DISCHARGE COEFFICIENT AND JET DEFLECTION FOR HOLES OF PARALLE FLOW

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Scientific Journal .
The University of Technology .
Baghdad

Vol . 1.
No . 2 .
December 1977

دراسة معامل السريان وزاوية الانحراف للحزم المنسابة من الفتحات المختلفة الاشكال ذات السريان الموازي لسطحها

دكتور قداح شاكر قداح وآخرون

المختصر

الهدف من البحث هو الدراسة النظرية والعملية لكل من معامل السريان وزاوية الانحراف لحزمة من المائع تنساب من خلال فتحات مختلفة الاشكال عندما يكون السريان موازيا لمستوى تلك الفتحات ، مع دراسة العوامل الهندسية ومتغيرات السريان المؤثرة .

ولقد روعي اثناء الدراسة اختيار مختلف الاشكال الهندسية شائعة الاستعمال في غرف الاحتراق للتوربينات الغازية ، وهي الدوائر ، الاشكال البيضاوية ، الاشكال المستطيلة ، والاشكال المربعة للفتحات . هذا الى جانب تغيير نسبة مساحة الفتحات الى مساحة مقطع الانبوب بنسبة تتراوح من 0.06 الى 0.6 . وتأثير نسبة طول الفتحة الى ارتفاع مقطع الانبوب بنسبة تتراوح من 1 الى 8 مع تغيير عدد الفتحات .

اما متغيرات السريان فكانت نسبة ضغط المائع قبل الفتحات الى ضغط الحزم بنسبة تتراوح من 1 الى 1.12 ، ونسبة معدل السريان من الفتحات الى معدل السريان الكلي بنسبة تتراوح من صفر الى 1 وكذلك تأثير سرعة سريان المائع قبل الفتحات وحتى 40 متر في الثانية .

ولقد امكن استنباط معامل خاص يسهل مهمة الربط بين مختلف العوامل الهندسية وبين متغيرات السريان المختلفة ، كما امكن الحصول على نتائج مرضية عند مقارنة الدراسات النظرية والعملية وكذلك بالمقارنة مع النتائج السابقة لمختلف الباحثين عند ظروف البحث المتشابهة .

Abstract

Theoretical and experimental investigations of discharge coefficient and jet deflection have been made for holes having parallel flow to the plane of the holes with and without cross flow.

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

The geometric factors were, ratio of hole area to approach duct area ranging from 0.06 to 0.6, slot aspect ratio ranging from 1 to 8, with a duct depth of 31.75 mm.

The flow factors were, static pressure ratio ranging from 1 to 1.12, bleed ratio through the holes and approach velocity.

The results of these investigations have been correlated with a dimensionless flow parameter incorporating both the geometric and the flow parameters.

Good agreement has been achieved between theoretical and experimental results as well as between this work and the previous work within the range of investigation.

Introduction

In simple tubular combustor systems for turbojets and ramjets, it is required to achieve high heat release and stable flame at the primary zone (figure 1), as well as to have a good air flow distribution and adequate penetration at the dilution zone(1).

Air flow distribution between those two zones is still the major problem of the design engineers. The flow of annular air to these zones is governed by the geometric and the flow parameters of the system under consideration.

The work presented in this paper is a theoretical and experimental study of the main geometric and flow parameters affecting the discharge coeffiecient and deflection angle for the most and common flush hole shapes used in combustor liners.

An attempt has been made to correlate discharge coefficient and deflection angle with a dimensionless flow parameter defined as the ratio of the jet dynamic pressure to the dynamic pressure of the approaching streamlines.

Although these data correspond to flow parallel to the plane of the hole with zero internal flow case, it has been shown (2) that such data can be satisfactorily applied to both internal and external flow cases, since the jet velocity is greater than the internal flow velocity. It has been also shown that the effects of wall inclination and curvature are negligible.

For special applications such as liners designed with high annular air velocity and low overall pressure loss, other hole types such as thumb-nail, scoops, step louvers and scoops over circular holes were also studied by many authors(3).

Notations

A	Area mm^2
a^*	ratio of slot to duct areas
C	discharge coefficient
K	flow paramete
M	momentum N
n	number of slots
P	absolute total pressure N/m^2
p	absolute static pressure N/m^2
Q	air flow rate m^3/s
V	velocity m/s
X,Y,Z	duct dimensions mm
α	bleed ratio $= Q_j/Q_1$
δ	momentum loss factor
μ	bleed to area ratio $= \alpha/a^*$
ρ	density Kg/m^3
θ	deflection angle to hole plane degrees

Suffices

h	hole
j	jet
o	no cross flow
1	hole upstream condition

2 hole downstream condition

1′ duct conditions above hole plane

Theory

The following assumptions were made and two analyses were investigated:

- flow was assumed incompressible and two dimensional
- discharge coefficient was defined as the ratio of the jet area at the vena contracta normal to the jet axis and the slot area
- steady and uniform flow conditions upstream and downstream the test section as well as at the jet vena contracta
- static pressure opposite to the holes was to be assumed uniform and equal to the approach stream static pressure.
- jet static pressure at the vena contracta was equal to the surrounding pressure

Analysis I

This analysis assumes ideal flow conditions with no change in the axial direction of the approaching stream.

Applying continuity, Bernoulli and momentum equations for the flow pattern shown in figure 2:

contiunity equation

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

Bernoulli's equation

$$p_2 - p_1 = \frac{\rho}{2}(V_1^2 - V_2^2) \qquad (2)$$

momentum equation

i) X direction

$$\rho A_1(V_1^2 - V_2^2) - C \rho A_h V_j^2 \cos \phi = A_1 (p_2 - p_1) \qquad (3)$$

ii) Z direction

$$p_1 - p_j = \rho C V_j^2 \sin \phi \qquad (4)$$

from above equations

$$C = \frac{1}{a^*} \left(\frac{V_1 - V_2}{V_j}\right) \qquad (5)$$

$$\Phi = \cos^{-1} \left(\frac{V_1 + V_2}{2V_j}\right) \qquad (6)$$

flow parameter K

It was found that the ratio of the jet velocity to the approach velocity of the stream, is a main factor governing both the discharge coefficient and the deflection angle. This parameter denoted by K was defined as:

$$K = (V_j / V_1)^2 \qquad (7)$$

In terms of K, the above equation give

$$C = \frac{\alpha}{a^*} \frac{1}{K^{1/2}} = \frac{\mu}{K^{1/2}} \qquad (8)$$

$$\Phi = \cos^{-1}\left(\frac{2-\alpha}{2\sqrt{K}}\right) \qquad (9)$$

equations 1 and 3 give

$$\Phi = \sin^{-1}\left(\frac{1}{2C} \frac{K-1}{K}\right) \qquad (10)$$

equation 9 and 10 give

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

equation 8 and 11 give

$$K = 1 + 2\mu^2 \pm \sqrt{4\mu^4 + \mu^2(4\alpha - \alpha^2)} \qquad (12)$$

The above equation represent two cases of flow

i) No cross flow

i.e all the approaching flow pass through the slots

$$\alpha = 1.0 \qquad , \mu_0 = 1/a^* \qquad (13)$$

$$C_0 = \frac{1}{a^* \sqrt{K}} \qquad (14)$$

$$\Phi_0 = \cos^{-1}\left(\frac{1}{2\sqrt{K}}\right) \qquad (15)$$

or

$$\Phi_0 = \cos^{-1}\left(\frac{a^* C_0}{2}\right) \qquad (16)$$

from equations 12 and 13

$$K = 1 + 2\mu_0^2 \pm \sqrt{4\mu_0^4 + 3\mu_0^2} \qquad (17)$$

ii) With cross flow

In this case $o < \alpha < 1.o$

from equation 8 and 9

$$\Phi = \cos^{-1} \frac{Ca^*}{2} \cdot \frac{2 - \alpha}{\alpha} \qquad (18)$$

Analysis II

In this analysis, the effect of change in the axial direction of the approaching stream was taken into consideration as shown in figure 3, and this change was denoted by the momentum loss factor δ.

Applying the momentum equation in the Z direction

$$(M_1 - M_j) \sin \Phi = A_h (p_j - p_1') \qquad (19)$$

equation 19 results in

$$\delta = M_j \sin \Phi / [A_h (p_1' - p_j) \qquad (20)$$

The value of δ was found experimentally and was varying between 0.75 for high values of flow parameter and 1.0 for low values of flow parameter as shown in figure 4 for rectangular slots. Substituting by vlaues of δ, the equations of flow parameter become as follows for the two cases of flow;

i) No cross flow

$$K = 1 + \frac{1.28}{a^{*2}} [1 + \sqrt{1 + 1.17 a^{*2}}\,] \qquad (21)$$

ii) With cross flow

$$K = 1 + 0.64 [2\mu^2 + \sqrt{4\mu^4 + 1.56\, \mu^2 (4\alpha - \alpha^2)}\,] \qquad (22)$$

Figure 5 shows the various relations between C_0 and Φ_0 versus area ration a^*.
Figure 6 shows the various relations between a^* and μ versus flow parameter K.
Figure 7 shows various relations between C and Ø versus the flow parameter K.

Apparatus

Figure 8 shows the apparatus used for the investigation. It consists of a 114 mm diameter steel pipe supplied with oil free air from a roots blower of capacity 90 m³/min at delivery pressure of 0.5

atmosphere and running at 400 R.P.M. Air flow was controlled by a spill valve at the compressor outlet and another three spill valves, one, upstream the test section, the second downstream the test section and the third downstream the jets. The test section was made from transparent perspex plate 6 mm thickness with dimensions 460 ×200 ×32 mm.

The jets were enclosed into a perspex plenum chamber underneath the slots of dimensions 185 ×185 ×300mm.

Test Plates

The test plates used for the investigation were made of a 1.5 mm thickness aluminium plates having flush suface with the duct floor. Leak proof connections were made using sealing strips of bostik 5 material. 20 configurations were investigated covering circular holes, oval, rectangular and square slots with different number of holes and an area ratio range from 0.06 to 0.6 and aspect ratio range from 1.0 to 8.0 as below:

i) circular holes

n	7	7	5	5	3
a^*	.059	.122	.254	.381	.595

ii) oval slots

n	7	7	5	5	3
a^*	.059	.122	.252	384	.604

iii) rectangulat slots

n	7	7	5	5	3
a^*	.059	.122	.252	.384	.600

iv) square slots

n	7	7	5	5	3
a^*	.060	.122	.252	.384	.600

Figure 9 shows a specimen of test plates

Instrumentation

Static pressure was measured by 17 static pressure tappings as shown in figure 10 and the jet static pressure was measured by static probes tangential to the jet profile downstream the test hole as shown in figure 11. Total pressure was measured by an ordinary pitot tube with square cylinderical nose arranged in two sets of 7 probes each 25 mm apart across the test section and located 174 mm upstream the test section and the other set at 67 mm downstream the test section. The probes were designed to move vertically to allow velocity survey across the test section. Differential mercury and water glass manometers were used for pressure measurements. The temperature was measured by mercury in glass thermometers, and mass flow rate was measured by sharp edged orifice plates with D and D/2 tappings according to B.S. specification 1042.

Deflection angle

Preliminary tests were made for jet deflection angle using tuft technique(4). A simple mechanism was designed for approximate measurement of the deflection angle using a rotating and thin mica sheet placed just below the hole centre line as shown in figure 11. Accurate measurement of the deflection angle was made using a thin aluminium plate (20 swg) coated with a wet powder (4) of saturn yellow submerged fluorescent pigment series A or carbon powder. The plate was fixed in a perpendicular direction to the plane of the test plate and in the jet direction parallel to the axis of the test section. This powder technique was found satisfactory in giving a clear jet pattern and was found suitable for measuring the deflection using a bevelled protractor as shown in figure 12.

Discussion of results

Analysis I of the investigation was found satisfactory as a first approximation and it was found that for the discharge coefficient,

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

for the deflection angle,

$$\Phi = \cos^{-1} \left(\frac{2-\alpha}{2\sqrt{k}}\right)$$

Results are shown in figure 7 as a relation between discharge coefficient and jet deflection versus flow parameter.

Analysis II was found more precise taking into account the momentum loss of the approach stream as shown in figure 7 compared with analysis I. The two cases of flow are discussed as follows;

i) No cross flow

It was shown that smaller holes have the largest values of discharge coefficient and deflection angle for the same pressure ratio and vice versa as shown in figure 13 for circular holes.

ii) With cross flow

For a given hole configuration, the rate of change of both the discharge coefficient and deflection angle was found to be small at high pressure ratios. As the pressure ratio approach unity, the rate of change become larger until both the discharge coefficient and deflection angle was found to be small at high pressure ratios. As the pressure ratio approach unity, the rate of change become larger until both the discharge coefficient and deflection angle tend to zero.

Both the dischagre coefficient and the deflection angle were found to increase with decreasing the approach velocity as shown in figure 14 for circular holes and similarly for other hole shapes.

With equal area ratio and number of holes, oval slots were found to have higher values of discharge coefficient over high flow range. Circular holes have higher values of discharge coefficient over low flow range. Rectangular slots lie in between circular and oval slots with respect to discharge coefficients as shown in figure 15 over large range of flow.

The effect with respect to the deflection angle was found to be the same, but rectangular slots were found to have higher values of deflection angles over high flow ranges as shown in figure 15 as well as over low range of flow parameter.

Figure 16 shows good agreement between analysis II of the investigation and both the experimental work and Fielding's work (5). Figure 17 shows satisfactory agreement between analysis II of the theoretical work and experimental results for circular holes as well as Gandamihardj's work(6).

Conclusions

From theoretical and experimental investigations, it was found that the dimensionless flow perameter, is of great importance for correlating the discharge coefficient and the deflection angle. It was also shown that the momentum loss of the approaching stream has a great effect on both the discharge coefficient and the deflection angle when comparing both analysis I and analysis II over all the flow range.

The effects of various geometric parameters were found to be;

Area ratio; small area ratios, were found to have higher values of discharge coefficient and deflection angle all over most of the flow range.

Hole shape: for small flow range, it was found that with large holes, the circular ones have top values of discharge coefficient and deflection angle over other shapes.

Square slots were found to have the lowest values of both discharge coefficient and deflection angle over most of the flow range. Oval slots were found to have higher discharge coefficient and jet deflection than rectangular slots over most of the flow range.

Ratio of hole width to plate thickness: it was found that both the discharge coefficient and the deflection angle increase with the decrease of this ratio.

Slot major dimension: for narrow slots (high aspect ratio), it was found that both the discharge coefficient and the deflection angle decrease as the slot major dimension exceeds the approach duct area.

Acknowledgements

The authors would like to express their most sincere thanks to professor A.H. Lefebvre, the former head of the department of Aircraft propulsion, the department staff and the workshop staff at Cranfield Institute of Technology for the helpful advice and assistance they offered, to carry out the experimental part of this work.

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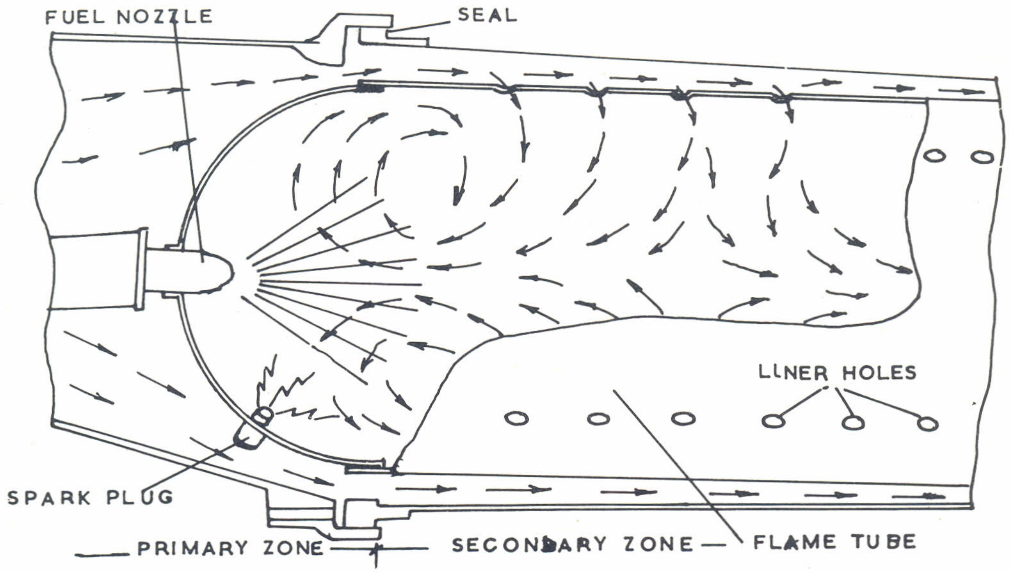

FIG. 1_ TYPICAL AIR FLOW THROUGH LINER

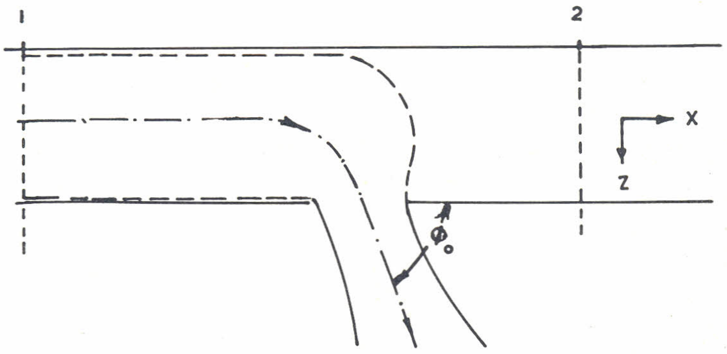

FIG. 2_ FLOW PATTERN_ ANALYSIS I_

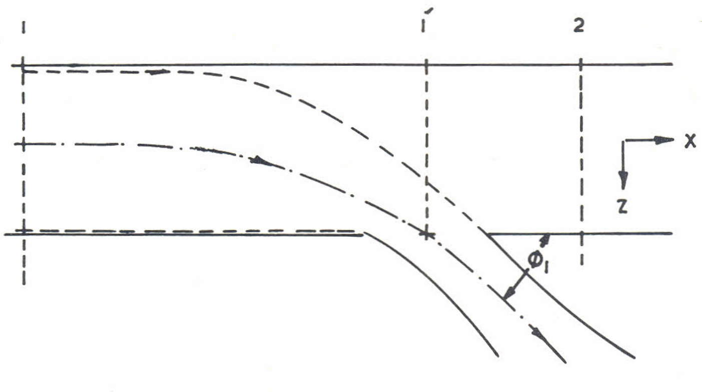

FIG. 3_ FLOW PATTERN_ ANALYSIS II_

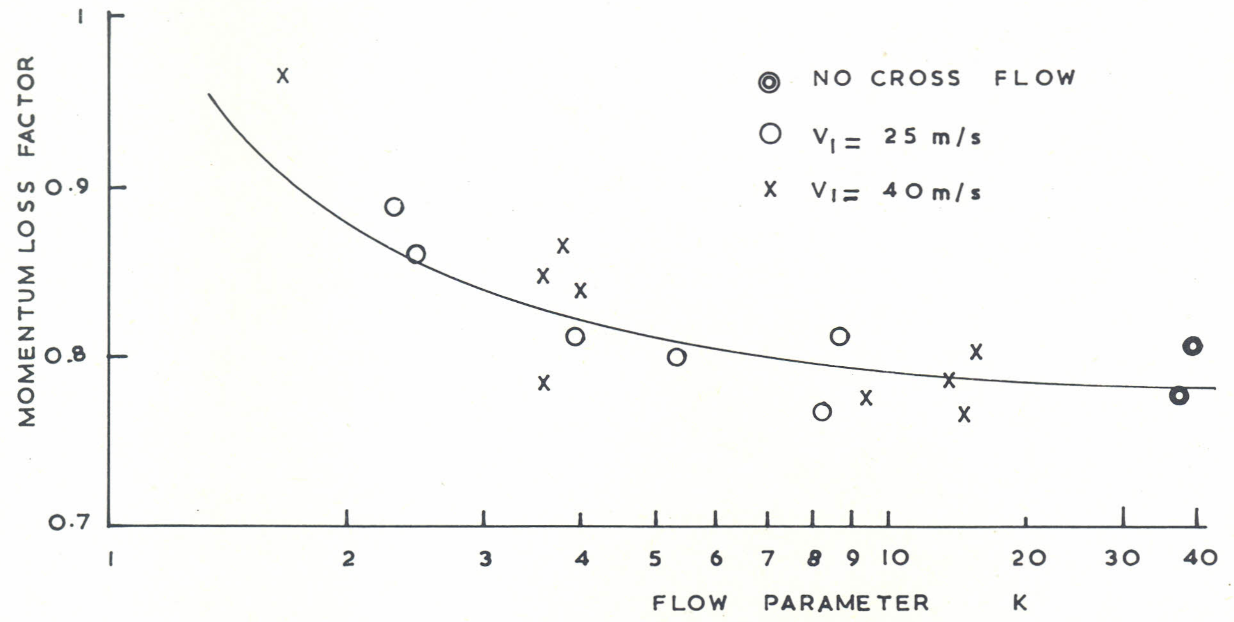

FIG. 4 _ MOMENTUM LOSS FACTOR $a^* = 0.25$

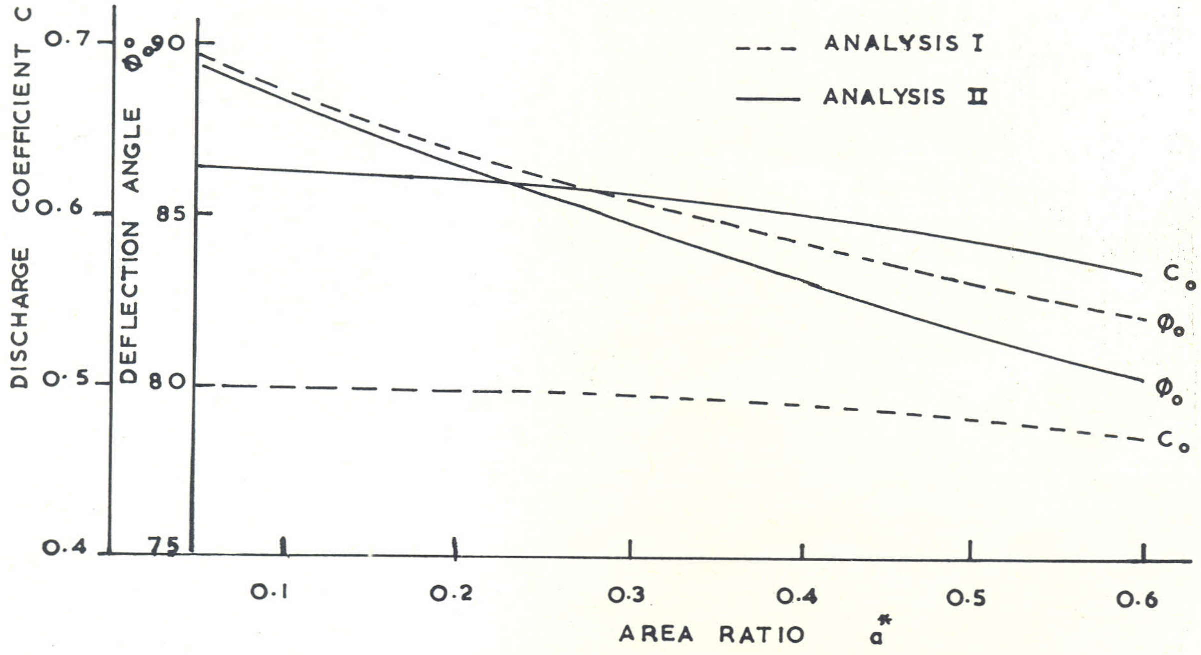

FIG. 5 _ THEORETICAL VARITION OF DISCHARGE COEFFICIENT & DEFLECTION ANGLE _ NO CROSS FLOW

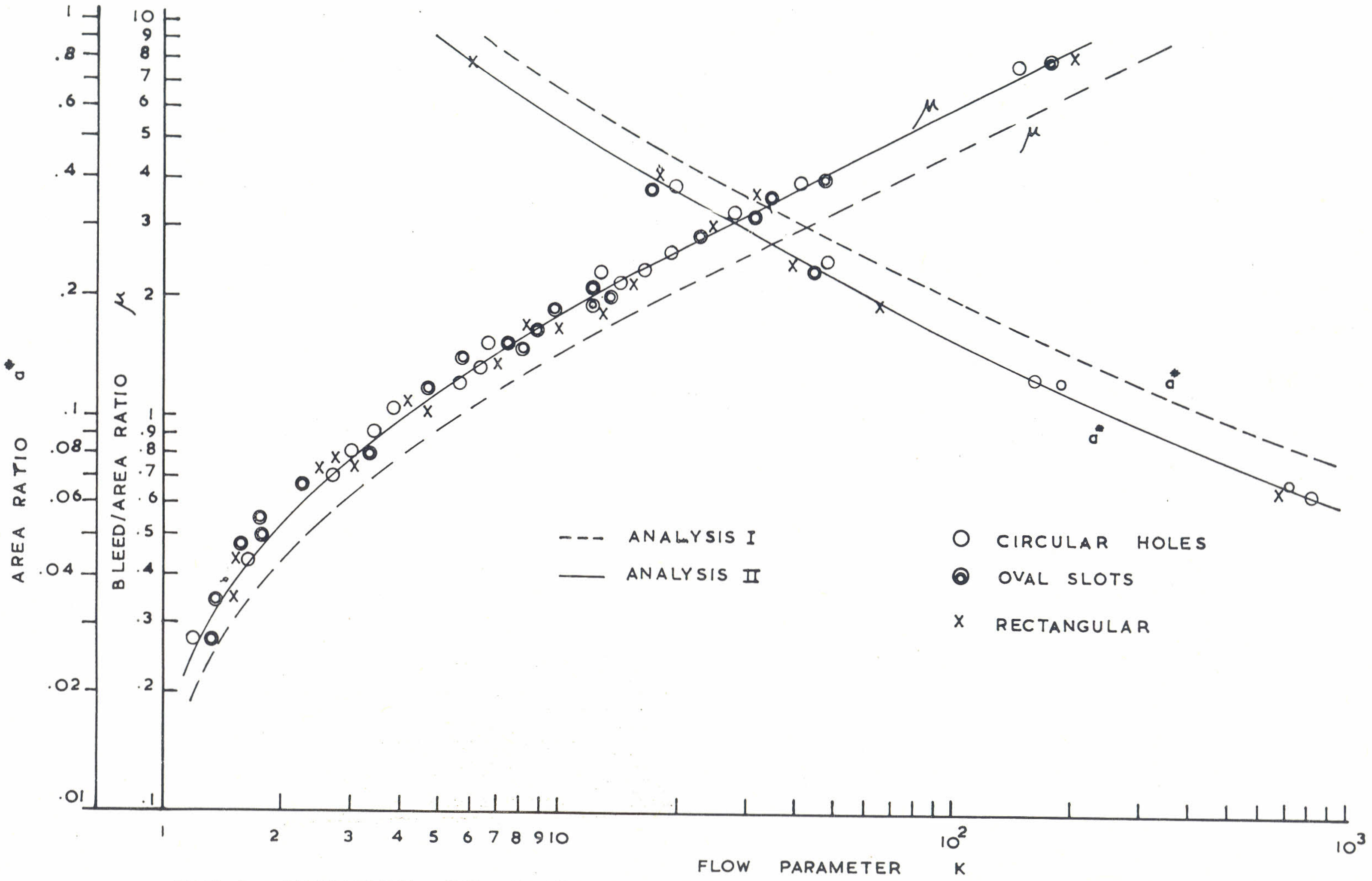

FIG. 6 – VARIATION OF FLOW PARAMETER WITH AREA AND BLEED/AREA RATIO

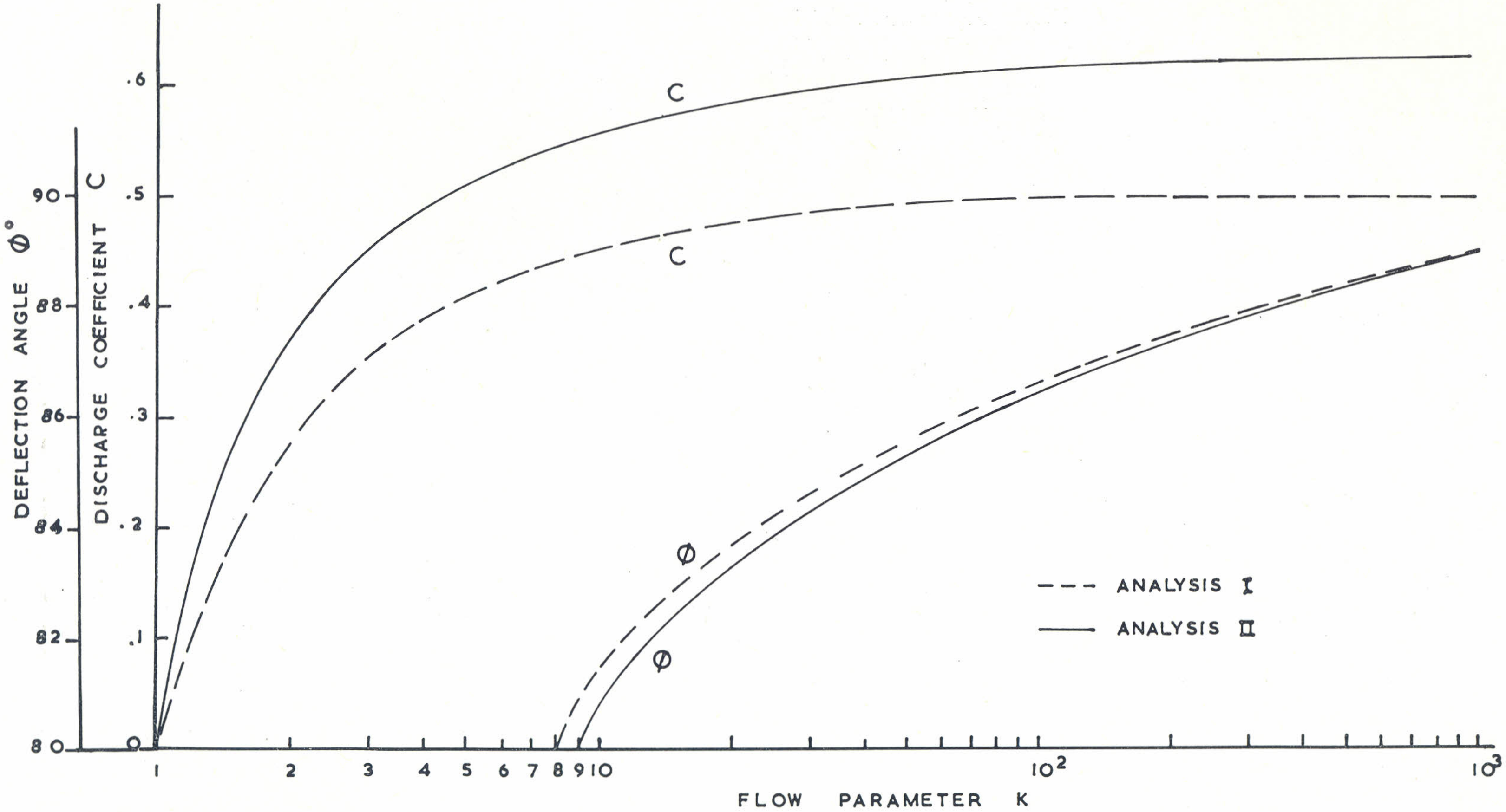

FIG. 7 _ VARIATION OF DISCHARGE COEFFICIENT AND DEFLECTION ANGLE WITH FLOW PARAMETER _ WITH CROSS FLOW

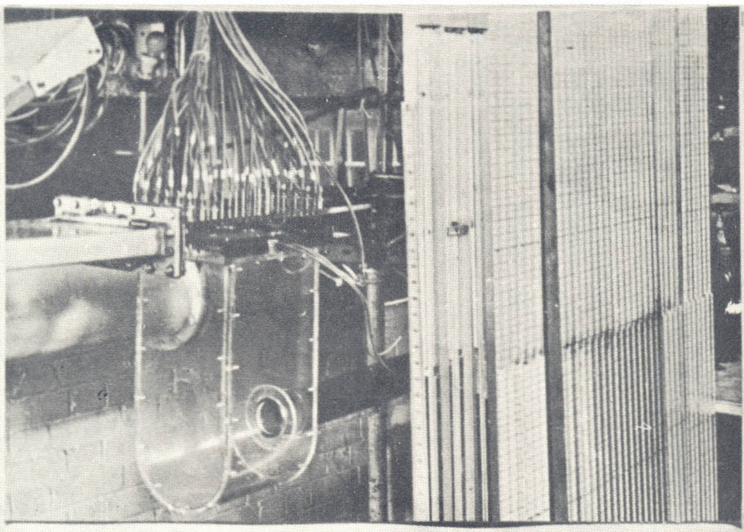

FIG. 8_ GENERAL RIG LAYOUT

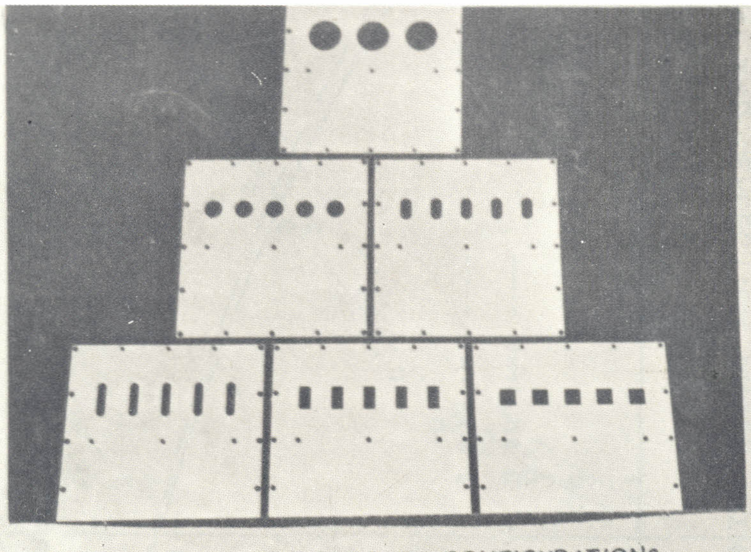

FIG. 9_ TEST HOLE CONFIGURATIONS

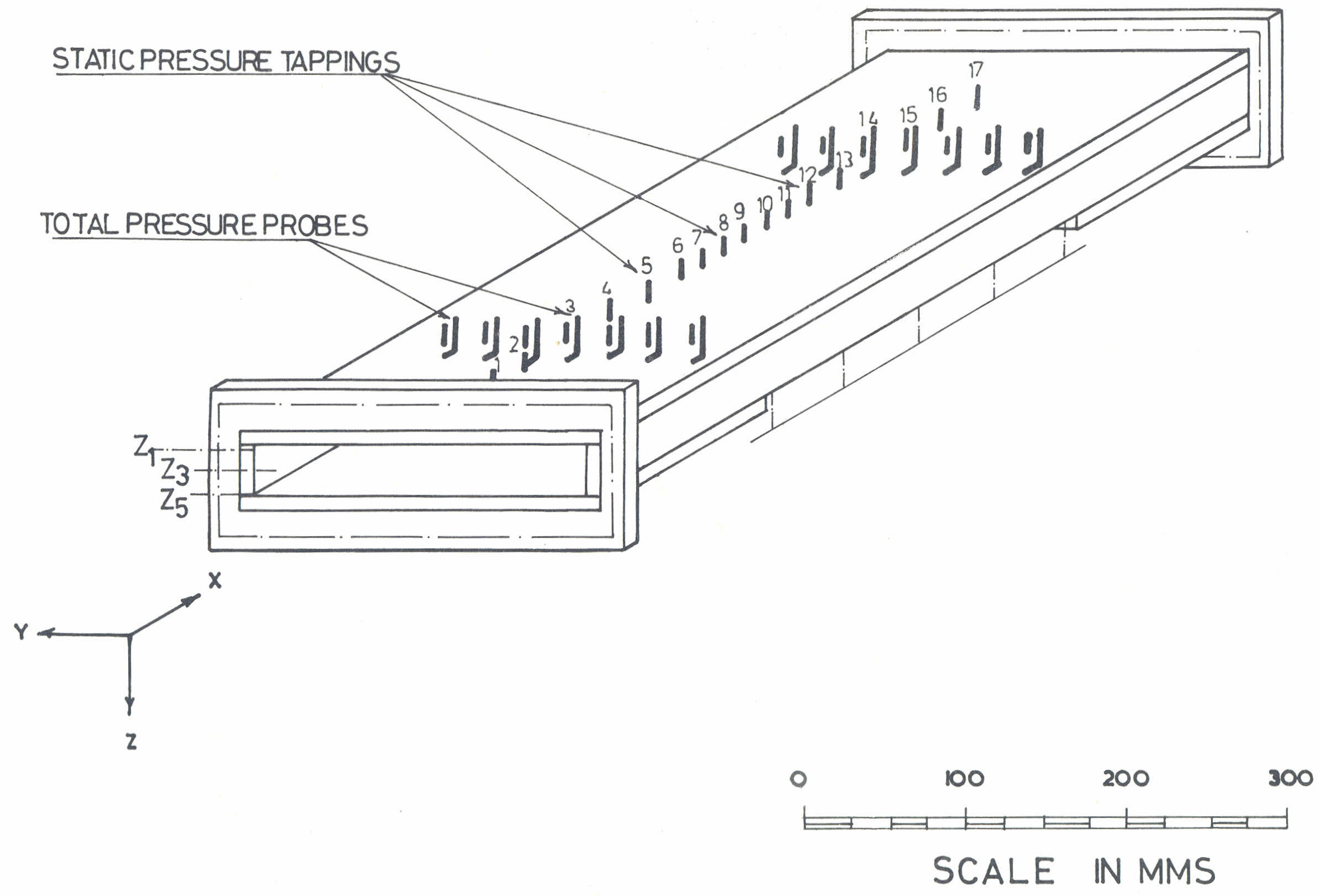

FIG.10_TEST SECTION AND INSTRUMENTATION

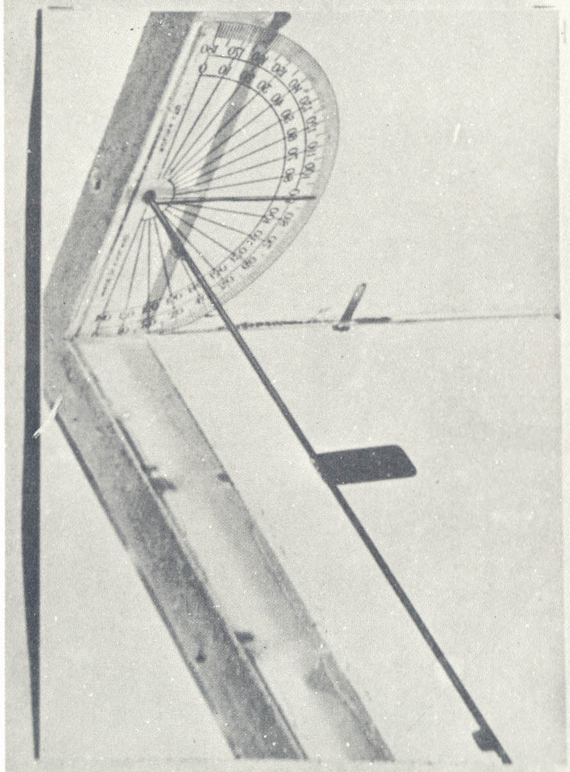

FIG.11_ DEFLECTION MEASUREMENT

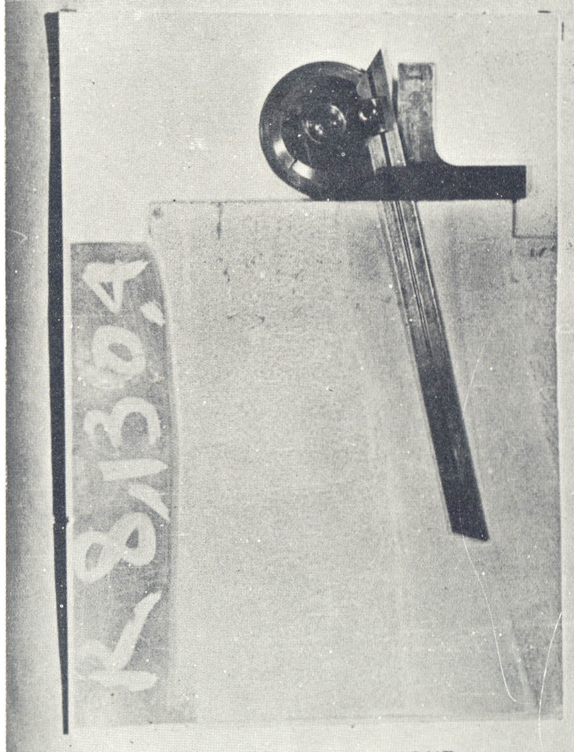

FIG.12_ POWDER TECHNIQUE

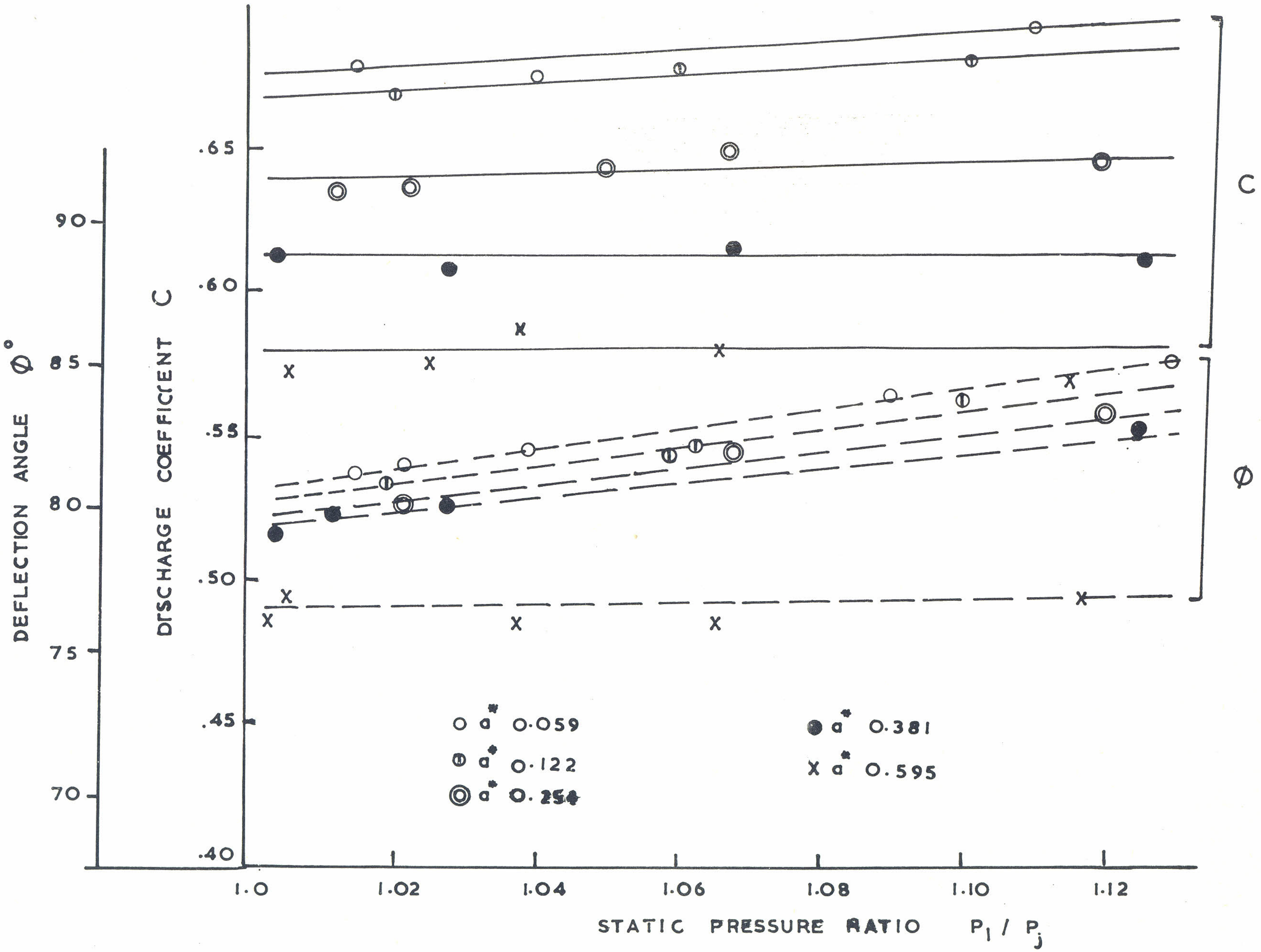

FIG_13. DISCHARGE COEFFICIENT & JET DEFLECTION FOR CIRCULAR HOLES

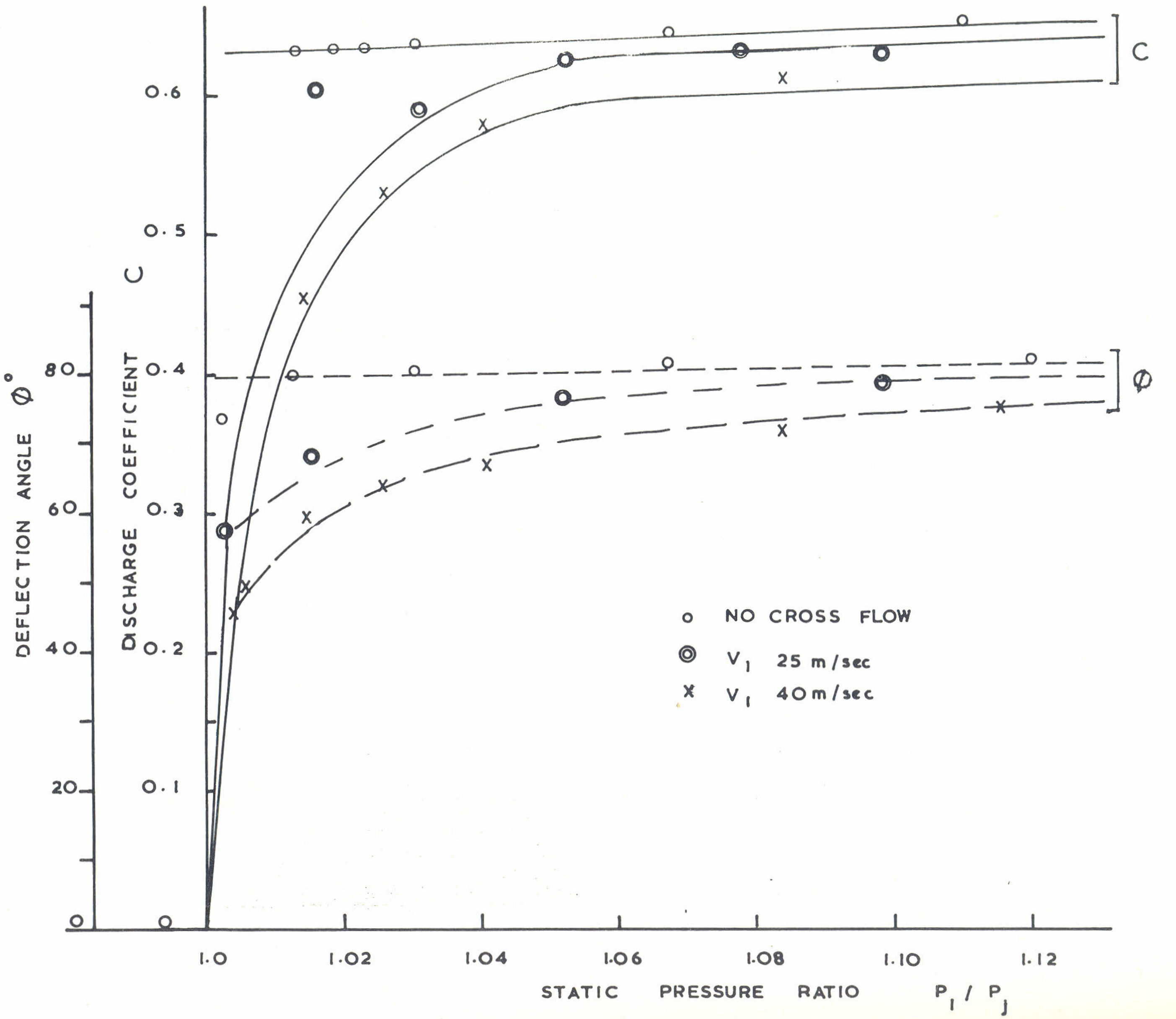

FIG.14_DISCHARGE COEFFICIENT & JET DEFLECTION FOR CIRCULAR HOLES

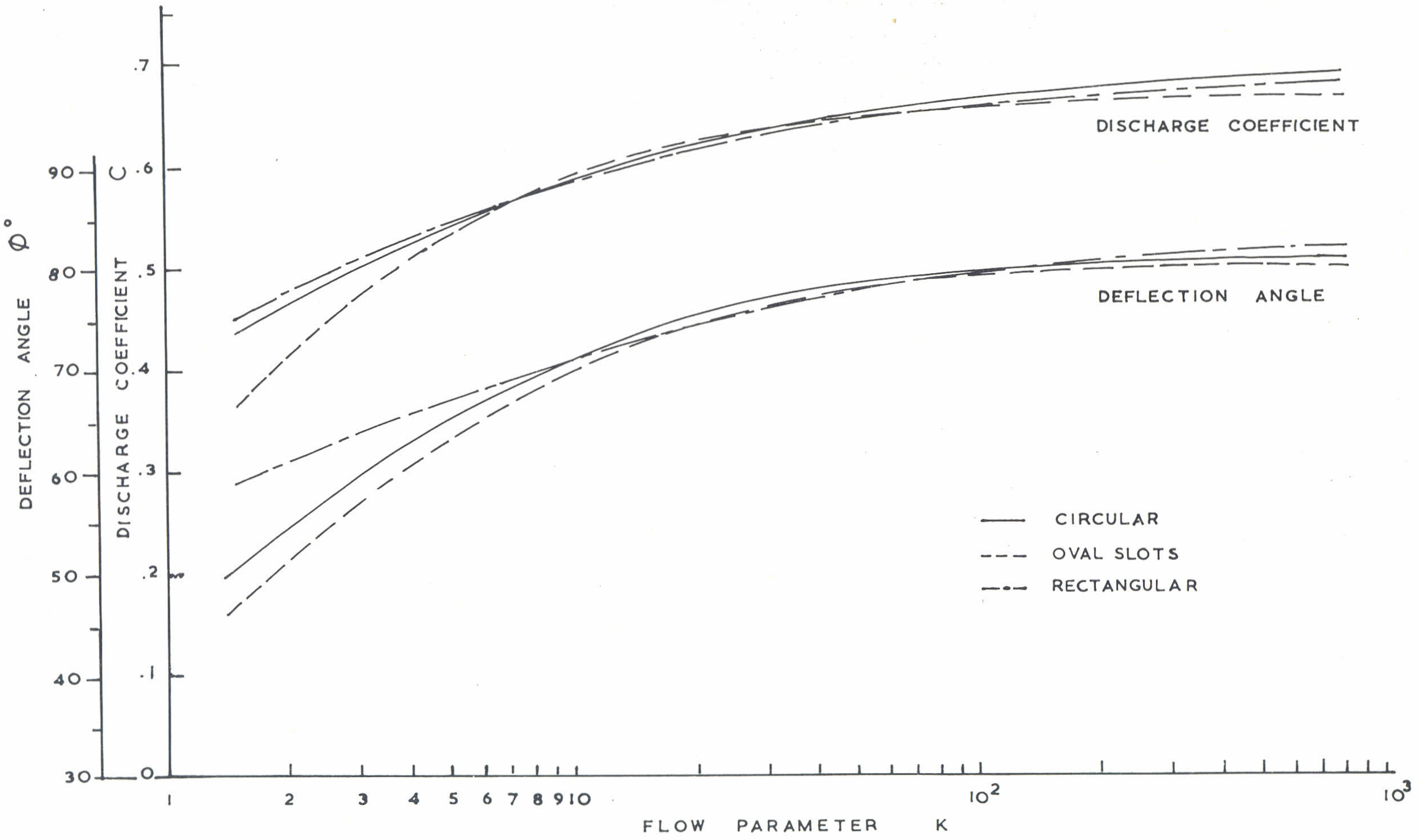

FIG. 15 – DISCHARGE COEFFICIENT AND JET DEFLECTION VERSUS FLOW PARAMETER

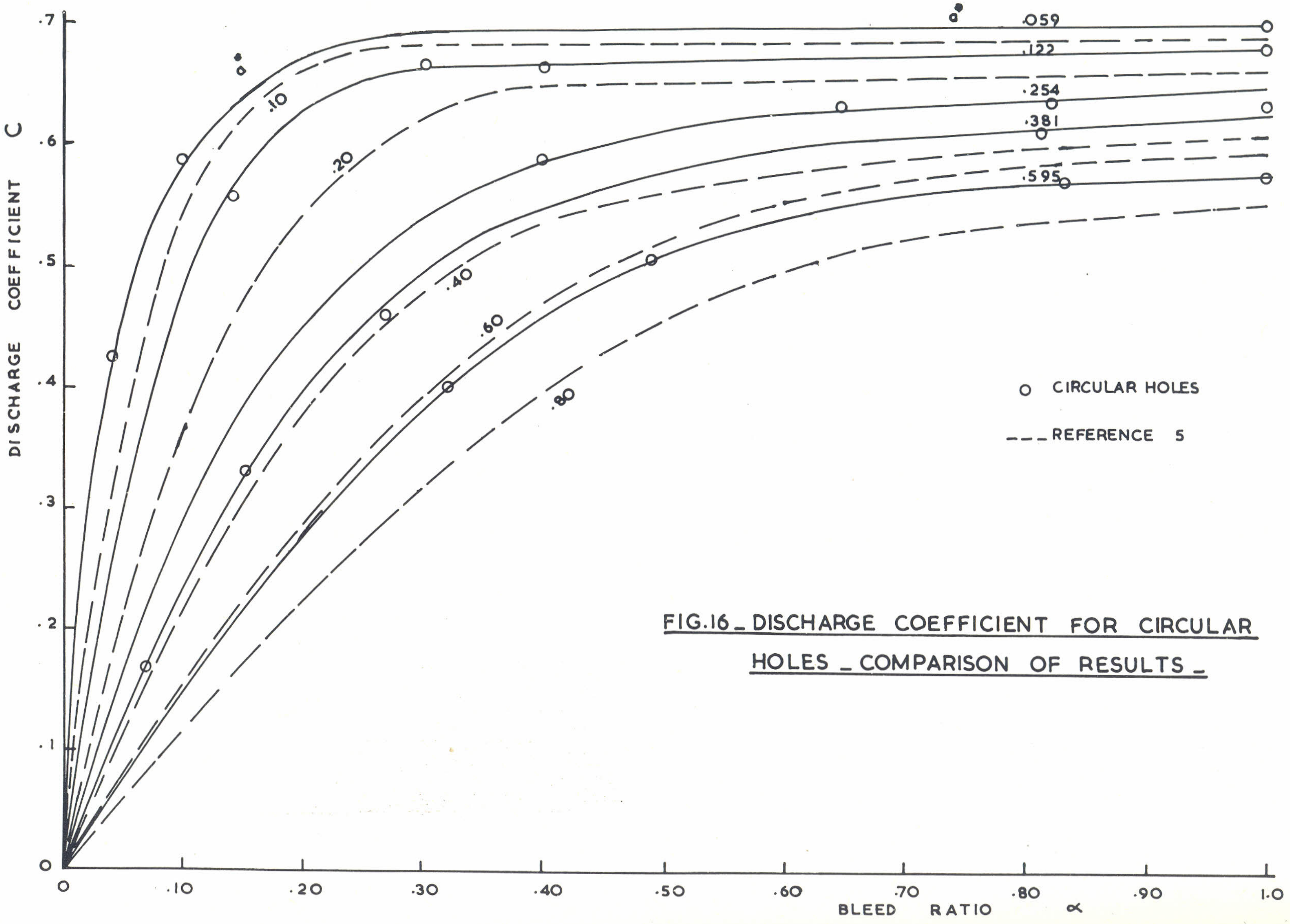

FIG.16 _ DISCHARGE COEFFICIENT FOR CIRCULAR HOLES _ COMPARISON OF RESULTS _

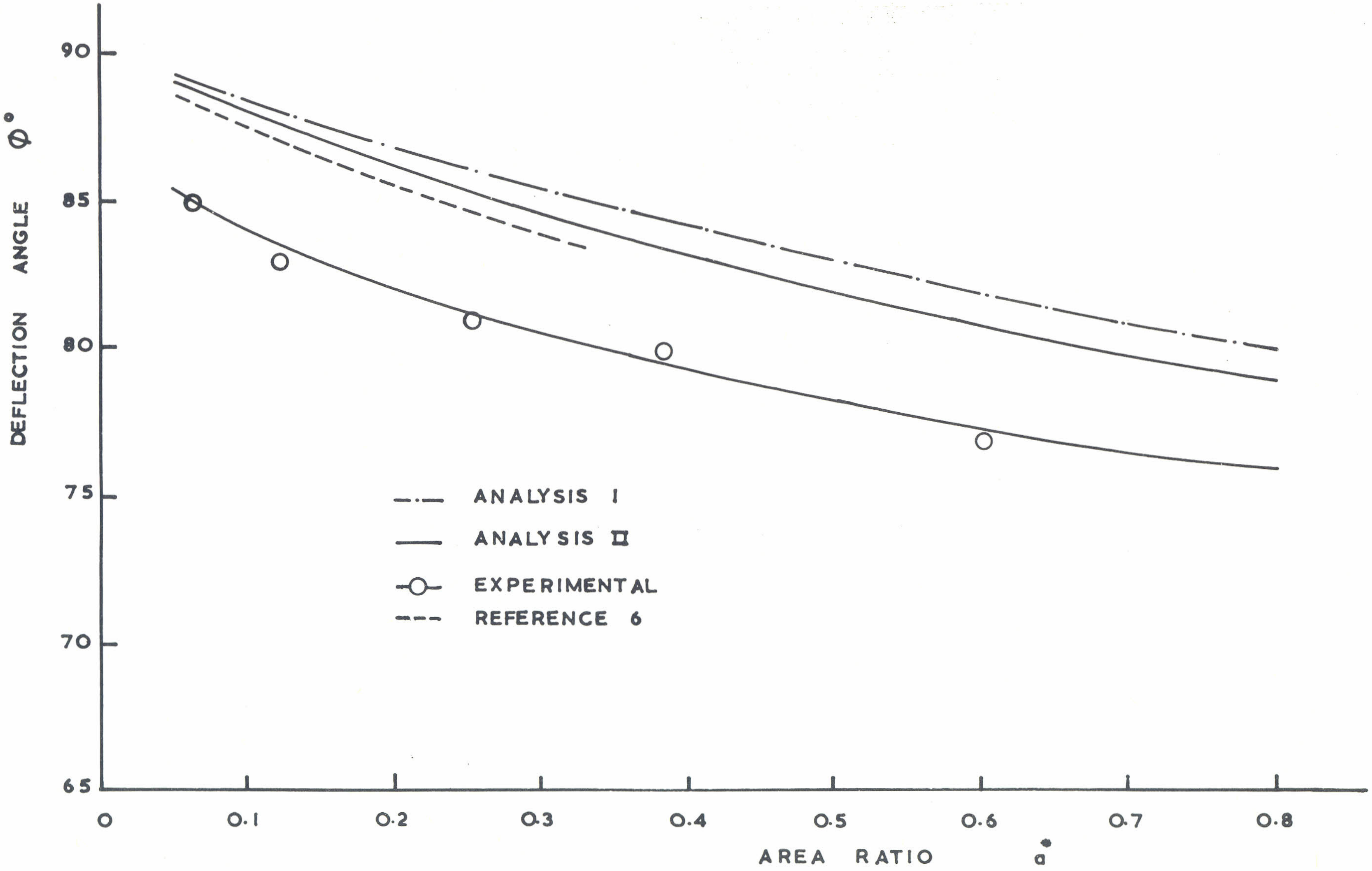

FIG.17 _ JET DEFLECTION FOR CIRCULAR HOLES _ COMPARISON _

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