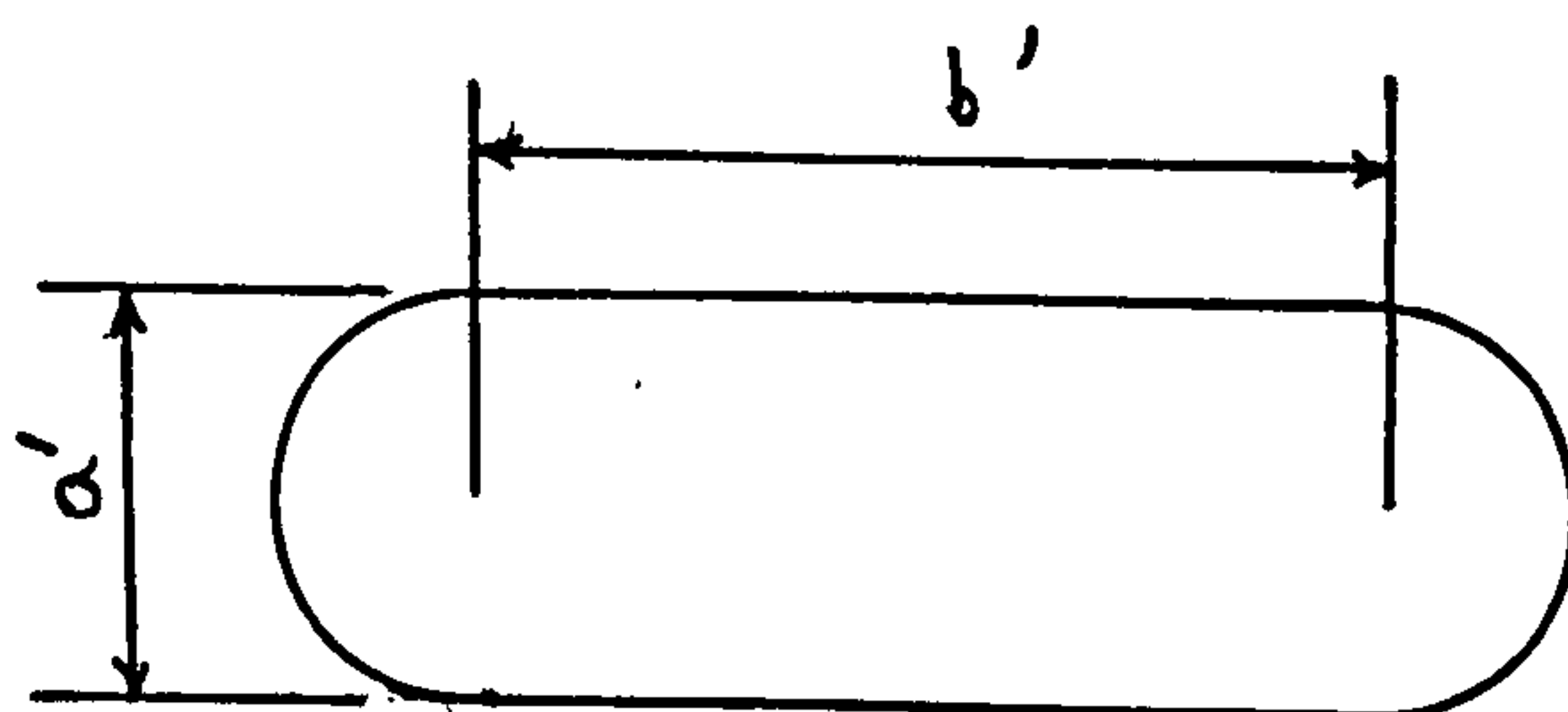
Test holes were designed with an aspect ratio of the approach stream ($6.4/n$) in the range of 2.5/1, to avoid vortex formation in the flow through the holes, (Ref. 8). A uniform approach stream was achieved by equi spacing each set of holes, which was taken an odd number with central hole centre line opposite to static tappings row. Holes have square edges. Smallest holes have a large number for accurate measurements.

The details of the 20 configurations investigated are shown below divided into three groups on basis of hole shape; Circular holes, oval slots and rectangular slots, covering area ratio range from 0.0595 to 0.600 and slot aspect ratio from 1 to 8, Plates 7, 8 and 9.

(i) Circular Holes: Code C - Plate 7

Five hole configurations

Hole code:	C1	C2	C3	C4	C5
No. of Holes:	7	7	5	5	3
Hole diameter inch:	.329	.472	.807	.985	1.59
Area ratio a^* :	.0595	.1223	.2542	.3810	.5950

(11) Oval slots: Code 0 - Plate 8

Aspect ratio

$$= 1 + \frac{b'}{a'}$$

Seven slot configurations divided to 2 sub-groups:

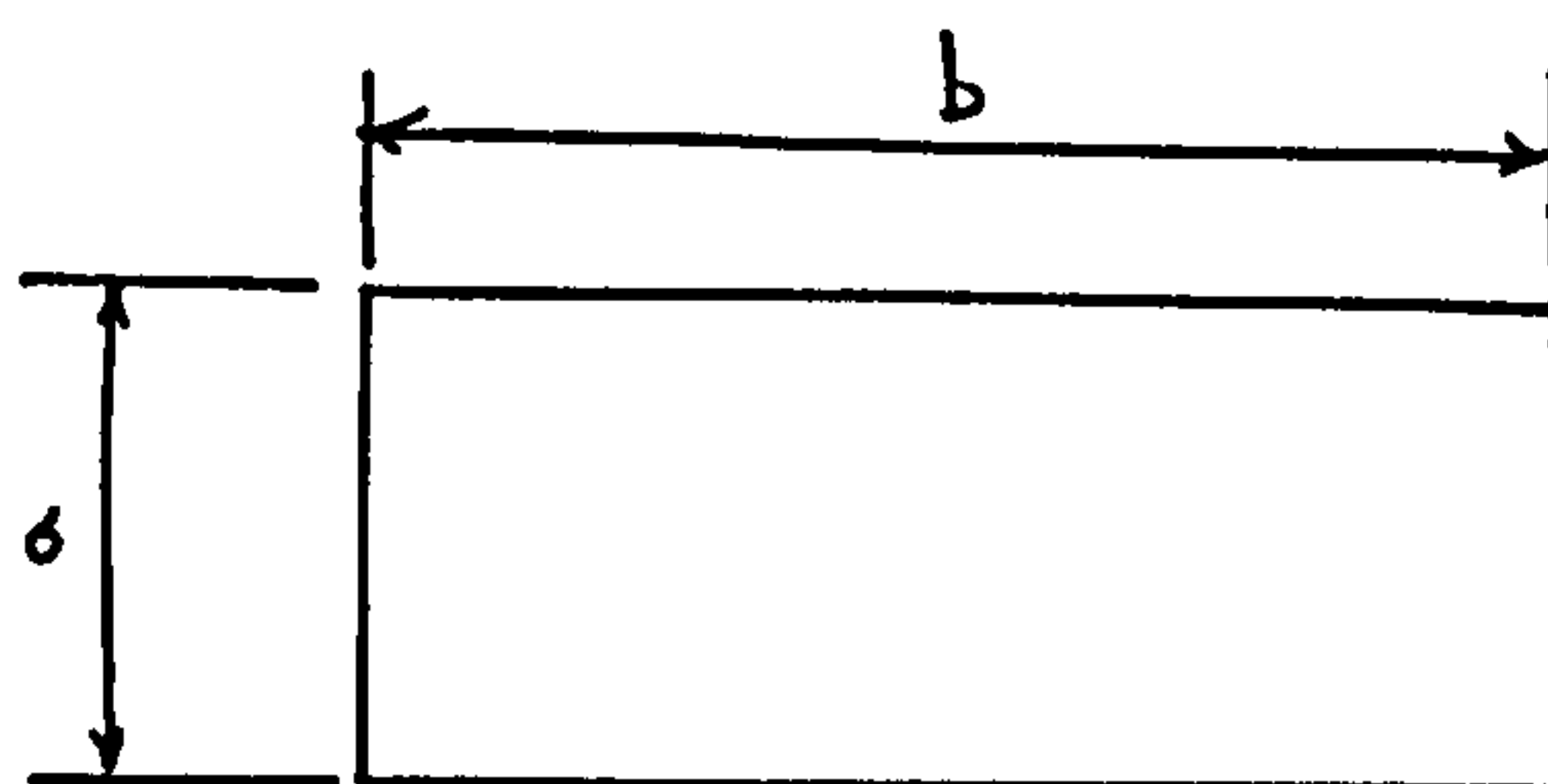
(a) five configurations with the same slot aspect ratio of 2.0, with similar number of slots and slot area to circular holes (1).

Slot code:	01	02	03	04	05
No. of slots:	7	7	5	5	3
$a' = b'$ inch:	.218	.312	.531	.656	1.062
Area ratio a^* :	.0595	.1217	.252	.384	.604

(b) For aspect ratio range from 1 to 8, with same area ratio of 0.252 and same number of slots 5 each. Slots code C3, 03 covers aspect ratio of 1 and 2 respectively. Slots Code 06 and 07 to cover aspect ratio of 4 and 8 respectively.

Slot aspect ratio	1	2	4	8
Plate code:	C3	03	06	07
No. of slots:	5	5	5	5
a inch:	.807 dia.	.531	.375	.25
b inch:	.807 dia.	.531	1.122	1.85
Area ratio a^* :	.2542	.252	.252	.252

(iii) Rectangular slots: Code R - Plate 9



slot aspect ratio
= b/a

Eight slot configuration divided to 2 sub-groups:

(a) Five configurations of aspect ratio 2.0, and similar in number and slot areas to circular holes and group (ii - a) oval slots

Slot code:	R1	R2	R3	R4	R5
No. of slots:	7	7	5	5	3
a inch:	.206	.295	.500	.62	1.0
b inch:	.412	.591	1.00	1.24	2.0
Area ratio a^* :	.0595	.122	.250	.384	.600

(b) For aspect ratio range from 1 to 8, with same area ratio of 0.252 and same number of slots, 5 each. Slots code R6, R7 and R8 together with slot code R3 for aspect ratio of 2.0.

These are similar to oval slots (11 - b)

Slot aspect ratio:	1	2	4	8
Plate code:	R6	R3	R7	R8
No. of slots:	5	5	5	5
a inch:	.708	.5	.355	.25
b inch:	.708	1.0	1.42	2.0
Area ratio:	.252	.250	.252	.250

7.4 Instruments and Calibrations

7.4.1 Pressure measurements

7.4.1.1 Approach static pressure: A complete study of static pressure distribution along test section Figure 29a to f and opposite to hole centre line was measured by 17 static tappings, Figure 28. Due to frictional losses and change in velocity profile, the approach static pressure should be measured as near to test hole as possible. Since the static pressure at the wall opposite to the centre of the hole, measured at station 12 varies with flow through the hole. This approach static pressure was found to be steady at station 2, 7.875 inches upstream hole centre line.

7.4.1.2 Jet Static pressure: Due to practical difficulties of measuring this pressure at the jet vena contracta, it was assumed

that this pressure is equal to the surrounding pressure measured by static probes made of 1.6 mm hypodermic steel tubes with static tapings of 0.0135 inch diameter located tangential with jet profile plates 4 and 6. Tap location is not critical in this case due to the absence of parallel flow on the downstream side of the plate. Secondary flow effect inside taps was neglected due to the very small size of these taps.

7.4.1.3 Total and dynamic pressures: These were measured by ordinary pitot tube with square cylindrical nose .039 inch O/D and .028 inch I/D. The tubes arranged in two sets of 7 probes each, 1 inch apart across the test section and located at station 3; 6.875 inches upstream hole centre and station 15; 2.625 inch downstream hole centre. These were designed to move vertically across the duct to allow velocity survey across the duct, Plate 3.

Manometers: Three types of double tube $\frac{3}{8}$ inch I/D, Plate 1.

(a) Inclined water manometers for accurate measurements of small and negative pressures up to 10 inches of water.

(b) Vertical water manometers for measurements of intermediate pressures 55 inch range.

(c) Vertical mercury manometers for measurements of higher pressures than 55 inch water.

Errors with water manometers lies within ± 0.1 inch water.

7.4.2 Temperature measurements

Air temperature was varying with delivery pressure and running time of the compressor. Temperature was changing within a small

range 25 - 50°C. All temperatures were measured by mercury expansion thermometers 55°C range.

7.4.3 Flow rate measurements

Air flow rates were measured using sharp edged orifice plate with D and D/2 tappings according to B.S.1042 (Ref. 10). Three orifice sizes had been used, 3 inch, 2.25 inch for upstream and downstream ends. For accurate measurements with small test hole sizes, 1.25 inch bleed orifice plate was used on the bleed pipe. Orifice arrangement is shown Figure 27. Flow characteristics of these plates are detailed in Appendix 3.1. The characteristic formulae used are summarised below.

3 inch orifice plate dia., $m = .445$

$$L = C_{fL} [103 Z \sqrt{h} \sqrt{p}] \quad \text{LB/Hr}$$

2.25 inch orifice plate dia., $m = 0.25$

$$L = C_{fL} [56.3 Z \sqrt{h} \sqrt{p}] \quad \text{LB/Hr}$$

1.25 inch orifice plate dia., $m = 0.39$

$$L = C_{fL} [18.3 x Z \sqrt{h} \sqrt{p}] \quad \text{LB/Hr}$$

where:

L = Air flow rate LB/Hr

C_{fL} = Flow rate temperature correction factor

Z = Combined multiplier

h = Differential pressure across the plate inches of water

p = Absolute pressure at the high pressure tapping inches of mercury.

Orifice plate calibrations:

A separate calibration for each arrangement used in the experiment has been done. The calibration curves are shown Appendix 3.1. Errors lie within $\pm 2\%$.

7.4.4 Velocity Measurements

Approach velocity was calculated by the measurement of approach dynamic pressure as the difference between total and static pressures at station 3.

$$V_a = C_{fv} \ 369 \sqrt{\frac{(P_1 - p_1)}{\rho_1}} \quad \text{ft./sec.}$$

Jet velocity was calculated by the measurement of jet dynamic pressure as the difference between total approach pressure and jet static pressure

$$V_j = 18.29 \sqrt{\frac{(P_1 - p_j)}{\rho_j}} \quad \text{ft./sec.}$$

where	C_{fv}	= Temperature correction factor	
	$P_1 - p_1$	= Approach dynamic pressure	inch H_2O
	$P_1 - p_j$	= Jet dynamic pressure	inch H_2O
	P_1	= Approach static pressure	inch H_g
	ρ_j	= Jet density	lb./ft. ³

Pitot tube calibration:

Details of pitot tube characteristics and calibration together with the derivation of above equation are shown in Appendix 3.2.

7.5 Deflection angle measurement and Jet Visualisation

The method used in (Refs. 4 and 7) was continued in this work at the high pressure ratios with test section arrangement, Plate 6. The carbon powder was replaced by "saturn yellow sunbonded fluorescent pigment series A", giving clearer picture and cleaner use. The method is simply by mixing suitable portions of the above powder and paraffin, then coating a thin aluminium plate (20 s.w.g.) with the mixture, evenly distributed using a special roller.

With the wet coating, the plate was inserted below the test plate normal to its surface, i.e. in the XZ plane with one of its straight sides bisecting the jet. Care should be taken for that side not to touch the test plate otherwise the effective hole area will decrease. A gap $\frac{1}{8}$ inch is sufficient. Also the plate was inserted and removed while the compressor is not running, with sufficient time allowed, for few seconds after the compressor gets its running speed. Thus a clear jet pattern was formed on the plate surface as shown on Plates . . 12 to 24 .

Deflection angle ϕ was measured directly using an accurate bevel protractor, with its edge running in line with jet core axis as shown on Plate 10.

At low pressure ratios, a simple mechanism was used on the plenum chamber; by trying to put a rotating deflector across the jet pattern within its core. Then the angle can be measured directly on a transparent protractor stuck on the inner surface of

the plenum chamber, Plate 11.

The deflector was made of a steel shim 42 s.w.g. (.004") thick, 1 inch long and $\frac{3}{8}$ inch wide. It was soldered at right angle, through a thin groove at the centre of a hypodermic tube 1.6 mm diameter, forming one plane with deflector surface. The tube was supported $\frac{1}{8}$ inch below and parallel to the test hole surface, and free to rotate around its axis with a pointer at its end opposite to the degrees scale.

To avoid gravitation effect on the measured angle, due to shim weight, it was balanced by two tin spots on the other side of the axis opposite to the shim.

The errors in both systems depends on the reading accuracy and was within ± 1 degree.

7.6 Preliminary work

7.6.1 Velocity profile

Some preliminary work had been attempted for the study of flow inside test section. From velocity survey of the approach stream, with the use of round 7/32 inch I/D, 1 inch long honeycombs located 22 inch upstream hole centre line, the resulting velocity profile was fluctuating within 9% of the mean velocity 100 ft./sec. measured at duct centre line. These fluctuations will cause uneven pressure distribution across test holes.

Since mesh gauze screens reduce these fluctuations more effectively due to large number of very small jets produced and rapidly blend, producing relatively uniform stream although pressure

drop is high. Several trials had been attempted using several mesh screens at different positions upstream (see author's lab. book), the best arrangement was found with 16 mesh screen located $\frac{1}{2}$ inch upstream the honeycombs together with 40 mesh screen located 11 inch upstream hole centre, this arrangement is shown Figure 30. The resulting fluctuations lies within 4.7% of the mean velocity 130 ft./sec., Figure 31. The velocity profile across test section Z direction, is shown Figure 32. The resulting static pressure distribution is shown Figure 33. Jet static pressure measured all over the set of holes was varying within $\pm 0.5\%$ Figure 34. Jet dynamic pressure was also measured across each hole and showed negligible variation $\pm 0.5\%$.

Preliminary work for static pressure survey with the 5 stations, arises the addition of more 12 stations for pressure measurement along test section as discussed (Section 7.2).

7.6.2 Deflection angle

For deflection angle measurement over a set of holes, preliminary work showed that the angle variation from one hole to another was negligible and within ± 1 degree. Also the angles measured by the mechanism, Plate 11, were checked using fine tuft pieces hung from duct floor through the holes with short length to lie within the potential core. Wall effect on side holes was considered in hole arrangements. Several tests with different deflector lengths using different hole configuration sizes gives a good deflector length of 1 inch with minimum pointer vibrations even with smallest holes.

7.6.3 Precautions

According to the type of compressor used, lubricating oil was necessary for cooling and lubrication of its moving parts. This oil mixes with the air inside the compressor and then separated by an oil separator at compressor delivery. But oil vapour still carried by the air which forms oil droplets after some time of running. These droplets forms on the tips of pitot probes and static tappings, so care should be taken to blow these droplets from time to time especially when significance pressure readings are notices on the manometer panel. Also to clean the inner surface of test section when needed.

Accurate measurement of deflection angle needs to check the free rotation of the pointer about the axis, and the zero reading before start. Also the right setting of the plate and the bevel protractor in the correct position.

The rig should be leak proof, so leakage was checked at different connections, especially the test section connection with the plenum chamber using soap solution.

7.7 Test procedure

For each test plate arrangement, two tests were carried out as follows, refer to the rig flow diagram Figure 27.

(a) With no cross flow (D.V. fully closed):

With this arrangement all the approach flow pass through the hole i.e. $\alpha = 1.0$. The approach duct flow was gradually increased and consequently increasing pressure ratio across the hole

and the flow range. The duct approach static pressure was kept constant at a value of 33" Hg absolute.

With each setting, the following observations were made:

- (i) Upstream pressure, temperature and pressure drop across orifice plates U.O., D.O. and B.O.
- (ii) Constant value of approach static pressure from the static pressure survey along the duct.
- (iii) Jet static pressure.
- (iv) Dynamic pressure drop across the test hole measured at station 3, 6.875 inch upstream hole centre.
- (v) Static pressure drop across test hole.
- (vi) Dynamic pressure of the approach stream measured at station 3.
- (vii) Deflection angle as shown Section 7.5.

(b) With cross flow:

With this arrangement, a fraction α of the approach flow passed through the holes so that $0 < \alpha < 1.0$, at two constant approach velocities of 80 and 130 ft./sec., and constant approach static pressure of 33" Hg abs. The approach mass flow was adjusted to give the required value of V_1 by means of the spill valve to keep the same approach boundary layer conditions. The value of α and hence the flow parameter was controlled by means of valves D.V. and B.V.

Some observations were made as above with case (a). At high

values of pressure ratios control was made by means of valves S.V. and D.V.

The method used for reducing experimental data in terms of bleed ratio α , bleed to area ratios μ , flow parameter K and discharge coefficient C , is shown in Appendix 2.1.

MISSING

PRINT

Section 8

PRESENTATION OF RESULTS AND DISCUSSION

8.1 Correlation of results

Discharge coefficient and deflection angle were correlated to the dimensionless flow parameter K , which is the ratio of jet dynamic pressure to approach dynamic pressure. The flow parameter is an indication to the flow range of the hole with minimum limit of 1.0. At this limiting value the pressure drop across the hole is zero and $p_1/p_j = 1.0$. K increases with increasing p_1/p_j , and with decreasing V_1 for a given pressure ratio. Appendix 1. Also K increases with increase in α and decrease in a^* . The combination of α , a^* is the bleed area ratio μ , as α/a^* . So μ increases with increase in α and with decrease in a^* , i.e. μ increases with increase in μ . Figure 22.

8.2 Discussion of theoretical analyses

8.2.1 Analysis I

This analysis assumes no momentum loss in the axial direction.

Although the solution is somewhat far from practical results as shown in the behaviour of K , Figures 17 and 22. It gives a good trend to the variation of C and Φ with flow and geometric factors.

(a) With No Cross Flow

This is the case of final entry holes of the liner where all the approach flow passes through the holes. Within the theoretical range investigated, $.05 \leq a^* \leq .8$. The main factor governing

C and Φ is the area ratio. C_0 varies from .44 with $a^* = .8$ to .5 with $a^* = .05$, Figure 12. Φ_0 varies from 79° with $a^* = .8$ to 89° with $a^* = .05$, Figure 14. Figure 15 shows the variation of Φ_0 and K with no cross flow.

(b) With Cross Flow:

Figure 16 shows the variation of C with K . As K tends to 1.0 C approaches zero at high rate of change. At high values of K , C increases slowly with increase in K . The limiting value of $C = 0.5$. Figure 17 shows the variation of μ and K . Figure 18 shows that for a given configuration, C increases with increase in α and hence p_1/p_j . At low values of α the rate of change is very high with smallest hole and small with the largest hole. At high values of α , the rate change is small, and C approaches C_0 as α tends to 1.0. Figure 19 shows the high rate of change of Φ with α with high values of a^* . With $a^* = .8$, Φ changes from 33° to 80° as α changes from .2 to 1.0., while with small value of $a^* = .05$ Φ changes from 83 to 89 as α changes from .2 to 1.0. Figure 20 shows the complete variation of Φ with K for all values of α and a^* .

At low flow ranges, with the same value of K , the largest holes give top values of Φ . This is because the value of μ for both holes is the same Figure 22. Hence as $\alpha = \mu a^*$ and α is larger with larger holes, equation 9 gives the value of Φ as

$$\Phi = \cos^{-1} \frac{2 - \alpha}{2\sqrt{K}}$$

i.e. at same value of K , Φ increases with increase in α and

hence with increase in a^* .

Figure 21 shows the direct relation between α , a^* and μ which gives great help in the application of data.

Equation 20 shows the relation between C and Φ as

$$C = \cos \Phi \frac{2}{a^*} \left(\frac{\alpha}{2 - \alpha} \right)$$

This relation shows that for a given hole configurations with increasing α , C increase due to the increase in Φ and hence in jet area.

8.2.2 Analysis II

With this analysis a broader approach to the practical case is achieved by considering the axial momentum loss. Figure 22 shows the complete agreement between theory and experiment with this analysis. Figures 23-25 show the variations of C and Φ with α , a^* and K . The trend is the same as with analysis I, but the values are higher for C and lower for Φ with the given flow and geometric conditions Figures 12-16.

8.2.2.1 Momentum loss factor

As discussed in appendix 2-2, the effect of axial momentum loss with analysis II is indicated by ζ . ζ varies within .75 with high momentum loss at high values of K , and 1.0 with low momentum loss at low values of K (Figures A2-1 to 5).

Although ζ was considered as 0.8 in analysis II, this was the mean value covering most of flow parameter range, and was used for comparison. For more accurate solution, exact values of ζ should be used within the flow range investigated. The effect of ζ is significant on the value of K as it appears as a second order factor in equations 26 and 27.

More work can be extended for further study of this momentum effect in both X and Z directions.

8.3 Discussion of experimental results

8.3.1 Discharge coefficient and jet deflection for circular holes

(a) With no cross flow:

Figures 35-41 show the variation of p_1/p_j with C and Φ for five circular configurations with $.059 \leq a^* \leq .595$. Figure 40 shows that smallest hole with $a^* = .0595$ have the largest value of C_0 up to 0.7 at $p_1/p_j = 1.12$ while the largest hole with $a^* = .595$ give the smallest value of $C_0 = .58$ at same pressure ratio.

Figure 41, shows the same effect on Φ while the smallest hole

have a value of $\Phi_o = 86^\circ$ at $p_1/p_j = 1.12$, the largest has a value of $\Phi_o = 77^\circ$ at same pressure ratio.

The effect of pressure ratio is small especially with large holes, but both C_o and Φ_o increase slightly with increasing pressure drop across the hole.

The effect of a^* can be explained as follows. With decreasing hole diameter for the same hole thickness, the flow passage inside the hole approaches flow inside a short pipe with pipe length equal to hole thickness and with diameter equal to hole diameter. This configuration gives the jet a guidance to flow along hole axis. Thus Φ_o increase and C_o increase due to the increase in jet area at vena contracta following Φ_o . The range investigated covers hole diameter to wall thickness ratio, from 5.25 - 25.4.

(b) With cross flow

Figures 35-39 show the variation of p_1/p_j with C and Φ , for two approach velocities of 80 and 130 ft./sec. For a given hole configuration at a constant value of V_1 , the rate of change of C and Φ is small at high values of p_1/p_j . As p_1/p_j approaches unity the rate of change becomes large and at the limit at $p_1/p_j = 1.0$ both C and Φ have a nul values. The effect of bleed ratio α is the same as that of pressure ratio Figures 111 and 120 respectively. For a given configuration with constant value of p_1/p_j , C and Φ increase with decrease in V_1 . The change is small at high pressure ratios and increases as p_1/p_j decreases and diminishes as p_1/p_j approaches 1.0.

Figures 42-46 show the variation of C and Φ with flow parameter.

Figure 47 shows that smallest holes have highest value of discharge coefficient over the whole range of flow parameter.

Figure 48 shows that small holes have top values of Φ with no cross flow as the top ends of the curves indicate. At low values of K , the largest holes gives the top values of Φ . The reason is discussed at Section 8.2.1.

8.3.2 Discharge coefficient and jet deflection for oval slots

(a) With no cross flow

Figures 49-55 show the variation of p_1/p_j with C and Φ for five configurations with same aspect ratio of 2.0 and with $.059 \leq a^* \leq .604$.

Figure 54 shows that the smallest slot with $a^* = .0595$ gives higher value of C_0 up to .64 at $p_1/p_j = 1.12$. The largest with $a^* = .604$ give a low value of $C_0 = .6$ at same pressure ratio.

Figure 55 shows same effect on Φ . while the smallest slot has a value of $\Phi_0 = 84^\circ$ at $p_1/p_j = 1.12$ the largest slot has a value of $\Phi_0 = 78^\circ$ at the same pressure ratio.

The effect of pressure ratio is small, but both C_0 and Φ_0 increase with increasing p_1/p_j .

Aspect ratio effect:

Figures 51 and 56-59 show the variation of C and Φ with p_1/p_j for 3 configurations of the same $a^* = .252$ and same number of slots. The aspect ratios are 2, 4 and 8 respectively.

Figure 58 shows that at a given value of p_1/p_j , C_o increase with increasing slot aspect ratio. But the slot of aspect ratio 8 gives the maximum values of C_o over the pressure ratio range. With geometric study of these configurations the major dimensions are respectively 1.06, 1.497 and 2.1 inches. The increase in value of C_o is clear with the first two slots, since the depth of the approach stream is in the range of duct depth. With the last slot, the approach stream has the whole depth of the duct, so it is more disturbed by boundary layer thickness before passing through the slot.

Figure 59 shows the same effect on Φ_o , but the last slot with aspect ratio 8 gives highest value at higher pressure ratios.

(b) With cross flow

Figures 49-53 and 56-57 show the variation of C and Φ with p_1/p_j for the same approach velocities of 80 and 130 ft./sec. The behaviour is the same as with circular holes.

Figures 60-66 show the variation of C and Φ with flow parameter.

Figure 65 shows that smallest slots have high values of discharge coefficient at high values of K . With largest slot, C has the top values over low flow parameter range. This is due to the increased slot major dimension in the direction of flow.

Figure 66 shows that small slots have highest values of Φ with no cross flow. But at low values of K the largest slots have top values of Φ as with circular holes.

Aspect ratio effect

Figures 51 and 56-57 show the variation of C and Φ with p_1/p_j

for the slots of different aspect ratios.

Figures 62, 67-70 show the variation of C and Φ with flow parameter.

Figure 69 shows that slots with large aspect ratio have high values of C all over the range of flow parameter. With slot major dimension within duct depth. As slot major dimension exceeds duct depth, C starts decreasing all over the flow range.

Figure 70 shows that slots with large aspect ratio have top values of Φ all over low ranges of flow parameter. Slots with low aspect ratio have high values of Φ all over high ranges of flow parameter.

8.3.3 Discharge Coefficient and jet deflection for Rectangular Slots

(a) With no cross flow

Figures 71-77 show the variation of C and Φ with p_1/p_j for five configurations with same aspect ratio of 2.0, and with $.0595 \leq a^* \leq .600$.

Figure 76 show that small slots have high C_0 values. $C_0 = .69$ with $a^* = .0595$ at $p_1/p_j = 1.12$. Large slots have low values of $C_0 = .59$ with $a^* = .600$ at same pressure ratio.

Figure 77 shows the same effect on Φ While the smallest slot has a value of $\Phi_0 = 83^\circ$, the largest have $\Phi_0 = 73^\circ$ at same pressure ratio of 1.12.

Also as pressure ratio increases both C_0 and Φ_0 increase with a small rate for a given configuration.

Aspect ratio effect

Figures 73, 78-82 show the variation of C and Φ with

p_1/p_j for four configurations with same $a^* = .25$, and same number of slots, 5 each, and four aspect ratios 2, 1, 4 and 8 respectively.

Figure 81 shows that C_o increases with increase in aspect ratio all over the pressure ratio range. Square slots (aspect ratio = 1.0) have the lowest value of C_o at low values of pressure ratio.

Figure 82 shows the same effect on Φ as with oval slots. Square slots have the lowest value of Φ_o all over pressure ratio range. The effect of slot major dimension is clear, as the slot with $b/a = 4$ has the top value of Φ_o as discussed with oval slots.

(b) With cross flow

Figures 71-75 and 78-80 show the variation of C and Φ with p_1/p_j at the same approach velocities of 80 and 130 ft./sec. The behaviour is the same as oval slots.

Figures 83-87 show the variation of C and Φ with flow parameter.

Figure 88 shows that at high flow range, small slots have top value of C all over this range. At low flow range large slots have top values of C all over this range except with the smallest slot.

Figure 95 shows the variation of Φ with K . Like oval slots, small slots have top values of Φ with no cross flow. But with cross flow largest slots have high values of Φ at low flow ranges all over this flow range.

Aspect ratio effect

Figures 73, 78-80 show the variation in C and Φ with p_1/p_j for slots with aspect ratios 2, 1, 4 and 8 respectively.

Figures 85, 90-94 show the variation of C and Φ with flow parameter.

Figure 93 shows an increase in C with increasing aspect ratio all over the range of flow parameter. The square have the lowest value of C all over the range of K .

Figure 94 shows that at high flow range Φ increases with increasing aspect ratio. Slot major dimension is still affecting Φ . At low flow range Φ increase with decreasing slot aspect ratio, although the slot with aspect ratio of 8.0 still has top values of Φ over most of this range.

8.3.4 Discharge coefficient and jet deflection for various configurations

In this section each figuration is compared with other similar configurations of different shapes.

8.3.4.1 Holes and slots with equal areas and numbers

Circular holes are compared with oval and rectangular slots having aspect ratio of 2.0. The comparison is based on equal hole area and number of holes.

Figure 95; 7 holes and $a^* = .0595$ show that ovals have higher values of C over high flow range, while circulars have top values over low flow range. Rectangulars lie in between circular and oval.

The effect on Φ is the same but rectangulars have top values of Φ at high flow range.

Figure 96; 7 holes and $a^* = .122$ show that circulars have top values of C and Φ over most of the flow range. Rectangulars have lowest values. Ovals lie in between.

Figure 97; 5 holes and $a^* = .252$ show that circulars still have top values of C all over flow range. Ovals have lowest values of C

at high flow range, rectangulars in between.

The effect on Φ show at high flow ranges ovals have highest values of Φ , circulars have the lowest and rectangulars in between. At low flow range circulars have top values of Φ , rectangulars have the lowest and ovals in between.

Figure 98; 5 holes, $a^* = .394$ show that ovals have top value of C all over flow range. Circulars have lowest values and rectangulars in between.

The effect on Φ show that circulars have top values of Φ , rectangulars have lowest and ovals in between all over the flow range.

Figure 99; 3 holes, $a^* = .600$, show that ovals have top values of C all over flow range, circulars have lowest values and rectangulars in between.

The effect on Φ show that circulars still have top values of Φ especially at low flow range. No significant change for ovals and rectangulars all over flow range.

8.3.4.2 Slots with equal areas, numbers and aspect ratios

Figure 100; 5 holes $a^* = .252$, aspect ratio = 1.0, comparison between circulars and squares. This shows that circulars have top values of C all over flow range.

Effect on Φ show that circulars have top values of Φ over low flow range and squares have top values over high flow range.

Figure 101; 5 slots, $a^* = .252$, aspect ratio = 2.0 show that ovals have top values of C over low flow range. Rectangulars have top values over high flow range.

Effect on Φ show that ovals have top values of Φ than rectangulars all over flow range.

Figure 102; 5 slots, $a^* = .252$, aspect ratio = 4, show that ovals have top values of both C and Φ than rectangulars all over flow range.

Figure 103; 5 slots, $a^* = .252$, aspect ratio = 8, show that ovals have top values of C than rectangulars over high flow ranges, the change is small.

Effect on Φ show that rectangulars have top values of Φ than rectangulars over high flow range. Ovals have top values over low flow ranges.

8.3.5 Analysis of experimental results

For all configurations studied, with a given hole geometry, both C and Φ increase with decreasing V_1 at constant pressure ratio. C and Φ reach the top values as V_1 approaches zero i.e. for small configurations with no cross flow. With cross flow for a given approach velocity C and Φ increase with pressure ratio increase. The effect of pressure ratio is small with no cross flow especially for large configurations. But with cross flow p_1/p_j effect is large at very low pressure ratios and small at higher pressure ratios. Bleed ratio effect is the same as pressure ratio effect. As p_1/p_j approaches 1.0, or α approaches zero, both C and Φ approaches a nul values. With a given flow factors, C and Φ generally increase with decreasing hole geometry, i.e. with decrease in a^* .

The combined effect of flow and geometric factors is the flow

parameter K . For a given hole configuration C and Φ increase with increasing flow parameter. At low flow ranges large configurations have higher values of C and Φ for circular holes and oval, rectangular slots with aspect ratio = 2.0. Other geometric factors affecting C and Φ for different configurations are:

Ratio of hole diameter to hole thickness: For circular holes both C and Φ increase with decrease in this ratio.

Slot major dimension: With narrow slots (high aspect ratios), as slot major dimension exceeds approach duct depth both C and Φ decrease.

Aspect ratio effect: With slot major dimension within approach duct depth an increase in slot aspect ratio discharge coefficient all over flow range, and increase Φ at high flow ranges.

Effect of hole geometry (shape): At low flow ranges with large configurations, circular holes have higher values of C and Φ than ovals (with aspect ratio = 2.0). Rectangular slots have the lowest values. Square slots have lowest values of C and Φ than circulars over most of the flow range.

Generally oval slots have higher values of C and Φ than rectangular slots over most of the flow range.

8.4 Comparison of experimental results with theory

8.4.1 Discharge Coefficient

Figures 104, 105 show a good agreement between theory (Analysis II) and experiment for circular holes, especially at low values of a^* with no cross flow and at low values of K with cross flow. At high values

of K because the momentum loss factor is rather than 0.8 as shown in Appendix 2.2.

Figures 106-110 show theoretical results quite close to experimental results for all the configurations studied. The slight difference is due to the effects of ζ and the aspect ratio effect which have not been studied theoretically.

8.4.2 Jet Deflection

Figures 112, 113, show quite agreement between theory (Analysis II) and experiment for circular holes, especially at low values of a^* with no cross flow and low values of K with cross flow, as discussed with discharge coefficient.

Figures 114-118 show the theoretical results within the experimental region for all configurations studied. The reason for the slight difference is the same as above.

8.5 Comparison of experimental results with previous work

8.5.1 Discharge coefficient

Figures 104-106 show good agreement between experimental results and those by Dittrich and Graves for circular holes (Ref. 5) all over the flow range. Figure 105 show comparison with Cox results (Ref. 9).

Figures 109,110 show results by Dittrich and Graves for rectangular slots (Ref. 6) lying within the experimental region for the investigated configurations, all over flow range.

Comparison with Fielding's results for circular holes, (Ref. 8) gives quite agreement Figure 111.

The slight variations between author's work and previous work is due to different conditions of experiments, and different apparatus geometry.

8.5.2 Jet deflection

Comparing with Gandamihardja's work for circular holes (Ref 7). Figures 112, 113 show quite good agreement with no cross flow. Figures 119, 120 show Gandamihardja's result quite close to author's results. Figure 120 show Gandamihardja's results are slightly higher especially at high flow parameter range i.e. with smaller holes. The reason for this may be due to the slight error he made in measuring the angle due to the partial blockage of the test hole with the measuring plate touching hole surface. This effect is more significant for smaller holes.

Figure 113 shows a comparison with Cox's results (Ref. 9) for estimating Φ as $\cos^{-1} V_1/V_j$. These results are somewhat far from both theoretical and experimental investigations.

Section 9USE OF DATA

Although these data are based on zero liner flow, it can be applied satisfactorily to both internal and external flows as the case of actual combustor, provided that jet velocity is greater than internal flow velocity and correct jet static pressure is used. Data are most suitable for low pressure loss combustors, and allows up to pressure loss factor of 10% across the hole.

9.1 For survey applications

The given data are; Area ratio a^* , duct geometry, and approach flow rate. It is required to check combustor behaviour, i.e. to find C , Φ and α . To find these parameters, the knowledge of pressure ratio p_1/p_j and flow parameter K is required. Either p_1/p_j and K can be calculated from combustor flow rate, air density, duct geometry, or from direct pressure measurements. Choose the suitable geometric similar configuration using (Section 7.3).

- (i) with the value of p_1/p_j , and calculated approach velocity V_1 (for holes rather than final liner holes), C and Φ can be read directly with suitable a^* from

Figures 35-41 for circular holes

Figures 49-59 for oval slots

Figures 71-82 for rectangular slots.

- (ii) For higher reasonable values of V_1 than 130 ft./sec. use the calculated value of K and by interpolation read C and Φ directly from

Figures 42 - 48 for circular holes

Figures 60 - 70 for oval slots

Figures 83 - 94 for rectangular slots.

To find α ; with the value of K calculated, from Figure 22 read bleed area ratio $\sqrt{K}$. From Figure 21, read α at the given value of a^* .

At values of $a^* > .6$ which is the top limit of this experimental investigation. Refer to the theoretical investigation Section 6, with the values of K , α calculated from above. Equations 8 and 9 give the required values of C and ϕ .

9.2 For design applications

The given data are

- a - Approach flow rate from compressor delivery and engine type.
- b - Air/Fuel ratio and hence α .
- c - Pressure loss factor across the hole $\frac{P_1 - P_2}{P_1} \%$ and hence P_2/P_1
- d - Combustor geometry according to compressor and turbine designs, and combustion efficiency.

It is required to find hole size and ϕ . The hole shape should be decided from point of view of mixing, penetration and liner size.

To find these parameters, K must be calculated from air flow rate, air density and duct geometry or from the ratio of V_2/V_1 using

Figure A1-1. From Figure 22, read the value of $\sqrt{K}$ at corresponding

value of K . From Figure 21, read value of a^* at the corresponding values of β and α .

∴ Hole area $A_h = a^* \times \text{Approach area}$.

With circular holes $A_h = .7854 n D^2$

With oval slots and suitable value of slot major dimension $b' + a'$ (according to duct depth).

$$A_h = n a'^2 \left[\text{slot aspect ratio} - .2146 \right]$$

With Rectangular slots; find b as for oval slots

$$A_h = n a'^2 \left[\text{slot aspect ratio} \right]$$

Suitable configuration choice can be referred to (Section 7.3) according to requirements of design with reference to (Section 8.3).

To find Φ , with the value of a^* calculated, p_1/p_j , and V_1 (for holes rather than final liner holes), read Φ directly from Figures as with 9.1 (1).

With the value of K calculated or with higher reasonable values of $V_1 > 130 \text{ ft./sec.}$ read Φ directly from Figures as with 9.1 (11), by interpolation.

Section 10CONCLUSIONS

The following results were obtained from theoretical and experimental studies of discharge coefficient C , and deflection angle Φ for various configurations. These results were correlated with the dimensionless flow parameter K incorporating geometric and flow factors affecting C and Φ .

1. The flow parameter indicate the flow range through the hole limiting value of K for flush holes is unity. Flow parameter K is function of area ratio a^* , bleed ratio α , both combined as bleed area ratio λ . Also K is a function of pressure ratio p_1/p_j , ratio of jet to approach velocities.
2. For a given hole configuration C and Φ increase with increasing p_1/p_j . With no cross flow the rate of change is small especially with large holes. With cross flow C and Φ increase with increasing p_1/p_j or α . Rate of change is high at very low values of p_1/p_j and α . With no cross flow C and Φ increase with decreasing a^* , and for circular holes C and Φ increase with decrease in the ratio of hole diameter to hole thickness.
3. Axial momentum loss have great effect on both C and Φ all over the flow range. This effect vanishes as flow parameter approach unity.
4. At low flow ranges, large configurations either circular or oval and rectangular with aspect ratio 2.0 have higher values of C and Φ than small configurations.
5. Discharge coefficient and usually deflection angle increase with

increasing slot aspect ratio, since slot major dimension is within the depth of the approach duct.

6. At low flow ranges with large configurations, circular holes have higher values of C and Φ than ovals (aspect ratio 2.0). Rectangulars have the lowest values.

7. Square slots have low values of C and Φ than circular slots.

8. Generally oval slots have higher values of C and Φ than rectangular slots over most of the flow range.

9. Good agreement have been achieved between experimental results and both theory and previous work.

Section 11RECOMMENDATIONS FOR FURTHER WORK

- (1) Work can be extended for studying the behaviour of other hole configurations such as triangular slots.
- (2) Although geometric and flow conditions studied were not too high, to cover all types of combustors, this was the maximum limit allowed by the rig to avoid compressor overloading. Extension of rig capacity can be made to allow for higher conditions. Compressibility effect should be taken into consideration.
- (3) More work can be extended for the study of the momentum effect in both directions.

REFERENCES

1. Grobman, J. S., Dittrich, R. T.: "Pressure drop and airflow distribution in Gas turbine combustors" Trans. ASME. Vol. 79, No. 7. October 1957, pp. 1601 - 1607.
2. Hawthorn, W. R., Olson, W. T.: "High speed aerodynamics and Jet propulsion". Prinston series Vol. XI.
3. Callaghan, E. E., Bowden, D. T.: "Investigation of flow coefficient of circular, square and elliptical orifices at high pressure ratios". N.A.C.A. T.N. 1947, 1949.
- ④ 4. Dewey, P. E.: "A preliminary investigation of aerodynamic characteristics of small inclined air outlet at transonic Mach numbers". N.A.C. T.N. 3442, 1955. (Supersedes N.A.C.A. R.M. 153610).
5. Dittrich, R. T., Graves, C. C.: "Discharge coefficients for combustor-liner air-entry holes. I: Circular holes with parallel flow". N.A.C.A. T.N. 3663, 1956.
6. Dittrich, R. T., Graves, C. C.: "Discharge coefficients for combustor-liner air-entry holes. II: Flush rectangular holes, step louvers and scoops".
7. Gandamihardja, O: Jet deflection. Thesis work submitted at College of Aeronautics, Cranfield. June 1962.
8. Fielding, S. H.: "Data on coefficient of discharge of a plain circular hole ina wall of a duct". Lucas report No. B45, 893. May 1960.

REFERENCES (continued)

9. Cox, H.: "Air flow and momentum exchange through the dilution holes of a combustion chamber". N.G.T.E. Note No. T.N.281, 1957.
10. "Flow measurement" - B.S. 1042, 1943.
11. Gracey, W., Letko, W., Russel, W. E.: "Wind tunnel investigation of a number of total pressure tubes at high angles of attack". N.A.C.A. T.N.2331, 1951. (Supersedes N.A.C.A. R.M. 150 G19).

Additional References:

12. Anon: "Fluid meters, their theory and application". Fourth edn. A.S.M.E. Res.pub. A.S.M.E.(N.Y.) 1937.
13. Lefebvre, A. H.: Supplement lectures on combustion at College of Aeronautics, Cranfield.
14. Lord Rayleigh: "Theory of Sound". Vol. II. Macmillan & Co.
15. Pankhurst and Holder: Wind Tunnel Technique. Pitman.
- ✓ 16. Roshko, Anatol: "Some measurements of flow in a rectangular cut out". N.A.C.A. T.N. 3488, 1955.
17. Stokes, G. M., Davies, D. D., Sellers, T. B.: "An experimental study of porosity characteristics of perforated materials in normal and parallel flow". N.A.C.A. T.N. 3085, 1954. (Supersedes N.A.C.A. R.M. 153H07).
18. Aerodynamic measurements. M.I.T. Press.

APPENDICES

APPENDIX 1FLOW PARAMETER K

It was found that the ratio of jet velocity to the approach velocity is the main factor governing discharge coefficient and deflection angle, Figure A1 - 1. For incompressible flow, this ratio is simply the square root of the ratio of jet dynamic pressure q_j . The approach dynamic pressure q_1 , thus

$$\left(\frac{V_j}{V_1}\right)^2 = q_j/q_1 \quad \text{A1.1}$$

The flow parameter was defined as the ratio of jet dynamic pressure to approach dynamic pressure, and for incompressible flow

$$K = q_j/q_1 \quad \text{A1.2}$$

$$\text{or } K = V_j^2/V_1^2 \quad \text{A1.3}$$

With an error less than 8% within the experiment conditions, equation A1.3 is represented graphically Figure A1-1. When $V_j/V_a = 0$ i.e. with no flow through the holes, $K = 1.0$ as discussed before (Section 6). This shows that K is an indication to the flow through the holes, which has a minimum value 1.0 for flush holes. This flow range can be extended at low values of K less than 1.0 by adding scoops to flush holes (Ref. 6).

From A1.3, using continuity equation

$$K = \frac{\alpha^2}{C a^{*2}} \longrightarrow C^2$$

or $K = M^2/C$ A1.4

A1.4 shows K as a function of flow and geometric factors α , a^* which both affects the discharge coefficient. With assumption 3, Section 6), using equation A1.2.

$$K = \frac{p_1 - p_j}{q_1} + 1$$

$$= \frac{\frac{p_1}{p_j} - 1}{\frac{\rho_1}{2 p_j} V_1^2} + 1$$

For a given approach density and with assumption 5 (Section 6), thus

$$K = m \frac{1}{V_1^2} \left(\frac{p_1}{p_j} - 1 \right) + 1 \quad \text{A1.5}$$

where m is a constant depending on ρ_1 and p_j .

Equation A1.5 is represented graphically Figure A1-2 with atmospheric jet pressure and a mean working conditions with velocity ranging from 50 to 200 ft./sec. Figure A1-2, shows that for any value of V_1 , when $p_1/p_j = 1$, in this case $K = 1.0$ and no flow passes through the hole.

With no cross flow, V_1 is a function of a^* , p_1/p_j and C .

From continuity equation,

$$V_1 - V_2 = C a^* V_j$$

using equation (7) Section 6

$$V_2/V_1 = (1 - \alpha)$$

$$\text{i.e. } V_1 = C a^* V_j \quad \text{A1.6}$$

But

$$\begin{aligned}
 V_j &= \sqrt{2g \frac{P_1 - P_j}{\rho_j}} \\
 &= \sqrt{\frac{2g}{\rho_j} \left[P_1 + \frac{\rho_j V_1^2}{2g} - P_j \right]} \\
 &= \sqrt{2g K_j \left(\frac{P_1}{P_j} - 1 \right)}
 \end{aligned}$$

using A1.6

$$V_1 = C \frac{a^*}{\alpha} \sqrt{m \left(\frac{P_1}{P_j} - 1 \right)} \quad \text{A1.7}$$

where m is the constant discussed before in A1.5.

With no cross flow i.e. $\alpha = 1.0$

$$V_1 = C_0 a^* \sqrt{m \left(\frac{P_1}{P_j} - 1 \right)} \quad \text{A1.8}$$

Equation A1.8 is represented graphically Figure A1-3, using a mean value of $C_0 = 0.65$ for a^* range of .05 to 0.6. Using this value of V_1 for a given value of P_1/P_j , K for no cross flow can be calculated from A1.5.

A complete study of flow parameter, the factors affecting it and its relations with discharge coefficient and deflection angle have been discussed at Section 6, which shows that from equation 13

$$K = 1 + 2 \mu^2 + \sqrt{4 \mu^4 + \mu^2 (4 \alpha - \alpha^2)}$$

for a given value of a^*

$$K = f(\alpha) \quad \text{A1.9}$$

and from equation A1-5

$$K = f\left(\frac{1}{V_1^2}, \frac{P_1}{P_j}\right) \quad \text{A1.10}$$

From A1.9 and A1.10, it is clear that for a given area ratio a^* , the bleed α is a function of V_1 and p_1/p_j

$$\text{i.e. } \alpha = f\left(\frac{1}{V_1^2}, \frac{p_1}{p_j}\right)$$

and for a given value of approach velocity V_1

$$\therefore \alpha = f(p_1/p_j) \quad \text{A1.11}$$

So the flow parameter K which is a function of α , a^* is also a function of V_1 , p_1/p_j and a^* , i.e. the value of K represents completely the flow across the hole.

Effect of momentum loss on flow parameter have been discussed in section 6 (Analysis II)

APPENDIX 2Reduction of Experimental ResultsA2-1 Method used for calculation of results

Discharge coefficient was calculated as the ratio of measured mass flow to theoretical mass flow through the holes or slots

$C = L_j / L_{th}$. Theoretical mass flow L_{th} was calculated as the product of jet density ρ_j , jet velocity V_j and hole or slot area A_h .

ρ_j was calculated assuming isentropic expansion through the holes

$$P_1 / \rho_1^\gamma = P_j / \rho_j^\gamma$$

$$\text{or } \rho_j = \rho_1 (P_j / P_1)^{1/\gamma} \quad \text{lb./cu.ft.}$$

$$\text{where } \rho_1 = \frac{P_1}{R T_1} \quad \text{lb./cu.ft.} \quad \text{A2.1.1}$$

V_j was calculated using Appendix 3-2 as

$$V_j = 18.28 \sqrt{h / \rho_j} \quad \text{ft./sec.} \quad \text{A2.1.2}$$

where h is the jet dynamic pressure, inches water.

A_h : Hole or slot area sq.inch

n : Number of holes or slots

$$\text{Thus } L_{th} = 25 \rho_j V_j n A_h \quad \text{lb./hr.} \quad \text{A2.1.3}$$

L_j : Jet flow rate measured as the difference between up and downstream orifice plate measurements, with suitable plate sizes. Using Appendix 3-1 this value of L_j was checked by bleed orifice plate measurements, thus:

$$C = \frac{L_j}{25 \sum_j V_j n A_h}$$

A2.1.4

The flow parameter was calculated as the ratio of the calculated jet dynamic pressure to the approach dynamic pressure. Due to the negligible temperature effect, K was calculated as follows

$$K = \frac{P_j}{P_1} \frac{V_j^2}{V_1^2}$$

Bleed ratio α is the ratio of the measured flow rate through the holes to the approach flow rate, i.e.

$$\alpha = \frac{L_j}{L_1}$$

$$\text{Bleed/area ratio } \mu = \frac{\alpha}{a^*}$$

Momentum loss factor ζ using equation (21), (Section 6),

$$\zeta = A_h (p_1 - p_j) / M_j \sin \Phi$$

Since the resulting force on the hole is due to the pressure difference across it. For more accurate values of ζ , it is recommended to calculate this force by static pressure survey over the hole, and integrating over hole cross section. In this work p_1 was taken as the static pressure acting on hole centre as p_1' , so

$$\begin{aligned} \zeta &= A_h (p_1' - p_j) / M_j \sin \Phi \\ &= 4.15 \times 10^4 \frac{a^* (p_1' - p_j)}{L_j V_j \sin \Phi} \end{aligned}$$

where

$(p_1' - p_j)$ = static pressure drop across the hole inch water

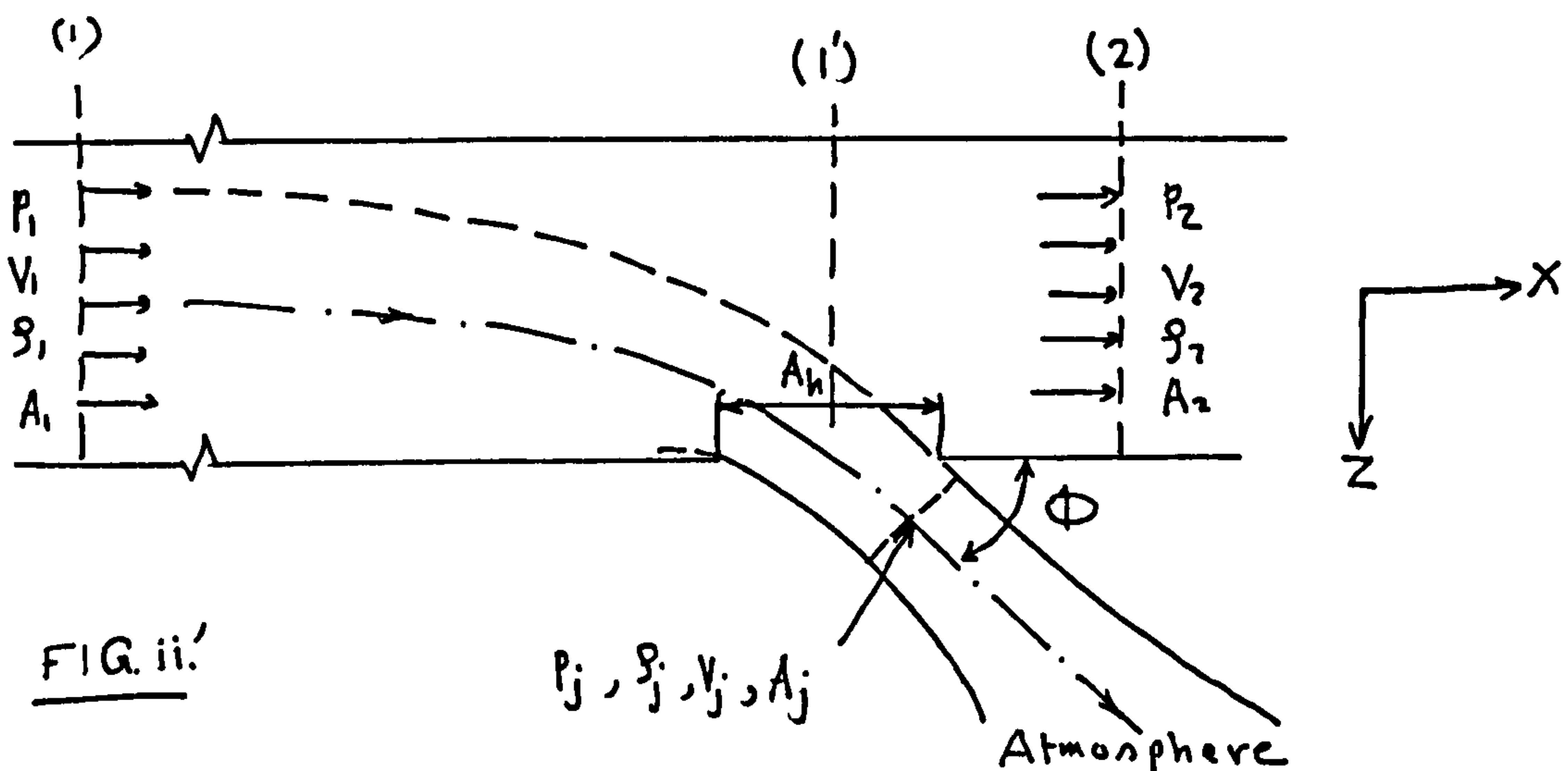
L_j = jet flow rate lb./Hr.

V_j = jet velocity ft./sec.

Experimental calculations are shown in Tables 11 to 30 and represented graphically Figures 35 to 120 .

A2-2 Momentum loss factor

Refer to (Section 6), Analysis II



From the physical observation of the approach stream lines behaviour, using fine tuft technique visualisation in the approach duct. The directional behaviour of the approach stream is rather than axial as assumed in Appendix 1. As the stream lines approach the test hole, it starts changing its direction and becomes inclined towards the holes. This inclination varies with flow range through the holes, i.e. with flow parameter. The effect of

this directional change is in fact an indication to the momentum loss in the axial direction, and the amount of axial momentum exchanged to the atmosphere and hence to the vertical direction.

At low values of K , i.e. with low values of Φ , the axial momentum loss is small, and the amount of momentum exchanged is also small. As the flow range reduces, i.e. K tends to 1.0, Φ tends to zero and both the momentum loss and amount of momentum exchanged tends to zero. With high values of K , i.e. large values of Φ , the amounts of axial momentum loss and momentum exchanged becomes large. In the limit at very high values of K , Φ tends to 90° , the axial momentum is completely lost and the amount exchanged is maximum.

Considering momentum equation in the axial direction the directional effect of approach momentum is small, because we are considering the undisturbed uniform upstream conditions. In the vertical direction the approach momentum behaviour has a significant effect as discussed before.

Applying momentum equation in the vertical Z direction

Figure (11')

$$\sin \Phi (M_1 - M_j) = A_n (p_j - p_1) \quad A2.2.1$$

$$\therefore \sin \Phi (M_j - L_1 V_1) = A_n (p_1 - p_j)$$

writing L_1, V_1 in terms L_j, V_j using A1 and A2-1

$$\therefore \sin \Phi (M_j - M_j \frac{1}{\alpha \sqrt{K}}) = A_n (p_1 - p_j)$$

$$\text{or } M_j \sin \Phi = \left\{ \frac{\alpha \sqrt{K}}{\alpha \sqrt{K} - 1} \right\} [A_n (p_1 - p_j)] \quad A2.2.2$$

Compared with that of Analysis I, equation 4 as

$$M_j \sin \phi = A_n (p_1 - p_j)$$

Thus another factor arises in the R.H.S. of equation A2.2.2. This factor is a function of the unknown value of K . Since the solution of the problem is to find the value of K , thus we need to find the value of this factor. Analytical solution of finding it is outside the scope of this work.

Equation A2.2.2 was written in another form

$$M_j \sin \phi = \zeta [A_n (p_1 - p_j)] \quad \text{A2.2.3}$$

In equation A2.2.3 this factor as a function of α , K is noted as ζ which is called the momentum loss factor. Values of ζ for various configurations have been calculated using experimental work as shown Figures A2-1 to A2-5.

These figures show that the value of ζ varies with the flow parameter for all configurations studied. The rate of change is small at high flow parameter values and high at low values of K . Also ζ was varying within 0.75 and 1.0. The value of $\zeta = 0.8$ as considered in Analysis II covers most of the flow parameter range. Unless at low values of flow parameter, ζ is rather than .8, but at this range the effect of ζ becomes small as K tends towards 1.0 as discussed before.

APPENDIX 3CALIBRATIONSA3.1 Orifice plate characteristics and calibration(1) Orifice plate characteristics

According to B.S. 1042, 1943 (Ref. 10) with D and D/2 tapping

$$L = 359.1 \times CZ d^2 E \sqrt{h} \sqrt{W} \quad A3-1.1$$

where

L = flow rate lb./hr.

C = orifice discharge coefficient

Z = combined multiplier for effects of R_d , E and D.

R_d , E and D are Reynolds number, expansion factor and pipe diameter respectively

d = orifice diameter inches

E = $\frac{1}{\sqrt{1 - m^2}}$ velocity approach factor

h = differential pressure inches of water at 60 °F
(under air)

W = $\frac{p}{RT}$ = fluid density lb. per cu.ft. at working
conditions at high pressure tapping

where

p = absolute pressure lb. per sq.ft. at high
pressure tapping

R = gas constant = 96 lb.ft. per lb. °K for air

T = absolute temperature at high pressure tapping °K

Due to the different flow ranges of the experiment with bleed range from 0 to 1.0 and different hole areas, accurate measurement of differential pressure h was attained by using three different orifice plate sizes arranged as shown Figure 27.

- (a) 3 inch orifice with $m = 0.445$ (U,O) mainly used at high flow conditions upstream to avoid compressor overloading.
- (b) 2.25 inch orifice with $m = 0.25$ (D,O) designed for low flow conditions mainly used at downstream end and at upstream with small hole areas.
- (c) 1.25 inch orifice with $m = 0.39$ (B,O) used at the downstream end of the plenum chamber for accurate bleed measurement at very low values of static pressure ratio across the holes, and with small hole areas.

For these orifice plates, equation A3.1.1 was arranged in terms of measured parameters, p in inches of mercury (absolute) and h . Considering constant air temperature of 300°K and introducing a flow temperature correction factor C_{fL} . Assuming constant absolute viscosity of air 3.88×10^{-7} slug per ft.sec. due to the small change in temperature.

$$C_{fL} = \sqrt{300/T} \quad \text{A3.1.2}$$

The resulting flow equations in order are

$$(U,O)_a \quad L = C_{fL} \left[103 \times Z \sqrt{h} \sqrt{p} \right] \quad \text{A3.1.3}$$

$$(D,0)_b = C_{fL} [56.3 \times Z \sqrt{h} \sqrt{p}] \quad A3.1.4$$

$$= C_{fL} [207.8 \times Z \sqrt{H} \sqrt{P}] \quad A3.1.4^1$$

$$(B,0)_o = C_{fL} [18.3 \times Z \sqrt{h} \sqrt{p}] \quad A3.1.5$$

$$= C_{fL} [67.4 \times Z \sqrt{H} \sqrt{P}] \quad A3.1.5^1$$

where H = Differential pressure, inch of mercury .

These equations are represented graphically Figures A3-1 to A3-3 and the value of C_{fL} from Figure A3-4 using equation A3.1.2.

(ii) Tolerances

These calculated values of flow rate allows for an overall tolerance limit of $\pm 1.5\%$.

(iii) Orifice plate calibrations

For all different orifice arrangements used in the experiment tabulated below, calibrations were down as shown Figures A3-5 to A3-7.

Arrangement	Flow Condition	Upstream Orifice	Downstream Orifice	Bleed Orifice	Maximum %age error
1	No Bleed	3 inch dia.	2.25 inch dia.	-	2
2		2.25 inch dia.	2.25 inch dia.	-	1.32
3	No Cross Flow	2.25 inch dia.	-	1.25 inch dia.	0.628
4	With	3 inch dia.	2.25 inch dia.	1.25 inch dia.	3.5
5	Cross Flow	2.25 inch dia.	2.25 inch dia.	1.25 inch dia.	4

A3.2 Pitot tube characteristics and calibration

(i) Pitot tube characteristics for velocity measurements

Applying Bernoulli equation for ⁱⁿcompressible flow

$$V = \sqrt{2g \frac{\Delta P}{\rho}} \quad A3.2.1$$

A3.1.1 can be written in terms of measured parameters, at given station as follows

$$V = 18.29 \sqrt{h/\rho} \quad A3.2.2$$

$$= 21.3 \sqrt{T h/p} \quad A3.2.3$$

$$= C_{fv} [369 \sqrt{h/p}] \quad A3.2.4$$

where at the given station,

V = velocity ft./sec.

C_{fv} = temperature correction factor for velocity. Since T is considered constant value of $300^\circ K$.

$$C_{fv} = \sqrt{T/300} \quad A3.2.5$$

T = absolute air temperature $^\circ K$

h = dynamic pressure inches of water = $P - p$

p = absolute air pressure inches of mercury

ρ = air density lb. per cu.ft.

Equation A3.2.4 is represented graphically Figure A3-8 with the value of C_{fv} from Figure A3-9 using equation A4.2.5.

(ii) Pitot tube calibration

The measured velocity represents the local velocity at stagnation point. So the use of pitot tube for measuring the mean stream velocity, is done either by velocity measurement survey across the

the section, or by flattening of velocity profile at given section and calibrating the measured value to the calculated mean velocity Figure A3-10.

(iii) Yaw effect on pitot tube reading

Calculated velocity from A3.2.1, is a function of nose shape of the tube, and the yaw angle to streamline direction,

$$V_1 = \xi \zeta \sqrt{2g \frac{\Delta P}{\rho}} \quad A3.2.6$$

where ξ , ζ are constants.

Gracey, (Ref. 11) showed that for cylindrical nose blunt tube, the range of insensitivity to misalignment was ± 11 to ± 23 degrees according to ratio of inner to outer diameters of the nose for 0.125 to 0.96 respectively, Figure A3-4. The tube used in this work was 1 mm o/d hypodermic tube with i/d 0.028 inch with i/d to o/d ratio of 0.72. So ξ in equation A2.1.4 can be assumed very close to unity.

The factor ζ in A3.2.6 depends on approach stream Mach number. The value of ζ is effective for sonic and supersonic flows due to shock formation ahead of the nose. The maximum approach velocity within experiment was such that the approach Mach number not to exceed 0.115 so, the factor ζ can be considered 1.0. Equation A3.2.1 can be applied satisfactorily, without considerable error.

(iv) Errors

For compressible flow relations

$$P = p + \frac{1}{2} \rho V^2 \left[1 + \frac{M^2}{2!} + \dots \right]$$

and for Mach number 0.115, an error of 0.66% arises in velocity calculation by equation A3.2.1 for the assumption of $\zeta = 1.0$.

APPENDIX 4CORRELATION OF GANDAMHARDJA WORK (REF. 7)

Experimental results for circular holes (Ref. 7) showed that deflection angle ϕ of a jet issuing into atmosphere from the wall of a duct with parallel flow, is a function of bleed $a^* U^*$, and area ratio a^* as shown Figure 11, where

a^* = ratio of hole area to duct approach area

U^* = jet velocity component normal to the plane of hole.

With replotting data of Figure 11, ϕ versus a^* with constant $a^* U^*$ values, Figure A4-1 shows a series of straight lines produced with a common meeting point at $\phi = 83$ degrees. This means that for all $a^* U^*$ values $\phi \rightarrow 20^\circ$ as $a^* \rightarrow 0$ and for a given value of a^* , $\phi \rightarrow 90^\circ$ as $a^* U^* \rightarrow 1.0$.

The negative slopes of these lines ϕ/a^* or deflection parameter $\lambda = (83 - \phi)/a^*$ decrease with increasing values of $a^* U^*$ as shown Figure A4-2, which when replotted on a logarithmic scale gives $\log \lambda$ as a unique function of $\log a^* U^*$ for the range $0.1 \leq a^* U^* \leq 0.7$, and a parabolic relation for the range $0.7 \leq a^* U^* \leq 1.0$, as shown Figure A4-3.

(1) $0.1 \leq a^* U^* \leq 0.7$

For the straight line part of Figure A4-3, its equation is in the form

$$\log \lambda = \log a + b \log a^* U^* \quad \text{A4.1}$$

$$\text{or} \quad \lambda = a (a^* U^*)^b \quad \text{A4.2}$$

where a and b are constants, and by substituting data from Figure A4-3 in equation A4.1 gives

$$\begin{aligned} 2.263 &= \log_{10} a - b \\ 2.023 &= \log_{10} a - .699b \\ 1.888 &= \log_{10} a - .523b \\ 1.818 &= \log_{10} a - .398b \\ 1.734 &= \log_{10} a - .301b \\ 1.686 &= \log_{10} a - .222b \\ 1.602 &= \log_{10} a - .155b \end{aligned}$$

adding first three and last four equations

$$\begin{aligned} 2.058 &= \log_{10} a - .777b \\ 1.710 &= \log_{10} a - .269b \end{aligned}$$

solving simultaneously

$$\begin{aligned} a &= 33.42 \\ b &= -0.69 \end{aligned}$$

and the empirical equation for $0.1 \leq a^* U^* \leq 0.7$ becomes

$$\lambda = \frac{33.42}{(a^* U^*)^{0.69}}$$

A4.3

$$(11) \quad \underline{0.7 \leq a^* U^* \leq 1.0}$$

For this range, equation A3.3 gives higher values of λ so that let λ^1 is the corresponding value on the straight line extension, and assume the difference $\lambda^1 - \lambda = f$. With plotting $\log f$ versus $a^* U^*$ on a semi logarithmic scale, gives a unique function as shown Figure A4-4

i.e.

$$\log \xi = C + d (a^* U^*) \quad A4.4$$

which is a logarithmic form of the equation

$$\xi = 10^{C + d (a^* U^*)} \quad A4.5$$

where C and d are constants, and by substituting data from Figure A4-4 in equation A4.3

$$2.5 = C + .7d$$

$$7.5 = C + .8d$$

$$10.2 = C + .9d$$

$$19.1 = C + d$$

adding first two and last two equations

$$.641 = C + .75d$$

$$1.145 = C + .95d$$

solving simultaneously

$$C = -1.249 = -1.25$$

$$d = 2.52$$

and the empirical equation for $0.7 \leq a^* U^* \leq 1.0$ becomes

$$\xi = 10^{-1.25 + 2.52(a^* U^*)} \quad A4.6$$

combining A4.3 and A4.6 by the relation $\xi = \lambda^1 - \lambda$ gives the general empirical equation for all $a^* U^*$ range within the area ratio range $0.0344 \leq a^* \leq 0.314$

$$i.e. \quad \lambda = \left[\frac{33.43}{(a^* U^*)^{.69}} - .0575 (330)^{a^* U^*} \right] \quad A4.7$$

equation A4.7 compared to experimental results gives a good correlation as shown Figure A4-5.

In terms of deflection angle Φ gives

$$= 88 - a^* \left[\frac{33.43}{(a^* U^*)^{.69}} - .0575 (330)^{a^* U^*} \right] \quad A4.8$$

With no cross flow

$$\Phi_0 = 88 - 14.43 a^* \quad A4.9$$

i.e. Φ is a unique function of a^* .

Comparison of Gandamihardja work, and author's work for circular holes gives quite a good agreement as shown Figures 112-113 and 119-120.

APPENDIX 5

JET STUDY

General discussion

With the development of high output combustors, the problem of obtaining adequate mixing has become increasingly difficult as combustor reference velocities and heat release rates have increased. In the primary zone of the combustor, the rapid mixing required for high heat release rate is usually obtained by means of high velocity air jets issuing into the combustion space from swirlers and openings in the dome and liner, resulting high turbulence level. Also adequate penetration and good mixing are required in the dilution zone for achieving a satisfactory temperature profile at turbine inlet. This requirement is also obtained by suitable shape and number of dilution jets in the secondary zone.

Jet structure

The flow pattern of gaseous jet can be divided into two main regions Figure A5.1. The region near the jet exit called as the potential core (or cone), where jet parameters of temperature, velocity and jet fluid concentration are maintained approximately constant. Outside and downstream of the potential core, a mixing region exists in which the jet expands and interaction occur between the jet and the surrounding fluid. Jet parameters of interest are usually, velocity, temperature and jet fluid concentration,

these are varying in this mixing region. Downstream jet exit, the jet draws in its boundary fluid from the surrounding.

So although the velocity downstream decreases, the mass of the fluid increase with increasing distance downstream, Figure A5.2.

Jet profile

Bidone (Reference 14) made some investigations for the study of the behaviour of water jets issuing horizontally. He showed that circular jets retain their circular profile along the jet axis. For elliptical jets with major axis horizontal, the jet lose its ellipticity with increasing distance till it becomes circular and elliptical again further downstream with major axis vertical. Finally the jet reduce to flat sheet in the vertical plane, very broad and thin. For equilateral triangle apertures, the jet resolve itself into three sheets disposed symmetrically round the axis. The planes of sheets being perpendicular to the sides of the aperture. Magnus (Reference 14) investigated the forms of the jet from rectangular and square apertures.

Plates 12-14 show the jet profile for the smallest circular holes with No Cross flow, $V_1 = 80$ and 130 ft./sec. The two regions of the jet are clear and also with the effect of approach velocity on jet deflection angle Φ . Plate 15-17 for the largest circular holes at same velocities, the effect of area ratio on jet deflection is also clear. Plate 18-19 for the small oval slot, both regions are still with a clear profile transformation compared with circular holes. Plate 20 for largest

oval slot with aspect ratio = 2.0. Plate 21, for oval slot with aspect ratio = 8.0. Plate 22 for small rectangular slot, also clear profile transformation can be observed. Plate 23 for rectangular slot with aspect ratio = 8.0.

Comparison of different profiles

Results of these profile show that smaller holes have high turbulence level than larger holes. This is advantageous with using small holes for good mixing and less engine smoke, but the main disadvantage with using small holes is the high pressure drop accompanying them. Also slots with high aspect ratios have adequate penetration due to the stronger produced jet. Plate 24 shows a comparison of four configurations at same flow conditions. The smallest slot (O1), the jet is weak with less penetration depth. For the other equal area slots, circular and oval slots (C2, O2) to have more adequate penetration depth compared with rectangular slots (R2).

TABLES

Table 1

Theoretical investigations of discharge coefficient and jet deflection .

K.Sh.Kaddah

Analysis I

No cross flow

a^*	μ	a^{*2}	$2/a^{*2}$	x	x^2	y	$\sqrt{y}$	K	C_o	Φ_o
.050	20	.0025	800	801	641600	640799	800.4	1601	.4999	89.3
.100	10	.0100	200	201	40400	40199	200.4	401	.4993	88.5
.200	5.0	.0400	50	51	2601	2550	50.5	101	.4965	87.2
.400	2.5	.1600	12.5	13.5	182.3	168.8	12.99	26.5	.4860	84.3
.600	1.67	.3600	5.67	6.67	44.49	37.82	6.15	12.82	.4656	82.0
.800	1.25	.6400	3.19	4.19	17.56	13.37	3.657	7.847	.4464	79.67

$$x = 1 + 2/a^{*2}$$

$$y = x^2 - x$$

Table 2

Bleed ratio $\alpha = 0.20$									
a^*	x	μ	$2/\mu^2$	$1 + 2/\mu^2$	$4/\mu^4$	$\mu^2 x$	y	$\sqrt{y}$	Φ°
.050	.760	4.0	32	33	1024	12.15	1036	32.2	32.18 .4956 83.5
.100	.760	2.00	8.0	9.0	64	3.04	67.04	8.18	17.2 .4836 77.5
.200	.760	1.00	2.0	3.0	4.0	.760	4.76	2.18	5.18 .4383 66.67
.400	.760	.500	.50	1.5	.250	.190	.440	.6632	2.16 .3399 52.20
.600	.760	.340	.230	1.23	.0528	.0873	.140	.3742	1.50 .2770 43.0
.800	.760	.250	.125	1.125	.0156	.0475	.0631	.2512	1.376 .2130 36.67

$$x = 4 \alpha - \alpha^2 = .760$$

$$y = 4 \mu^4 + \mu^2 x$$

Table 3 ----- **Theoretical investigations of discharge coefficient and jet deflection.** **K.Sh.Kaddah**

Analysis I
Bleed ratio $\alpha = 0.40$

$\frac{x}{d}$	μ	$2\mu^2$	$1+2\mu^2$	$4\mu^4$	$\mu^2 x$	y	$\sqrt{y}$	K	C	ϕ°
.050	1.44	8.0	128	16384	92.2	16476.2	128	257	.498	87
.100	1.44	4.0	32	1024	23	1047	32.4	65.3	.495	84.3
.200	1.44	2.0	8.0	64	5.77	69.7	8.35	17.3	.480	79.0
.400	1.44	1.0	2.0	4.0	1.44	5.440	2.33	5.33	.433	70.0
.600	1.44	.67	.89	.792	.641	1.433	1.197	3.08	.382	63.0
.800	1.44	.50	.50	.250	.360	.6100	.781	2.28	.331	58.0

Table 4 Bleed ratio $\alpha = 0.60$

.050	2.04	12	288	82960	294	83254	288.5	577	.4985	88.3
.100	2.04	6.0	72	5184	73.4	5257.4	72.5	145.5	.4965	86.5
.200	2.04	3.0	18	324	18.4	342.4	18.5	37.5	.4900	83.5
.400	2.04	1.5	4.5	20.3	4.6	24.85	4.98	10.3	.4630	77.5
.600	2.04	1.0	2.0	4.0	2.04	6.04	2.458	5.46	.4279	72.5
.800	2.04	.75	1.124	1.26	1.145	2.405	1.551	3.67	.3920	68.5

Table 5 Bleed ratio $\alpha = 0.80$

.050	2.56	16	512	513456	655	262815	512.7	1025	.4998	89.0
.100	2.56	8.0	128	16384	164	16548	128.7	257.7	.4980	87.8
.200	2.56	4.0	32	1024	40.9	1065	32.6	65.6	.4940	85.75
.400	2.56	2.0	8.0	64	10.25	74.3	8.62	17.62	.4800	81.67
.600	2.56	1.34	3.59	4.59	4.6	17.5	4.20	8.77	.4520	78.34
.800	2.56	1.0	2.0	3.0	2.56	6.56	2.56	5.55	.4247	75.20
$x = 4 \alpha - \alpha^2$				$y = 4 \mu^4$	$+ \mu^2 x$					

Table 6 Theoretical investigations of discharge K.Sh.Kaddah
 Co efficient and jet deflection .
 Analysis II ($\delta = 0.80$)

No cross flow .								
a^*	μ	a^{*2}	x	$1+x$	$\frac{1.28}{a^{*2}}$	K	C_o	$\phi.$
.050	20	.0025	.00292	1.0015	512	1023	.625	89
.100	10	.0100	.0117	1.005	128	257	.621	88
.200	5.0	.0400	.0467	1.023	32	65.7	.618	86.5
.400	2.5	.1600	.1870	1.089	8.0	17.7	.595	83
.600	1.67	.3600	.4220	1.193	3.56	8.80	.565	80
.800	1.25	.6400	.7500	1.323	2.00	5.63	.530	78

$x = 1.17 . a^2$.

Table 7 Bleed ratio $\alpha = 0.20$

a^*	x	y	$2\mu^2$	z	$\mu^2 y$	$z+\mu^2 y$	K	C	$\Phi.$
.050	.760	1.18	32	1024	18.9	1043	32.3	.617	82
.100	.760	1.18	8.0	64	4.73	68.7	8.29	.595	74
.200	.760	1.18	2.0	4.0	1.18	5.18	2.275	.522	62
.400	.760	1.18	.500	.250	.296	.540	.735	.373	47
.600	.760	1.18	.230	.0528	.136	.188	.433	.285	40
.800	.760	1.18	.125	.0156	.074	.089	.298	.223	36

$x = 4\alpha - \alpha^2 = .760$, $y = 1.56 x$, $z = 4\mu^4$

Table 8

Theoretical investigations of discharge coefficient and jet deflection .

Analysis II ($\delta = 0.80$)

K. Sh. Kaddah

Bleed ratio $\alpha = 0.400$

a	x	y	μ	$2\mu^2$	z	$\mu^2 y$	$z + \mu^2 y$	$\sqrt{z + \mu^2 y}$	K	C	ϕ°
.050	1.44	2.25	8.0	128	16384	144	16528	128.5	165	.625	86
.100	1.44	2.25	4.0	32	1024	36	1060	32.56	42.2	.617	83
.200	1.44	2.25	2.0	8.0	64	9.0	73	8.540	11.5	.592	76
.400	1.44	2.25	1.0	2.0	4.0	2.25	6.25	2.500	3.88	.508	66
.600	1.44	2.25	.67	.89	.792	1.01	1.80	1.34	2.42	.432	59
.800	1.44	2.25	.500	.50	.250	.562	.810	.900	1.89	.365	54.3

Table 9 Bleed ratio $\alpha = 0.60$

.050	2.04	3.18	12	288	82960	458	83418	288.8	369	.625	87.8
.100	2.04	3.18	6.0	72	5184	104	5288.5	72.7	93	.622	85.3
.200	2.04	3.18	3.0	18	324	28.6	352.6	18.7	24.5	.607	81.8
.400	2.04	3.18	1.5	4.5	20.25	7.15	27.4	5.23	6.93	.570	74.5
.600	2.04	3.18	1.0	2.0	4.0	3.18	7.18	2.68	4.0	.500	69.5
.800	2.04	3.18	.75	1.124	1.26	1.79	3.05	1.746	2.84	.447	65.3

Table 10 Bleed ratio $\alpha = 0.80$

.050	2.56	4.0	16	512	262160	1025	263185	513	656	.625	88.5
.100	2.56	4.0	8.0	128	16384	256	16640	129	165	.622	87.3
.200	2.56	4.0	4.0	32	1024	64	1088	32.9	42.6	.613	84.6
.400	2.56	4.0	2.0	8.0	64	16	80	8.94	11.8	.583	80
.600	2.56	4.0	1.34	3.59	12.9	7.2	20.1	4.47	6.15	.540	76
.800	2.56	4.0	1.0	2.0	4.0	4.0	8.0	2.82	4.08	.495	72.67

$x = 4\alpha - \alpha^2$
,
 $y = 1.56 x$
,
 $z = 4\mu^4$

Discharge coefficient and jet deflection for circular holes .
Hole code C1

NO cross flow p1/pJ α°	λ	$L1 \frac{lb_s}{Hr}$	$LJ \frac{lb_s}{Hr}$	$\rho_1 \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$\rho_j \frac{lb}{cuft}$	$VJ \frac{ft}{sec}$	$L_{th} \frac{lb_s}{Hr}$	C	K	ϕ°	Σ
1.015	100	17	129	129	6.6	.0800	166	190	.678	625	81	.755
1.039	100	17	206	206	10.5	.0786	276	306	.672	665	82	.743
1.072	100	17	255	255	13	.0786	365	402	.635	740	82	.790
1.090	100	17	293	293	14.9	.0785	425	458	.640	750	84.0	.770
1.132	100	17	365	365	18.7	.0788	493	525	.700	620	85	.717

Approach velocity = 80 ft /sec												
1.005	4.2	.710	1550	65	.0765	80	.0765	135	152	.427	3.5	.870
1.030	10.45	1.76	1550	162	.0765	80	.0750	251	277	.585	3.4	.835
1.054	14.3	2.42	1550	222	.0763	80	.0740	332	361	.615	15.2	.822
1.096	19	3.21	1550	295	.0763	80	.0720	433	458	.642	25.5	.790
1.113	19.4	3.28	1550	300	.0763	80	.0715	468	490	.613	30.8	.860

Approach velocity = 130 ft /sec												
1.015	4.40	.770	2500	110	.0770	130	.0762	218	245	.450	3.0	.855
1.034	7.25	1.22	2500	180	.0762	130	.0735	298	322	.558	5.58	.765
1.062	8.80	1.49	2500	220	.0761	130	.0730	373	400	.551	8.65	.845
1.085	10	1.69	2500	250	.0759	130	.0720	427	450	.556	11.2	.857
1.117	11.6	1.95	2500	290	.0758	130	.0700	487	500	.580	13.8	.870

Table 12

Discharge coefficient and jet
deflection for circular holes .
Hole code C2

K.Sh.Kaddah

No cross flow

p1/pj	$\alpha\%$	μ	$L1 \frac{lb}{Hr}$	$L2 \frac{lb}{Hr}$	$\rho_1 \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$\rho_j \frac{lb}{cuft}$	$Vj \frac{ft}{sec}$	$L_{th} \frac{lb}{Hr}$	C	K	ϕ°	δ
1.020	100	8.17	340	340	.0790	17.2	.0780	214	510	.658	152	81	.750
1.050	100	8.17	435	435	.0738	26.5	.0726	309	677	.642	130	82	.773
1.060	100	8.17	510	510	.0740	27.6	.0715	344	753	.680	145	82	.747
1.062	100	8.17	521	521	.0740	28	.0715	346	755	.683	143	82	.735
1.101	100	8.17	655	655	.0768	33.6	.0715	440	960	.683	156	84	.730

Approach velocity = 80 ft /sec

1.008	14.2	1.16	1520	210	.0768	80	.0766	161	378	.555	4.3	65	.763
1.022	21.2	1.72	1520	308	.0730	80	.0720	227	500	.617	8.0	71	.772
1.040	28.5	2.33	1520	433	.0745	80	.0723	291	645	.672	12.2	72	.727
1.102	41.7	3.4	1520	653	.0765	80	.0715	450	985	.663	27.4	74	.743
1.052	32.3	2.64	1520	478	.0767	80	.0744	330	750	.638	17.3	73	.785

Approach velocity = 130 ft/sec

1.020	11.4	.93	2420	278	.0750	130	.074	240	545	.511	3.35	61	.743
1.058	20.2	1.65	2420	493	.0748	130	.0724	367	810	.608	7.30	67	.715
1.064	21.8	1.78	2420	520	.0736	130	.0707	379	820	.632	8.2	69	.745
1.102	27	2.20	2420	660	.0751	130	.0700	470	1010	.652	11.9	69	.755
1.115	29.2	2.38	2420	700	.0765	130	.0700	505	1080	.649	14.5	76	.750

Discharge coefficient and jet
deflection for circular holes .

K.Sh.Kaddah

Hole code C3

No cross flow

p1/pj	α %	μ	$L1 \frac{lb_s}{Hr}$	$LJ \frac{lb_s}{Hr}$	$\rho \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$\rho \frac{lb}{cuft}$	$VJ \frac{ft}{sec}$	$Lth \frac{lb_s}{Hr}$	C	K	ϕ°	δ
1.012	100	4.06	475	475	.0794	24.3	.0763	154	750	.635	40	80	.872
1.022	100	4.06	657	657	.0785	33.6	.0758	215	1033	.636	40.3	80	.800
1.030	100	4.06	695	695	.0725	38.3	.0708	241	1085	.640	38.3	81	.772
1.067	100	4.06	1075	1075	.0750	57.3	.0730	362	1650	.650	37.5	82	.770
1.120	100	4.06	1400	1400	.0770	72.3	.0710	482	2170	.645	39.5	83	.757

Approach velocity = 80 ft /sec

1.002	11.	.447	1540	179	.0773	80	.0770	109	535	.369	1.68	57	.900
1.015	36.	1.46	1540	555.	.0723	80	.0720	199	910	.610	5.4	58	.758
1.020	38.9	1.58	1540	626	.0765	80	.0755	221	1060	.591	5.8	74	.787
1.052	65.5	2.66	1540	970	.0743	80	.0718	337	1540	.630	17.1	77	.783
1.098	82.5	3.35	1540	1270	.0772	80	.0722	435	2000	.642	27.3	80	.772

Approach velocity = 130 ft/ sec

1.014	18.1	.735	2500	450	.0750	130	.0747	209	990	.454	2.48	60	.785
1.025	25.7	1.045	2500	642	.0747	130	.0735	259	1210	.532	3.70	63	.850
1.040	34.9	1.420	2500	820	.0723	130	.0702	313	1400	.585	5.55	67	.790
1.083	48.3	1.950	2500	1170	.0747	130	.0705	422	1890	.610	9.80	72	.790
1.115	57.7	2.340	2500	1430.	.0768	130	.071	493	2220	.645	13.2	77	.755

REMARKS:

Hole Code C5

DATE

No cross flow

P_1/P_j	α°	μ	$L_1 \frac{\text{lbs}}{\text{Hr}}$	$L_j \frac{\text{lbs}}{\text{Hr}}$	$g_1 \frac{\text{lb}}{\text{cuft}}$	$V_1 \frac{\text{ft}}{\text{sec}}$	$g_j \frac{\text{lb}}{\text{cuft}}$	$V_j \frac{\text{ft}}{\text{sec}}$	$L_{th} \frac{\text{lbs}}{\text{Hr}}$	C	K	Φ	δ
1.005	100	1.68	733	733	.0782	37.6	.0782	112	1290	.570	8.8	77	.740
1.025	100	1.68	1530	1530	.0753	81	.0737	231	2650	.577	7.9	78	.740
1.038	100	1.68	1790	1790	.0765	93.5	.0735	280	3050	.588	8.6	76	.855
1.066	100	1.68	2300	2300	.0758	121	.0727	368	3960	.583	8.6	76	.830
1.115	100	1.68	2950	2950	.0753	157	.0705	493	5170	.570	9.0	76	.830
Approach Velocity = 90 ft/sec													
1.003	15.6	.262	1510	236	.0775	80	.0775	88	1040	.227	1.27	57	.710
1.004	32.5	.547	1510	492	.0773	80	.0772	106	1210	.407	1.84	62	.910
1.006	49	.824	1510	725	.0773	80	.0772	126	1450	.500	2.63	64	.900
1.021	78	1.31	1510	1175	.0775	80	.0762	210	2380	.500	7.10	73	.970
1.030	100	1.68	1510	1510	.0727	80	.0717	239	2550	.542	8.00	76	.815
Approach Velocity = 130 ft/sec													
1.002	16.2	.272	2520	410	.0782	130	.0780	142	1650	.248	1.19	58	.895
1.006	28.8	.484	2520	705	.0777	130	.0775	170	1950	.362	1.77	61	.990
1.036	70.8	1.19	2520	1800	.0770	130	.0740	292	3210	.560	4.67	71	.895
1.052	83	1.39	2520	1993	.0738	130	.0723	330	3500	.570	6.10	73	.855
1.072	100	1.68	2380	2380	.0744	130	.0744	383	4030	.590	8.4	76	.825

Discharge coefficient and jet
deflection for circular holes .
Hole code C4

Table 14

No cross flow												
p1 / p3	α%	μ	$L1 \frac{lbs}{Hr}$	$L2 \frac{lbs}{Hr}$	$\rho \frac{lb}{cuft} V1 \frac{ft}{sec}$	$\rho \frac{lb}{cuft}$	$V2 \frac{ft}{sec}$	$L_{th} \frac{lbs}{Hr}$	C	K	Φ°	δ
1.004	100	2.63	512	512	.0773 26.5	.0773	114	835	.613	18.5	79	.775
1.012	100	2.63	700	700	.0770 36.4	.0767	164	1200	.583	20	80	.842
1.028	100	2.63	920	920	.0717 53.3	.0690	230	1510	.608	18.1	80	.810
1.058	100	2.63	1480	1480	.0735 80.5	.0705	357	2400	.617	18.5	83	.785
1.125	100	2.63	2000	2000	.0760 105	.0707	485	3280	.610	19.2	83	.792

Approach velocity = 80 ft /sec												
1.002	15.6	.405	1540	240	.0762 80	.0760	103	727	.330	1.53	57	.710
1.005	27.3	.718	1540	417	.0766 80	.0765	127	930	.488	2.50	62	.845
1.015	45	1.18	1540	687	.0763 80	.0760	178	1290	.532	4.90	68	.820
1.046	83.5	2.20	1540	1297	.0759 80	.0727	317	2190	.593	14	76	.840
1.088	100	2.63	1480	1480	.0735 80	.0705	357	2400	.617	19.5	80	.895

Approach velocity =130 ft/sec												
1.003	7.1	.187	2510	178	.0767 130	.0766	150	1100	.162	1.31	50	.772
1.017	27.7	.7277	2510	690	.0757 130	.0753	218	1580	.437	1.68	60	.815
1.036	42	1.10	2510	990	.0750 130	.0687	284	1850	.535	4.35	67	.795
1.060	57.8	1.52	2510	1460	.0750 130	.0722	361	2480	.588	6.80	71	.812
1.135	81	2.13	2510	1980	.0750 130	.0695	492	3250	.610	12.3	78	.815

Table 16

Discharge coefficient and jet
deflection for oval slots .
Slot code 01

K.3h.Kaddah

No cross flow .

P_1/P_2	$\propto \%$	μ	$L_1 \frac{lb}{Hr}$	$L_2 \frac{lb}{Hr}$	$\rho \frac{lb}{cuft}$	$V_1 \frac{ft}{sec}$	$\rho \frac{lb}{cuft}$	$V_2 \frac{ft}{sec}$	$L_{th} \frac{lb}{Hr}$	C	K	Φ°	δ
1.012	100	16.8	104	104	.078	5.32	.077	154	176	.592	830	80	.78
1.025	100	16.8	160	160	.078	8.2	.075	230	256	.628	770	80	.78
1.054	100	16.8	225	225	.077	11.6	.075	328	369	.610	760	82	.75
1.08	100	16.8	270	270	.077	13.9	.073	388	420	.643	720	82	.76
1.113	100	16.8	335	335	.077	17.4	.072	463	490	.685	645	83	.74

Approach velocity = 80 ft /sec .

1.005	4.8	.81	1520	74	.078	77.5	.078	137	159	.465	3.45	60	.760
1.017	8.75	1.47	1520	133	.077	78.5	.076	194	220	.605	6.45	67	.730
1.044	13.8	2.32	1520	210	.077	78.8	.075	304	337	.625	15.4	71	.775
1.080	18	3.02	1520	273	.077	79	.072	397	427	.640	25.5	73	.782
1.115	22.3	3.73	1520	338	.076	79.3	.071	473	507	.667	34.4	77	.730

Approach velocity = 130 ft /sec .

1.005	3.06	.50	2450	75	.076	130	.075	170	190	.394	1.88	50	.680
1.037	5.12	.86	2450	130	.075	130	.075	245	269	.483	3.73	61	.820
1.070	9.81	1.65	2450	244	.075	130	.071	400	424	.577	9.6	69	.792
1.095	11.7	1.97	2450	286	.075	130	.072	457	475	.502	12.2	71	.790
1.115	12.6	2.12	2450	310	.075	130	.069	492	507	.610	14	73	.785

Table 17

Discharge coefficient and jet
deflection for oval slots .
Slot code 02

K.Sh.Kaddah

No cross flow

P_1/P_j	$\alpha\%$	M	$L_1 \frac{lb_s}{ft^2}$	$L_j \frac{lb_s}{ft^2}$	$\gamma_1 \frac{lb}{cuft}$	$V_1 \frac{ft}{sec}$	$\gamma_j \frac{lb}{cuft}$	$V_j \frac{ft}{sec}$	$L_{th} \frac{lb_s}{ft^2}$	C	K	ϕ°	S
1.006	100	8.25	277	277	.0782	14.2	.0780	182	432	.542	161	79	.755
1.031	100	8.25	370	370	.0778	19	.0760	250	577	.542	159	80	.762
1.040	100	8.25	437	437	.0777	22.5	.0760	300	693	.633	171	81	.767
1.062	100	8.25	500	500	.0773	25.8	.0740	347	787	.638	171	82	.770
1.113	100	8.25	665	665	.0770	34.6	.0710	473	1025	.650	171	84	.755

Approach velocity = 80 ft /sec .

1.004	8.13	.670	1535	125	.0762	80	.0761	134	310	.402	2.93	56	.86
1.018	18.9	1.56	1535	290	.0762	80	.075	217	495	.587	8.4	67	.775
1.042	27.5	2.27	1535	423	.0763	80	.0747	300	680	.625	14.4	71	.768
1.062	32.6	2.69	1535	500	.0763	80	.0732	355	790	.632	19.8	73	.770
1.100	38.8	3.20	1535	605	.0770	80	.072	448	990	.613	31.2	76	.805

Approach velocity = 130 ft /sec .

1.013	9.27	.765	2450	227	.0770	130	.0768	215	500	.435	3.04	55	.745
1.028	13.8	1.14	2450	337	.0763	130	.0745	267	606	.557	4.57	62	.745
1.060	19.3	1.59	2450	472	.0757	130	.0730	362	805	.587	8.22	65	.807
1.106	25	2.06	2450	610	.0753	130	.0705	473	1010	.603	13.5	71	.805

Discharge coefficient and jet for oval logs

Discharge coefficient and jet for oval logs

Slot code 03

Approach velocity = 80 f.t /sec

1.003	12.2	.494	1530	186
1.025	41.3	1.67	1530	632
1.085	69.2	2.8	1530	1060
1.115	83.3	3.37	1530	1290

Approach velocity = 130 ft /sec

1.002	7.43	•300	2450	182
1.025	26.3	1.06	2450	640
1.085	43	1.74	2450	1040
1.118	51.2	2.08	2450	1250

Table 19

**Discharge coefficient and jet
deflection for oval slots .
Slot code 04**

K.Sh.Kaddah

No cross flow													
p1/pJ	$\alpha\%$	μ	$L1 \frac{lb\%}{Hr}$	$LJ \frac{lb\%}{Hr}$	$\rho_1 \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$\rho_j \frac{lb}{cuft}$	$VJ \frac{ft}{sec}$	$L_{th} \frac{lb\%}{Hr}$	C	K	Φ°	δ
1.005	100	2.61	480	480	.0780	24.7	.0760	109	795	.602	19.4	80	.870
1.012	100	2.61	675	675	.0777	34.7	.0772	154	1140	.592	19.7	80	.822
1.062	100	2.61	1470	1470	.0767	76.3	.0740	348	2470	.595	19.4	83	.832
1.115	100	2.61	2020	2020	.0775	104	.0725	480	3340	.605	19.3	83	.808

Approach velocity = 80 ft /sec

1.002	18.5	.482	1510	280	.0762	79	.0760	102	750	.373	1.68	47	1.03
1.010	46.2	1.2	1510	700	.0762	79	.0757	173	1269	.557	4.7	67	.880
1.045	84.5	2.2	1510	1290	.0766	80	.0742	305	2170	.593	14	77	.825
1.090	88.5	2.3	1490	1322	.0770	80	.0715	316	2180	.605	15.2	79	.793

Approach velocity = 130 ft /sec

1.002	10.4	.271	2500	260	.0775	129	.0772	150	1110	.235	1.33	35	1.02
1.012	28	.73	2500	700	.0770	130	.0770	202	1490	.470	2.37	57	.950
1.057	59.5	1.55	2500	1450	.0762	130	.0738	357	2530	.572	7.4	72	.850
1.115	79.8	2.508	2500	2035	.0765	130	.0705	493	3340	.608	12.6	77	.805

Table 20

Discharge coefficient and jet
deflection for oval slots .
Slot code 05

K.Sh.Kaddah .

No cross flow

p1/pJ	$\alpha\%$	μ	$L1 \frac{lbs}{Hr}$	$LJ \frac{lbs}{Hr}$	$S_1 \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$S_2 \frac{lb}{cuft}$	$VJ \frac{ft}{sec}$	$L_{th} \frac{lbs}{Hr}$	C	K	Φ°	δ
1.002	100	1.66	585	585	.0768	30.4	.0768	86	995	.587	8.0	77	.61
1.005	100	1.66	722	722	.0768	37.7	.0766	105	1220	.592	7.70	77	.675
1.018	100	1.66	1340	1340	.0735	73	.0720	207	2250	.595	7.95	77	.740
1.032	100	1.66	1790	1790	.0760	94.5	.0740	274	3060	.585	8.20	77	.720
1.120	100	1.66	3250	3250	.0757	186	.0700	510	5400	.602	6.80	78	.74

Approach velocity = 80 ft /sec

1.002	16.6	.275	1560	260	.0765	80	.0765	93.5	1080	.241	1.31	50	.402
1.0025	38	.630	1560	440	.0765	80	.0765	105	1210	.365	1.65	52	.480
1.005	46	.760	1560	720	.0765	80	.0765	127	1470	.490	2.13	60	.505
1.015	87	1.44	1560	1277	.0710	80	.0700	202	2140	.597	5.80	73	.710
1.030	100	1.66	1790	1790	.0760	94	.0740	274	3060	.585	8.2	76	.726

Approach velocity = 130 ft /sec

1.003	21.5	.357	2540	545	.0768	130	.0768	153	1780	.306	1.3	36	1.07
1.005	28.4	.472	2540	720	.0788	130	.0788	161	1920	.375	1.54	47	.680
1.032	73.7	1.22	2540	1865	.0765	130	.0740	283	3160	.590	4.60	72	.667
1.050	92	1.52	2540	2220	.0732	130	.0710	352	3770	.590	7.50	73	.752

Table 21

Discharge coefficient and jet
deflection for oval slots.
Slot code 06

Z.3h .Kaddah

No cross flow		μ	$L1 \frac{lb}{hr}$	$LJ \frac{lb}{hr}$	$\rho \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$\rho \frac{lb}{cuft} VJ \frac{ft}{sec}$	$Lth \frac{lb}{hr}$	C	R	ϕ°	δ
p1/pJ	$\alpha\%$											
1.002	100	3.97	258	258	.0778	13.2	.0778 87.7	430	.600	44	84	.84
1.020	100	3.97	608	608	.0768	31.7	.0757 203	965	.638	110	85	.795
1.077	100	3.97	1165	1165	.0760	61.3	.0720 397	1800	.645	39.5	85	.755
1.117	100	3.97	1410	1410	.0760	74.2	.0705 478	2120	.665	38	86	.745

Approach velocity = 80 ft /sec

1.003	13.8	.547	1575	218	.0760	80	.0760 110	525	.416	1.75	113	.965
1.022	40.7	1.61	1575	640	.0760	80	.0745 222	1040	.615	7	70	.790
1.080	74	2.94	1575	1163	.0760	80	.0715 398	1790	.650	21.3	82	.755
1.090	82.7	3.28	1575	1190	.0730	80	.0690 420	1830	.650	26	80	.755

Approach velocity = 130 ft /sec

1.003	8.4	.333	2490	210	.0760	130	.0760 152	720	.291	1.33	30	.930
1.015	23	.913	2490	575	.0760	130	.0750 221	1040	.553	2.75	57	.807
1.080	49	1.98	2490	1220	.0750	130	.0707 412	1830	.668	8.85	75	.735
1.120	57.6	2.29	2490	1435	.0748	130	.0690 493	2150	.668	12.4	75	.755

Table 22

Discharge coefficient and jet deflection for oval slots, Slot code 07

K.Ch.Kaddah

No cross flow

p1/pJ	α°	λ	$L1 \frac{lb}{hr}$	$LJ \frac{lb}{hr}$	$g_1 \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$g_j \frac{lb}{cuft}$	$VJ \frac{ft}{sec}$	$L_{th} \frac{lb}{hr}$	C	K	Φ°	δ
1.002	100	3.97	163	163	.0773	8.4	.0773	55	273	.597	144	78	1.06
1.015	100	3.97	530	530	.0765	27.7	.0755	174	840	.630	39	80	.800
1.022	100	3.97	648	648	.0760	34.1	.0750	221	1060	.610	41	85	.790
1.035	100	3.97	1150	1150	.0753	61	.0710	403	1830	.627	40.5	87	.785
1.125	100	3.97	1390	1390	.0768	72	.0715	475	2170	.641	39	87	.768

APProach velocity = 80 ft /sec

1.003	20.4	.810	1570	320	.0750	83	.0750	133	640	.500	2.55	58	.780
1.012	30.9	1.23	1570	485	.0746	80	.0745	175	825	.587	4.40	63	.840
1.024	42.3	1.68	1570	665	.0740	80	.0730	237	1110	.600	7.30	69	.788
1.085	74	2.93	1570	1163	.0735	80	.0700	415	1830	.636	22.5	75	.812
1.105	83	3.3	1570	1300	.0760	80	.071	445	2020	.645	26.5	80	.755

APProach velocity = 130 ft /sec

1.007	17.3	.687	2480	430	.0753	130	.0750	196	940	.457	2.20	57	.797
1.015	23	.913	2480	570	.0748	130	.0745	227	1075	.530	2.87	59	.802
1.023	26	1.03	2480	650	.0748	130	.0735	253	1190	.545	3.50	62	.817
1.080	41.7	1.66	2480	1155	.0745	130	.0700	423	1900	.608	9.40	66	.835
1.118	54	2.14	2480	1390	.0765	130	.071	493	2240	.620	12.10	75	.787

Table 23

Discharge coefficient and jet
for rectangular slots .
Slot code R1

K. Th. Kaddah

No cross flow		α %	μ	$L1 \frac{lb}{Hr}$	$LJ \frac{lb}{Hr}$	$\rho \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$\rho \frac{lb}{cuft}$	$VJ \frac{ft}{sec}$	$Lth \frac{lb}{Hr}$	C	K	ϕ°	δ
p1/pJ														
1.040	100	100	16.8	200	200	.0800	10	.0782	280	325	.617	750	80	.800
1.065	100	100	16.8	260	260	.0797	13	.0765	350	395	.657	690	81	.770
1.088	100	100	16.8	305	305	.0793	15.4	.0735	408	445	.685	650	81	.723
1.117	100	100	16.8	338	338	.079	17.2	.0732	465	503	.670	660	82	.753

Approach velocity = 80 ft /sec

1.012	6.8	1.14	1540	105	.0777	80	.0775	177	204	.515	4.85	65	.825
1.022	8.8	1.48	1540	135	.0773	80	.0762	214	242	.557	7.0	69	.822
1.056	15	2.52	1540	232	.0773	80	.0745	337	374	.620	16.8	73	.785
1.104	20.8	3.5	1540	320	.0773	80	.0725	443	480	.667	28	76	.740
1.107	22.1	3.72	1540	340	.0772	80	.0720	476	506	.672	32	76	.742

Approach velocity = 130 ft /sec

1.006	3.62	.610	2490	90	.0778	128	.0776	162	187	.480	1.54	46	.705
1.040	6.82	1.15	2490	170	.0775	128	.0760	285	322	.530	4.65	66	.832
1.074	10.4	1.75	2490	260	.0772	130	.0733	397	432	.600	8.20	68	.795
1.090	11.5	1.93	2490	285	.0768	129	.0720	437	466	.610	10.4	72	.777
1.118	14.2	2.38	2490	350	.0767	129	.0715	490	520	.672	14	74	.725

Discharge coefficient and jet deflection for rectangular slots.
Slot code R2

K.Sh.Kaddah

p1/pJ	$\alpha\%$	μ	$L1 \frac{lb}{ft}$	$LJ \frac{lb}{ft}$	$\rho \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$\rho \frac{lb}{cuft}$	$VJ \frac{ft}{sec}$	$Lth \frac{lb}{ft}$	C	K	ϕ°	Σ
1.002	100	8.2	81	81	.0787	4.12	.0785	54.7	131	.618	176	80	.695
1.020	100	8.2	298	298	.0777	15.4	.0767	206	482	.620	176	80	.770
1.050	100	8.2	450	450	.0775	23.3	.0750	318	728	.620	177	82	.790
1.065	100	8.2	493	493	.0773	25.5	.0742	351	790	.625	177	82	.817
1.115	100	8.2	635	635	.0770	33	.0715	465	1015	.625	180	82	.788

Approach velocity = 80 ft /sec

1.005	10.8	.885	1510	163	.0767	80	.0766	145	338	.482	3.27	60	.745
1.032	22.9	1.88	1510	348	.0767	80	.0750	263	602	.578	12.5	70	.787
1.045	18.6	2.34	1510	432	.0763	80	.0740	315	710	.610	14.8	72	.790
1.062	31.8	2.60	1510	480	.0753	80	.0725	350	775	.618	18	73	.785
1.122	38.2	3.14	1510	604	.0750	80	.0700	468	992	.610	30	75	.820

Approach velocity = 130 ft /sec

1.002	2.70	.222	2500	68	.0770	130	.0770	152	356	.191	1.47	40	.687
1.015	9.30	.760	2500	232	.0763	130	.0755	223	514	.453	3.14	52	.855
1.042	15.3	1.25	2500	380	.0753	130	.0740	313	710	.535	6.05	62	.835
1.062	19	1.55	2500	470	.0755	130	.0725	373	822	.575	8.40	66	.820
1.118	25.6	2.10	2500	630	.0750	130	.0690	483	1025	.515	13.6	71	.795

Table 25

Discharge coefficient and jet
deflection for rectangular slots .
Slot code R3

K.Sh.Kaddah

No cross flow												
p1/pj	α%	μ	$L1 \frac{lb_s}{Hr}$	$LJ \frac{lb_s}{Hr}$	$\rho_1 \frac{lb}{cuft} V1 \frac{ft}{sec}$	$\rho_1 \frac{lb}{cuft}$	$VJ \frac{ft}{sec}$	$L_{th} \frac{lb_s}{Hr}$	C	K	Φ°	δ
1.012	100	4.0	420	420	.0782 21.5	.0780	144	703	.598	44.5	79	.865
1.025	100	4.0	618	618	.0780 31.7	.0767	210	1010	.612	43	80	.810
1.082	100	4.0	1155	1155	.0775 59.5	.0720	408	1840	.627	43.5	82	.777
1.118	100	4.0	1360	1360	.0782 69.5	.0725	472	2140	.637	42	83	.770

Approach velocity =80 ft /sec												
1.005	16.2	.650	1540	250	.0767 80	.0767	118	563	.443	2.18	52	.887
1.017	33.4	1.34	1540	510	.0763 80	.0759	187	877	.582	5.35	67	.800
1.025	42.5	1.70	1540	650	.0762 80	.0750	235	1110	.587	8.4	70	.807
1.085	76.2	3.05	1540	1167	.0762 80	.0717	410	1840	.632	24.2	78	.782
1.120	83	3.32	1540	1378	.0777 80	.0720	480	2160	.637	28.5	82	.757

Approach velocity =130 ft /sec												
1.003	8.85	.354	2490	220	.0768 130	.0766	162	775	.284	1.55	38	1.08
1.025	25.7	1.03	2490	640	.0763 130	.0745	264	1230	.520	4.05	62	.840
1.082	45.7	1.83	2490	1130	.0760 130	.0715	420	1880	.602	9.65	72	.807
1.118	54.5	2.18	2490	1360	.0760 130	.0707	490	2170	.627	12.4	78	.762

**Discharge coefficient and jet
deflection for rectangular slots.
Slot code R4**

K. Sh. Kaddah

No cross flow

$p1/pj$	$\alpha\%$	μ	$L1 \frac{lbs}{Hr}$	$Lj \frac{lbs}{Hr}$	$\int \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$\int \frac{lb}{cuft}$	$Vj \frac{ft}{sec}$	$L_{th} \frac{lbs}{Hr}$	C	K	Φ°	δ
1.006	100	2.6	549	549	.0787	27.9	.0785	127	955	.575	20.2	78	.855
1.012	100	2.6	705	705	.0785	35.9	.0775	162	1210	.582	20	80	.805
1.063	100	2.6	1460	1460	.0775	75.5	.0745	353	2530	.577	20.3	80	.850
1.115	100	2.6	2060	2060	.0770	107	.0715	483	3320	.620	18.5	83	.782

Approach velocity = 80 ft /sec

1.005	28.9	.750	1520	445	.0768	80	.0766	132	970	.457	2.68	56	.915
1.012	44.2	1.15	1520	680	.0768	80	.0758	174	1270	.535	4.60	66	.880
1.045	83.5	2.17	1520	1227	.0750	80	.0726	314	2190	.560	15.4	76	.875
1.050	88.5	2.3	1520	1300	.0733	80	.0710	309	2110	.615	14.3	82	.805

Approach velocity = 130 ft /sec

1.007	17.2	.447	2525	437	.0768	130	.0767	177	1300	.336	1.77	44	.975
1.014	26.7	.695	2525	670	.0767	130	.0776	210	1530	.437	2.57	54	.927
1.058	58.	1.51	2525	1470	.0763	130	.0735	357	2520	.582	6.90	72	.857
1.115	80.	2.08	2525	2035	.0762	130	.0705	494	3340	.615	12.3	77	.792

Table 27

Discharge coefficient and jet
deflection for rectangular slots .
Slot code R5

K.Sh.Kaddah

No cross flow

p1/pj	α°	μ	$L1 \frac{lb}{Hv}$	$Lj \frac{lb}{Hv}$	$f_1 \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$f_j \frac{lb}{cuft}$	$Vj \frac{ft}{sec}$	$Lth \frac{lb}{Hv}$	C	K	ϕ°	Σ
1.005	100	1.49	710	710	.0800	35.5	.0780	98	1280	.555	7.6	75	.910
1.028	100	1.49	1860	1860	.0788	94.5	.0770	255	3300	.553	7.1	76	.810
1.135	100	1.49	3400	3400	.0745	183	.0690	515	6000	.567	7.0	78	.813

Approach velocity = 80 ft /sec

1.005	47	.70	1580	750	.0753	80	.0750	125	1580	.475	2.2	59	.795
1.015	86	1.28	1580	1380	.0723	80	.0720	202	2440	.567	5.45	70	.820
1.020	95.5	1.42	1580	1460	.0700	80	.0690	212	2480	.582	5.95	72	.800

Approach velocity = 130 ft /sec

1.005	29.3	.437	2500	735	.0758	130	.0756	162	2060	.357	1.5	46	.910
1.027	75.2	1.11	2500	1860	.0750	130	.0750	267	3360	.552	4.0	70	.815
1.060	91.5	1.36	2500	2265	.0725	130	.0720	329	3980	.570	10.3	75	.785
1.063	100	1.49	2440	2440	.0722	130	.0700	360	4230	.577	12.9	77	.805

Table 28

Discharge coefficient and jet
deflection for rectangular slots .

K.Sh.Kaddah

Slot code R6

No cross flow

p1/pj	$\alpha\%$	λ	$L1 \frac{lb}{Hr}$	$Lj \frac{lb}{Hr}$	$q \frac{lb}{cuft} V1 \frac{ft}{sec}$	$q_j \frac{lb}{cuft} Vj \frac{ft}{sec}$	$L_{th} \frac{lb}{Hr}$	C	K	ϕ°	ζ
1.006	100	4.0	387	387	.0800 19.4	.0795	126	.620	42	81	.780
1.025	100	4.0	662	662	.0795 33.4	.0785	222	.608	43.5	82	.800
1.085	100	4.0	1155	1155	.0785 58.8	.0740	407	.615	44.2	82	.800
1.115	100	4.0	1370	1370	.0788 69.5	.0732	468	.642	44	83	.772

Approach velocity =80 ft /sec

1.008	26.9	1.07	1520	395	.0782 80	.0780	156	.520	3.97	63	.813
1.023	43.7	1.75	1520	660	.0780 80	.0770	230	.595	8.50	70	.815
1.082	77	3.08	1520	1156	.0780 80	.0735	402	.627	24.5	76	.805
1.095	82.5	3.30	1520	1263	.0795 80	.0740	427	.640	28	81	.770

Approach velocity =130 ft/sec

1.005	8.9	.356	2520	220	.0792 130	.0790	163	.272	1.57	47	.975
1.025	25.6	1.03	2520	645	.0783 130	.0768	258	.520	3.93	63	.870
1.080	45.7	1.83	2520	1150	.0780 130	.0765	408	.588	9.30	73	.810
1.115	56	2.24	2520	1385	.0770 130	.0755	473	.618	11.9	78	.782

Discharge coefficient and jet deflection for rectangular slots .

K. Sh. Kaddah

Slot code R7

No cross flow

p1/pj	$\alpha/\%$	μ	$L1 \frac{lb}{hr}$	$Lj \frac{lb}{hr}$	$S_1 \frac{lb}{cuft}$	$V1 \frac{ft}{sec}$	$S_j \frac{lb}{cuft}$	$Vj \frac{ft}{sec}$	$L_{th} \frac{lb}{hr}$	C	K	Φ°	Σ
1.012	100	3.96	440	440	.0810	21.7	.0807	141	720	.612	41.8	83	.813
1.025	100	3.96	659	659	.0805	32.7	.0785	235	1045	.630	50	85	.782
1.085	100	3.96	1165	1165	.0795	58.5	.0745	402	1890	.617	43.5	88	.797
1.118	100	3.96	1350	1350	.0798	67.5	.0743	470	2210	.612	43.5	88	.805

Approach velocity = 80 ft /sec

1.005	18.4	.727	1550	286	.0775	80	.0773	125	610	.467	2.45	52	.860
1.025	47	1.86	1550	660	.0775	80	.0762	236	1130	.583	8.60	72	.810
1.078	35.3	2.80	1550	1160	.0778	80	.0732	399	1850	.628	23.5	80	.777
1.105	83	3.28	1550	1283	.0785	80	.0733	445	2060	.623	28.7	82	.790

Approach velocity = 130 ft /sec

1.008	12.6	.500	2530	320	.0783	130	.0780	176	867	.370	1.86	38	1.09
1.025	25	.990	2530	640	.0778	130	.0767	253	1225	.522	3.60	58	.850
1.080	45	1.78	2530	1145	.0770	130	.0725	415	1900	.603	9.10	74	.785
1.117	53.3	2.11	2530	1360	.0772	130	.0720	494	2240	.607	12.6	75	.800

Table 30

Discharge coefficient and jet
deflection for rectangular slots.
Slot code R8

K.Sh.Kaddah

No cross flow												
p1/pJ	α%	μ	$L1 \frac{16s}{Hv}$	$LJ \frac{16s}{Hv}$	$g \frac{16}{cuft} V1 \frac{ft}{sec}$	$g \frac{16}{cuft} VJ \frac{ft}{sec}$	$Lth \frac{16s}{Hv}$	C	K	Φ°	δ	
1.012	100	4.0	487	487	.0800 24.4	.0795 158	785	.622	41.5	83	.813	
1.022	100	4.0	642	642	.0788 32.6	.0776 211	1025	.625	41	83	.790	
1.073	100	4.0	1155	1155	.0780 59.3	.0745 392	1820	.637	40.9	84	.827	
1.115	100	4.0	1365	1365	.0775 70.5	.0722 473	2140	.638	40.5	85	.772	

Approach velocity = 80 ft / sec

1.002	19.6	.785	1520	298	.0770 80	.0770 123	592	.503	2.42		57	.675
1.022	43.7	1.75	1520	660	.0767 80	.0755 228	1075	.613	8.1		75	.765
1.080	75.7	3.03	1520	1135	.0770 80	.0725 406	1840	.617	25		80	.795
1.115	84.2	3.37	1520	1404	.0785 80	.0730 477	2180	.613	27.5		81	.768

Approach velocity = 130 ft/ sec

1.006	16	.64	2440	390	.0770 130	.0765 183	875	.445	2.1		47	.837
1.024	26.4	1.06	2440	644	.0765 130	.0753 245	1150	.560	3.57		64	.785
1.075	46.8	1.87	2440	1140	.0762 130	.0725 408	1850	.617	9.50		76	.780
1.115	53.5	2.14	2440	1325	.0770 130	.0715 492	2200	.603	13.3		76	.810

See VOLUME 2.

C O N T E N T S

	<u>Number of</u>
FIGURES	126
APPENDICES FIGURES	26
PHOTOGRAPHIC PLATES	24
<u>Design drawings</u> (Separate document)	10