C.P. No. 206
(14,871)
A.R.C. Technical Report

C.P. No. 206
(14,871)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
CURRENT PAPERS

Experiments on a Slotted Wall Working Section in a Wind Tunnel.

By

F. Vandrey and K Wieghardt

LONDON · HER MAJESTY'S STATIONERY OFFICE
1955

TWO SHILLINGS NET

C.P. No. 206

ADMIRALTY RESEARCH LABORATORY

A.R.L./R.4/G/HY/4/1

Experiments on a Slotted-Wall Working Section in a Wind Tunnel.

- By -

F. Vandrey and K. Wieghardt

18th March, 1952

Abstract

The present investigation was undertaken in order to develop a test section for a planned water tunnel with the correction properties of a free jet, but with a considerably greater length than a conventional open working section.

The experiments were carried out in air (V = 96 f.p.s.) with a jet of 5" diameter and 30" length, enclosed in a cage of 16 longitudinal rods with an opening ratio of 18% of the total boundary. The cage was surrounded by a rigid cylinder of 12½" diameter representing the outer boundary of the water tunnel.

The main results were: The velocity distributions of the jet in the cage are about the same as in a free jet at half the distance from the nozzle. The static pressure in the cage is constant. Pressure distributions of models in the cage are the same as in a free jet. Even considerable alterations of the design and deformations of the cage have practically no influence on the results.

Introduction

1. The work described in this report was undertaken to assist in evolving a suitable form of working section for a water tunnel intended for the testing of long bodies (Fineness ratio 1/10).

2. A theoretical investigation[1] showed that the tunnel corrections on long streamlined bodies of revolution are much greater and more variable in a closed section than in a free jet. The advantage of the free jet is, however, off-set by the rapid turbulent dissolution of the jet which makes only a short working section possible. It was therefore decided to explore the possibility of delaying the dissolution of the jet by enclosing it in a cage of longitudinal bars.

3. A cage of this type can be considered as a partly open, partly closed boundary of the tunnel. Generally, the corrections of such tunnels may be expected to be between those of a closed tunnel and of a free jet*.

In the present case, however, a cage with a comparatively great number of bars will have to be used in order to maintain the angular symmetry of the pressure distribution. Pistolesi has shown that the

corrections/

---

*In fact, such arrangements have been recommended for the design of tunnels with zero correction, the signs of the correction being opposite in the closed and open tunnel (cfr. Ref. (2)).

corrections of a mixed boundary converge always towards those of a free jet if the number of the rigid parts is increased and the opening ratio kept constant[3]. This result assures that for a moderate opening ratio, where the losses of energy in the gaps and the influence of imperfections of manufacture are small, the corrections are practically those of a free jet, provided that the number of the bars is sufficiently great.

4. A physical explanation of Pistolesi's result can be given in the following way: In a closed tunnel, any pressure distribution on the boundary is possible, depending only on the model in the tunnel. In an open tunnel, the pressure on the boundary is always constant and equals the pressure outside the jet whichever model may be in the tunnel. If a single slot is cut into the wall of a closed tunnel, the pressure along this slot will be the constant outside pressure. If a sufficient number of slots is distributed over the boundary of a closed tunnel, the constant outside pressure is enforced on so many lines of the boundary that the pressure on its rigid parts between the slots cannot differ much from the value outside the tunnel, i.e., is practically constant on the whole boundary. This being the essential feature of a free jet, the slotted wall will then behave like the boundary of an ideal free jet.

5. Preliminary tests were carried out with a jet of 5" diameter, enclosed in a cage of 25 brass rods (diameter $\frac{1}{2}$", length 12") held by flanges at the end[4]. The velocity distribution of the jet, the static pressure and pressure distributions of two Rankine bodies were measured in the cage and compared with measurements in a conventional free jet of the same diameter. The results confirmed the expectation that the jet in the cage has the same corrections as a free jet, but can be used to a much greater length.

6. The present report gives measurements in an improved model of a slotted-wall test section. Some observations are added on the effect of alterations of the design, which was found to be negligible within wide limits.

Experimental Arrangement

7. The principle of the construction of the slotted-wall section is shown in figure 1. The jet issuing from the nozzle (diameter 5") is "guided" by 16 rectangular bars (length 30", cross-section 0.8" x 3/16", their width being tapered down to 0.4" along the last 8" of the length). The gaps between the bars were 0.18" wide on the untapered part, leaving 18.5% of the boundary open for the compensation of pressure differences. On the tapered part, the gaps widened uniformly to 60% of the boundary at the end of the working section.

8. In a water tunnel, there must be an outside rigid boundary in any case, therefore a cylinder of 12$\frac{1}{2}$" diameter was fixed round the cage. In this way, a reservoir is produced in which only slow air flow occurs. Within the last 8" of its length, the cross-sectional area of the reservoir is reduced in order to accelerate the air before it combines with the main flow through the wider gaps. At the end of the model working section, the jet was discharged into the open air.

9. The effect of several alterations of this basic arrangement was investigated. This will be discussed below together with the results for the basic design.

Experiments/

Experiments in the Empty Tunnel

Velocity Distributions

10. The velocity distribution was measured in the empty tunnel and compared with measurements in a free jet. The velocity of the jet was 96 f.p.s., corresponding to a Reynold's number of 2.5×10^5. At the end of the reservoir, three different contractions were tested (to be referred to as long contraction, short contraction and no contraction, figure 2).

11. Figure 3 shows the velocity profiles at various distances from the nozzle (15", 22" and 30", corresponding to 3, 4.4 and 6 diameters of the jet). At $x/D = 3$, the core of the jet in the cage has still 80% of its original diameter (45% for the free jet). At $x/D = 4.4$, the core of the free jet has just come to its end, whereas the jet in the cage has still a core of 0.6D. Even at $x/D = 6$, the enclosed jet has a core of 0.45D, equal to that of the free jet at $x/D = 3$.

12. The results were practically identical for all three contractions of the reservoir except at the end of the working section, where the reservoir without contraction produced a definitely inferior velocity distribution (figure 3c). The short contraction was, however, sufficient to avoid this undesired effect.

13. These results show that the bars considerably delay the dissipation of the jet and, roughly speaking, double the useful length of the working section.

Static Pressure

14. The static pressure in the tunnel was measured by pushing a long static tube along its axis. In addition, the static pressure in the reservoir was measured at various stations on its cylindrical part. Results were obtained with the three contractions, and tests were also done with the short contraction using bars of double thickness.

15. Figure 4 shows the distribution of the static pressure along the axis of the tunnel for all three contractions. Along the main part, p_{st} is practically constant. Near the nozzle, a slight rise of the pressure is to be noted, extending to a distance of about $\frac{1}{2}$ - 1 diameter of the jet. This is likely to be caused by an incomplete transformation of pressure energy into kinetic energy in the nozzle, a better shape of the nozzle can therefore be expected to reduce this effect. Another rise of the pressure is to be seen near the end of the working section, obviously caused by the contraction of the flow in the reservoir. This effect is not very strong in the case with no contraction, but the large drop in pressure and the rather poor velocity distribution at the end (figure 3c) indicate that the losses will be considerably greater for this form than for the others. For the two other contractions, the maximum rise of the pressure is about equal, but the interval of increased pressure is greater for the long contraction. The velocity distributions in the tunnel being practically equal in these two cases, the short contraction can be considered as giving slightly better results.

16. The static pressure in the case of the short contraction with the thicker bars (figure 3d) is slightly more variable than in the preceding cases, but the variations are still small enough to be neglected for many practical applications. The losses in the gaps are of course greater in this case, this may be responsible for the small irregularities.

17./

17. The static pressure in the reservoir was found to be practically constant in its cylindrical part, but slightly smaller than in the tunnel due to the losses of energy in the gaps between the bars. In the three cases with thin bars, the difference

$$\Delta p_{st} = p_{st\ tunnel} - p_{st\ reservoir}$$

was found to be

$$\Delta p_{st} = +0.005 \frac{\rho}{2} V^2$$

i.e., by mere coincidence, about the theoretical value of the pressure in a free jet surrounded by still air (ref. (5), p. 251-52). In the case of thick bars the pressure difference was

$$\Delta p_{st} = +0.009 \frac{\rho}{2} V^2$$

18. Generally, the difference of p_{st} in the tunnel and in the reservoir is so small that it can be neglected for many practical purposes. The static pressure in the tunnel can then be assumed to equal the static pressure in the reservoir, the same assumption as is usually made with a conventional free jet where the excess pressure in the jet is of the same order. If a greater accuracy is required, a small correction has to be added to the pressure in the reservoir which will depend on the performance of the cage and, for tests with a model, mainly on the blockage-ratio of the model in the tunnel. The present experimental arrangement did not permit a reliable determination of this second part of the correction, the investigations on this subject will be resumed with the final water tunnel.

Loss of Energy in the Empty Working Section

19. The pressure being almost equal at the beginning and at the end of the slotted-wall section, the loss of energy can be calculated from the velocity distribution at the end (figure 2c). The kinetic energy passing through a cross-section of the tunnel per unit of time is

$$E = \int_0^{D/2} 2\pi\rho\, V^3(r)\, r\, dr\ ,$$

where $V(r)$ is the velocity at the distance r from the axis. This gives the loss of energy in the working section

$$\frac{\Delta E}{E} = 2\int_0^1 \left(1 - \frac{V^3(r^*)}{V_0^3}\right) r^*\, dr^*$$

$$r^* = \frac{r}{D/2}$$

The/

The numerical evaluation of this integral gives

$$\frac{\Delta E}{E} \approx 0.26 \qquad \text{for the slotted wall (long or short contraction)}$$

and

$$\frac{\Delta E}{E} \approx 0.54 \qquad \text{for a free jet of equal length.}$$

$$\frac{\Delta E}{E} \not\approx 0.23 \qquad \text{for a free jet of half the length of the slotted wall section.}$$

20. The losses in a free jet can still be somewhat reduced by a collector, as a considerable part of the moving air is passing through the plane $x = 6D$ at a greater distance from the axis than $r = D/2$. The total energy of the free jet at $x = 6D$ is

$$\frac{E}{E_o} = 2\int_o^{\infty} \frac{V^3(r^*)}{V_o^3}\, r^*\, dr^* = 0.62 = 1 - 0.38$$

Part of the difference $0.54 - 0.38 = 0.16$ can therefore be recovered in a suitable collector.

21. The losses in a closed circular working section of equal dimensions can be estimated from experiments on the flow through smooth pipes at high Reynolds numbers. On the assumption of fully turbulent flow, the loss between two cross-sections of a pipe is

$$\frac{\Delta E}{E_o} = \frac{\Delta p}{\frac{\rho}{2}V^2} = \lambda(\mathrm{Re})\,\frac{L}{D}$$

with $\lambda = 0.015$ for $\mathrm{Re} = 250000$ (ref. (6), p. 149). This gives with $L/D = 6$

$$\frac{\Delta E}{E_o} \approx 0.09 \qquad \text{for a closed working section of equal length.}$$

In fact, the flow in the working section will not be turbulent except near the wall. But assuming on the other hand a thin turbulent boundary layer on the wall, beginning at the nozzle, and an almost constant pressure, the drag of the wall should be approximately that of a flat plate of total surface πDL moving through the air with the velocity V_o. This second assumption gives after simple calculation 10% loss of energy in the closed working section*, i.e., practically the same value.

22./

---

* Drag coefficient of flat plates $C_D = 0.074\left(\frac{V_o L}{\nu}\right)^{-1/5}$ for fully turbulent boundary layer (ref. (6), p.175).

22. According to these results, the loss in the slotted wall is between that in a closed tunnel and that in a free jet of the same length, it equals approximately the loss in a free jet with half the length of the slotted wall. The value of 26% for the empty slotted wall tunnel is still rather high. Considering, however, that the planned water tunnel will be operated at a much higher Reynolds number ($\sim 5 \times 10^6$ instead of 2.5×10^5) and that the surface of the wood bars used in the present experiments was rather rough, the losses of energy can be expected to be appreciably smaller for the final design.

Summary of Further Experiments with the Empty Tunnel

Diameter of the Reservoir

23. From the practical point of view, the diameter of the reservoir should be as small as possible. If it is too small, however, there will be an appreciable flow in the reservoir, the behaviour of the working section will then tend to resemble that of a closed tunnel.

24. Before deciding on a diameter of 2.5D where D is the diameter of the jet, two reservoirs of 2D and 3D diameter were tested. A 2D reservoir has been used in the preliminary experiments of ref. (4) with a cage of 2.4D in length. In the present case, where the length of the cage was 6D, a slight gradient of the static pressure was produced along the axis of the tunnel which indicates that the reservoir was too small in diameter. The 3D reservoir was found to be satisfactory, a further experiment showed then that the diameter of the reservoir could be safely reduced to 2.5D. It is not impossible that a reservoir of 2D is sufficient for the planned water tunnel, but this cannot be decided without experiments at much greater Reynolds numbers than that of the present investigation.

Number of Rods, Opening Ratio of the Cage

25. The preliminary experiments[4] were carried out with a cage of 25 circular rods and gaps between them of 28% of the total boundary. In order to obtain a longer working section than the 2.4 diameters used in (4), it was thought advisable to reduce the opening ratio of the cage, at the same time increasing the number of the rods to make sure that the correction properties of the working section remained unaltered (cfr. section 3 above and ref. (3)). Two cages each having 36 rods, circular section in one case and square in the other, with an opening ratio of 18% were therefore tested. Both were found to be satisfactory and to give practically the same results.

26. Since it will be necessary to observe and photograph cavitation phenomena in the water tunnel the cage will require to be made of transparent material, and, furthermore, to obtain the best optical conditions, the number of bars should be kept to a minimum. The 36 bars were, therefore, reduced to 18 by removing alternate bars, the opening ratio being restored to 18% by fixing strong cardboard strips to the remaining bars. The results for this cage were practically the same as those with 36 rods. The only difference was that, due to the cardboard being much thinner than the former bars the losses in the gaps were so small that the difference of the static pressure in the reservoir and in the tunnel became too small to be measured. This confirms the expectation that the use of thicker rods with the same geometric opening ratio amounts to a certain reduction of the "effective" or "aerodynamic" opening ratio of the cage.

27. The number of the rods was then further reduced to 12 with opening ratios of 18% and 14% and to 9 with an opening ratio of 18%. The results with 12 rods and 18% opening ratio were still quite good, but both the reduction of the opening ratio to 14% and of the number of rods to 9 produced a slight gradient of the static pressure in the tunnel. This indicates that 12 rods with 18% opening ratio is near the lower limit for which good results can be obtained with a slotted wall under the conditions of the present investigation. For experiments with models in the tunnel, the losses can be expected to be somewhat greater than in the empty tunnel. In order to allow for this, it was decided to use 16 rods and an opening ratio of 18% for the final design.

End of the Working Section

28. Some of the air moving in the tunnel enters the reservoir through the gaps between the bars. Near the end of the working section, it has to leave the reservoir again for reasons of continuity. In order to facilitate this and to avoid the formation of a complicated flow pattern in the reservoir with a back flow along its outer boundary and unnecessarily high velocities, it was first thought advisable to leave a gap between the end of the cage and the end of the reservoir. In this first design, the ends of the bars were held together by a streamline-shaped ring. Although being effective in avoiding back flow in the reservoir, this arrangement had the disadvantage that the wake of the ring disturbed the velocity distribution at the end of the working section. This disturbance was undesirable as it was likely to reduce the efficiency of the adjoining diffuser in the water tunnel.

29. It was then found that a back flow in the reservoir could be suppressed without appreciable disturbance of the velocity distribution by continuing the bars to the end of the reservoir and by tapering them at the downstream end in order to widen the gaps. This form was adopted for the final design of the working section.

Pressure Distributions of Four Models in the Slotted Wall Section and in a Free Jet

Description of the Models

30. The shapes of the models tested in the following experiments are given in figure 5. Their main dimensions were:

Model	Large long	Large short	Small long	Small short
Length (1):	12"	6"	6"	3"
Diameter (d):	1.5"	1.5"	0.75"	0.75"
Fineness ratio (d/1):	1/8	1/4	1/8	1/4
Blockage ratio $(d/D)^2$:	9%	9%	2.25%	2.25%
1/D	2.4	1.2	1.2	0.6

The head and the tail of the bodies were similar to the head of a semi-infinite Rankine body (point source in parallel flow). A common head and tail were used for the two large bodies and a similar common head and tail for the two small bodies. The bodies were supported at the tail, where they were screwed to a steel tube of $\frac{1}{2}$" or $\frac{1}{4}$" diameter.

Experimental Technique

31. In the slotted wall, the models were placed so that their centre was at the centre of the working section, i.e., at a distance of 3D from the nozzle. In the free jet, they were placed so that the head was at a distance of $\frac{1}{2}$D from the nozzle. All pressure holes but one were sealed with soft wax and the pressure measured with a manometer filled with alcohol and inclined at an angle of 11.5° to the horizontal in order to increase the sensitivity. The static pressure was measured at various stations along the reservoir in the case of the slotted wall, and assumed to be that of the surrounding air in the case of the free jet. The accuracy of the measurements was of the order of $\frac{1}{2}$% to 1% of the head.

Correction of the Results

32. The purpose of the present investigation being a comparison between the slotted wall and a free jet, no tunnel corrections were applied to the experimental results. The only correction which had to be used was the difference of the static pressure in the reservoir and in the slotted wall, or in the surrounding air and in the free jet, respectively.

33. For the free jet, Görtler's theoretical correction

$$\Delta p_{st} = p_{st\ jet} - p_{st\ air} = + 0.0046 \frac{\rho}{2} V^2$$

was used (ref. (5)). For the slotted wall, it was found sufficient to use the correction of the empty working section (cfr. paragraph 17 above). More accurate measurements are of course likely to show a certain influence of the blockage ratio on this correction.

Pressure Distribution of the Models without Incidence

34. The pressure distributions of the four models at zero incidence are shown in figure 6 (large models) and figure 7 (small models). The differences between the results in the slotted wall and in the free jet are in general less than 1% of the head and do not show a pronounced regularity, the slotted wall and the free jet can therefore be considered as giving the same results within the accuracy of the present measurements.

35. A variation of the position of the models in the tunnel had no effect on the results. The two large models were also tested in the slotted wall with bars of double thickness. Taking into account the greater correction of p_{st} for this case $\left(\Delta p_{st}' = + 0.009 \frac{\rho}{2} V^2\right)$, the results were practically the same as for single-thickness bars. In order to see the influence of deformations of the cage, the bars were deflected inwards halfway along their length, the diameter of the cage thereby being reduced to about 90%. The large long model was tested in this deformed cage; no appreciable influence of the deformation could be observed.

Pressure Distribution with an Angle of Incidence

36. The two large models were tested in the slotted wall and in the free jet with angles of incidence of 7° (long model) and 8° (short model). The result is given in figure 8. Again, the slotted wall gives the same results as the free jet within the accuracy of the present experiments.

Conclusion/

Conclusion

37. The results of the present investigation can be summarized as follows:-

(a) The velocity distributions of the jet in the cage are about the same as in a free jet at half the distance from the nozzle.

(b) The static pressure is constant inside the cage, except very near to its ends. It is only slightly higher than in the reservoir. This difference depends mainly on the design of the cage, the influence of the blockage ratio of models is very small for values < 10%

(c) The pressure distributions of models in the slotted wall are the same as in a free jet, even with a considerable angle of incidence.

(d) The loss of energy in the slotted wall is about the same as in an open working section of half its length.

(e) For the design of a slotted wall test section of a length of about 6 diameters of the jet, the use of 15-20 rods with an opening ratio of about 20% will give satisfactory results. If the tunnel has to be fitted with an outer rigid boundary (water tunnel or variable pressure wind tunnel) a diameter of the reservoir of $2\frac{1}{2}$ diameters of the jet will be sufficient. In this case, the gaps between the bars should be widened towards their ends and the end of the reservoir should have a contraction in order to allow the flow in the reservoir to join the main flow and to produce a better velocity distribution at the entrance of the diffuser.

(f) The influence of even considerable alterations of the design (number and thickness of the rods, opening ratio etc.) and of deformations of the cage on the results obtained with this type of working section was found to be very small and negligible within wide limits.

38. The results (a) - (c) can be considered as experimental evidence that a slotted wall working section has the same corrections as a free jet, and has a much greater useful length than a conventional open working section. This will permit the testing of considerably larger models of elongated bodies than can be tested in a conventional free jet, or in a closed tunnel where the tunnel corrections would then become too great.

Acknowledgements

The authors wish to thank Mr. R. G. Lewis and Mr. A. S. Pitcher for their assistance with the experimental work.

References/

References

No.	Author(s)	Title, etc.
(1)	F. Vandrey	Theoretical corrections for long Rankine ovoids in a closed or open tunnel of circular cross-section. A.R.L. Teddington, Report A.R.L./R.2/G/HY/4/1.
(2)	W. F. Durand:	Aerodynamic theory. Vol. III, p. 294-297. Berlin, 1935.
(3)	E. Pistolesi	Sul interference di una galleria aerodinamica a contorno misto. Commentationes della Pontificia Academia, Vol. IV, No. 9 (1940).
(4)	F. Vandrey and K. Wieghardt	Wind tunnel with slotted walls. Preliminary tests. A.R.L., Teddington, Report A.R.L./R.1/G/HY/4/1. January, 1950. A.R.C. 13,032.
(5)	H. Görtler	Berechnung von Aufgaben der freien turbulenz. Zeitschr. f. Angew. Math. u. Mech. 22 (1942) 244-254.
(6)	L. Prandtl	Führer durch die strömungslehre. 2nd ed. Braunschweig 1944.

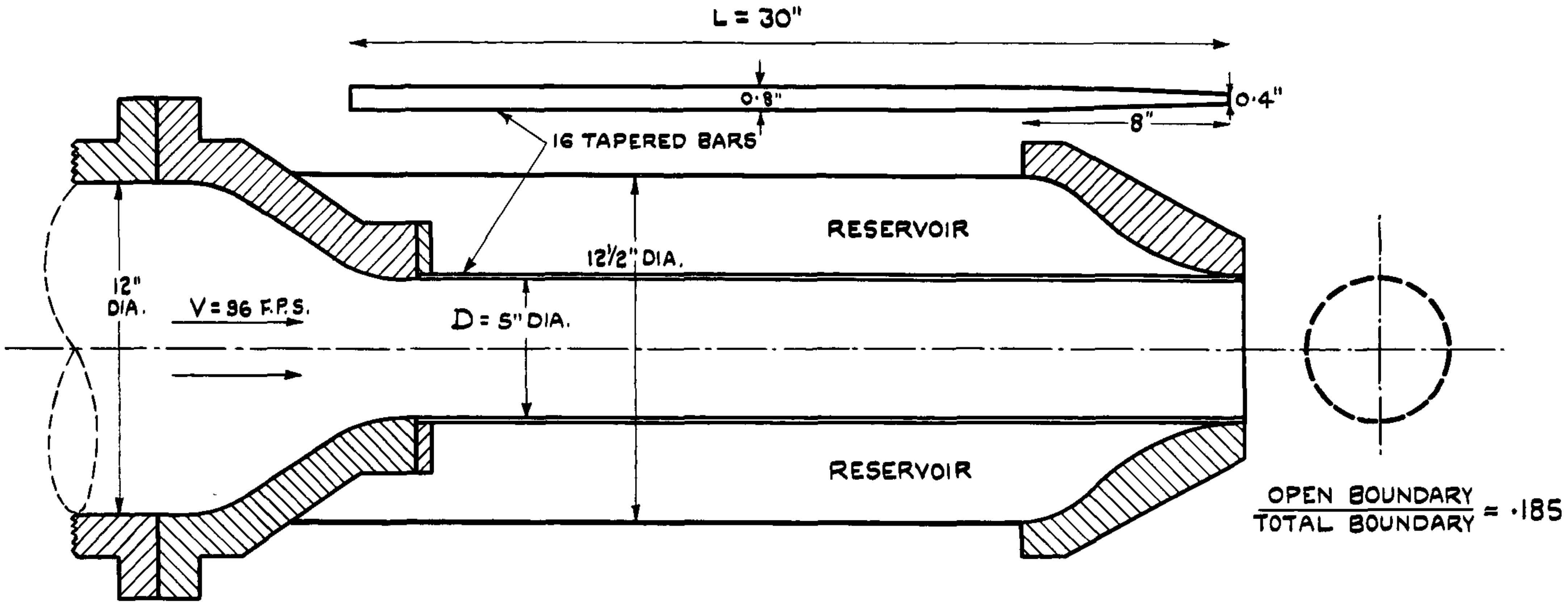
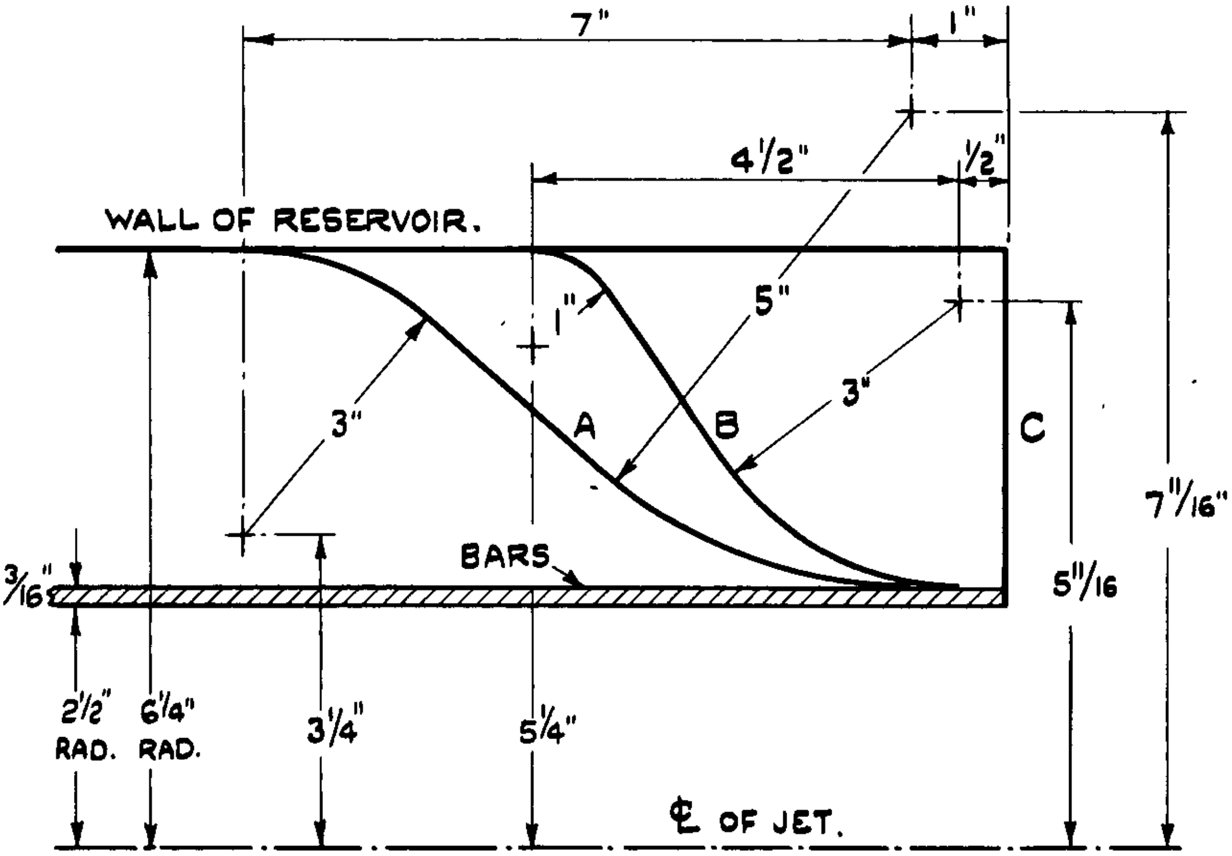


FIG. 1

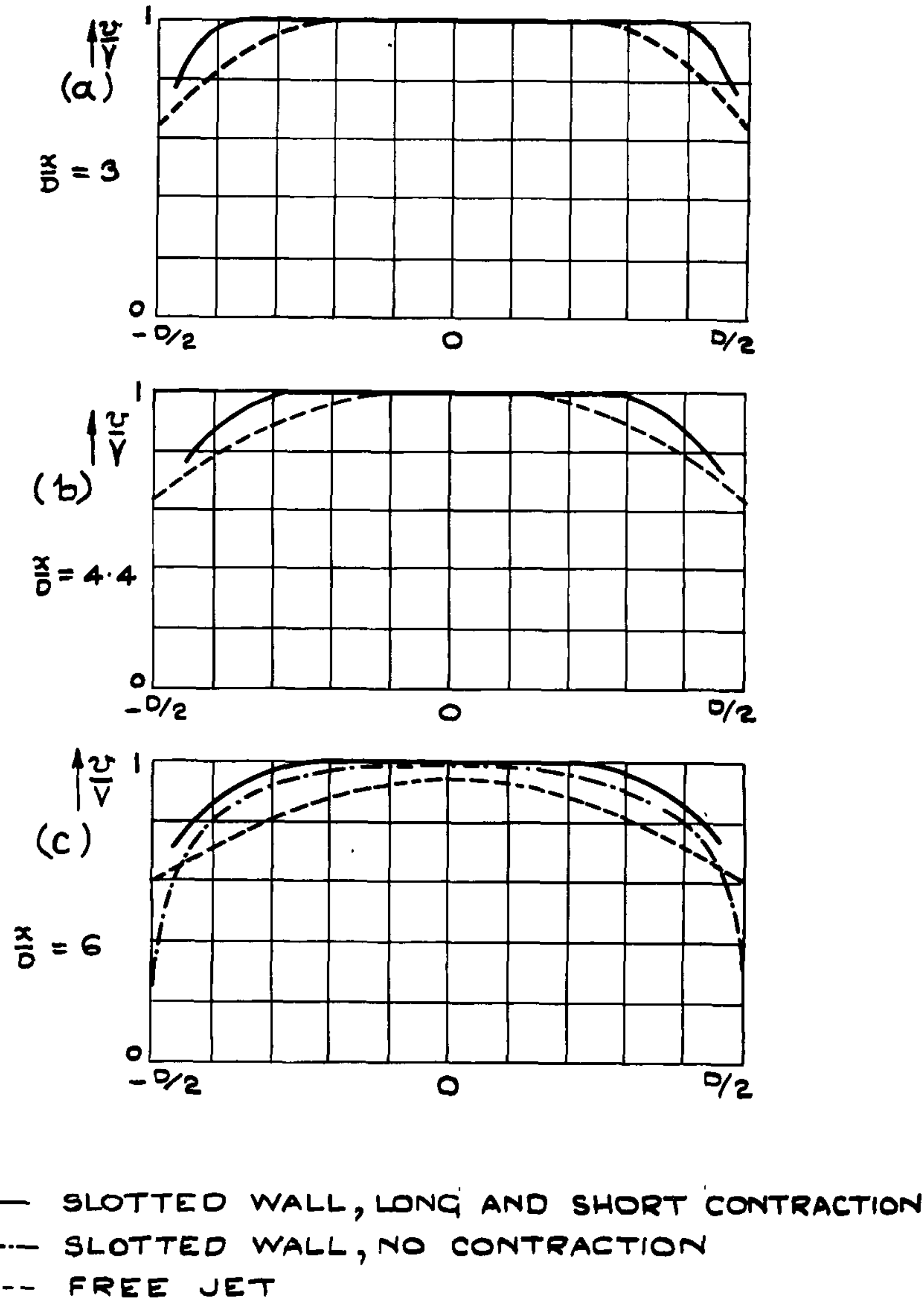
SLOTTED-WALL TEST SECTION.



A: LONG
B: SHORT } CONTRACTION.
C: NO

CONTRACTIONS OF THE RESERVOIR AT THE END OF THE TEST SECTION.

FIG. 2



VELOCITY PROFILES OF THE SLOTTED-WALL TEST SECTION AND OF A FREE JET.

FIG.3.

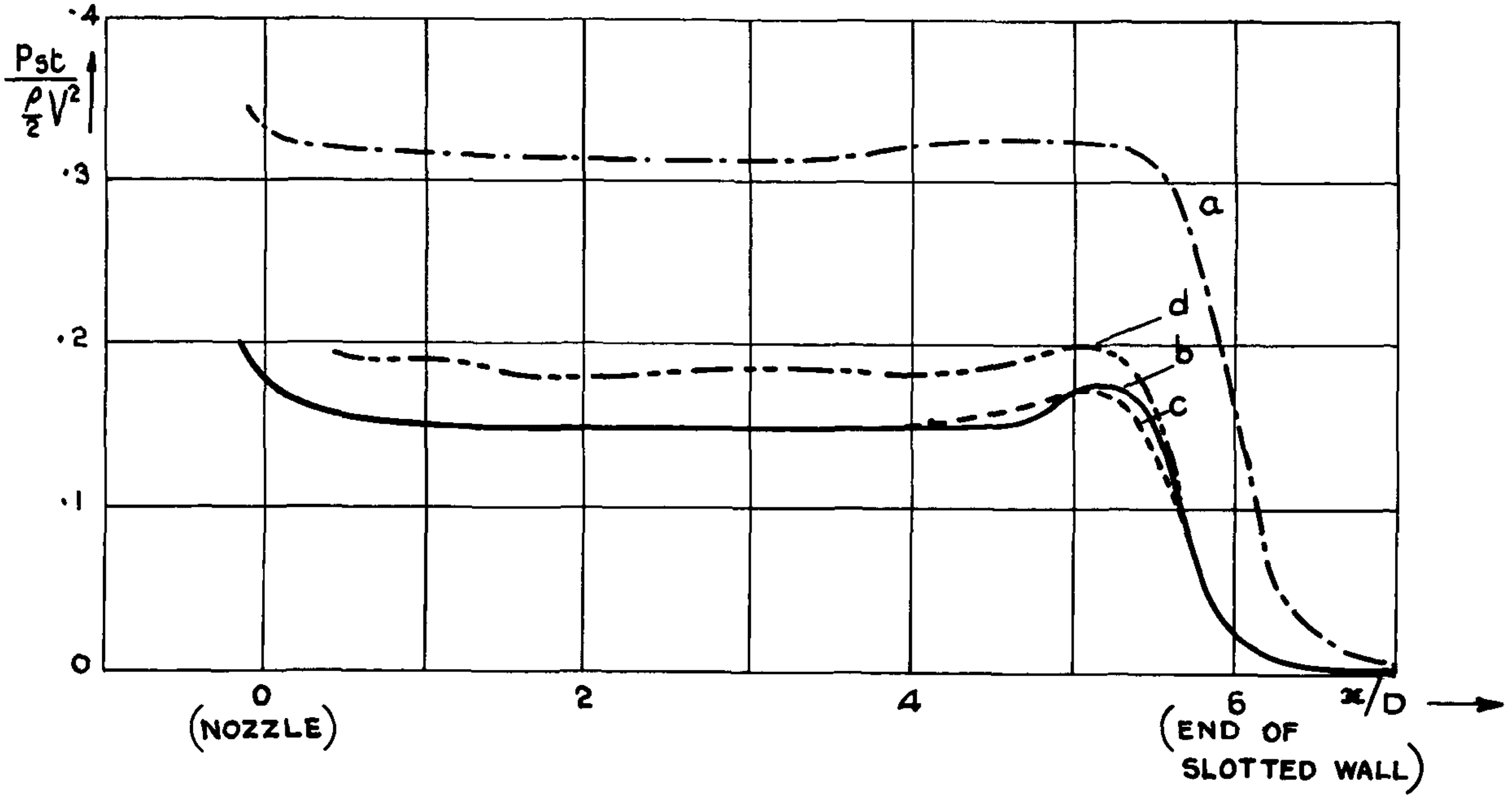
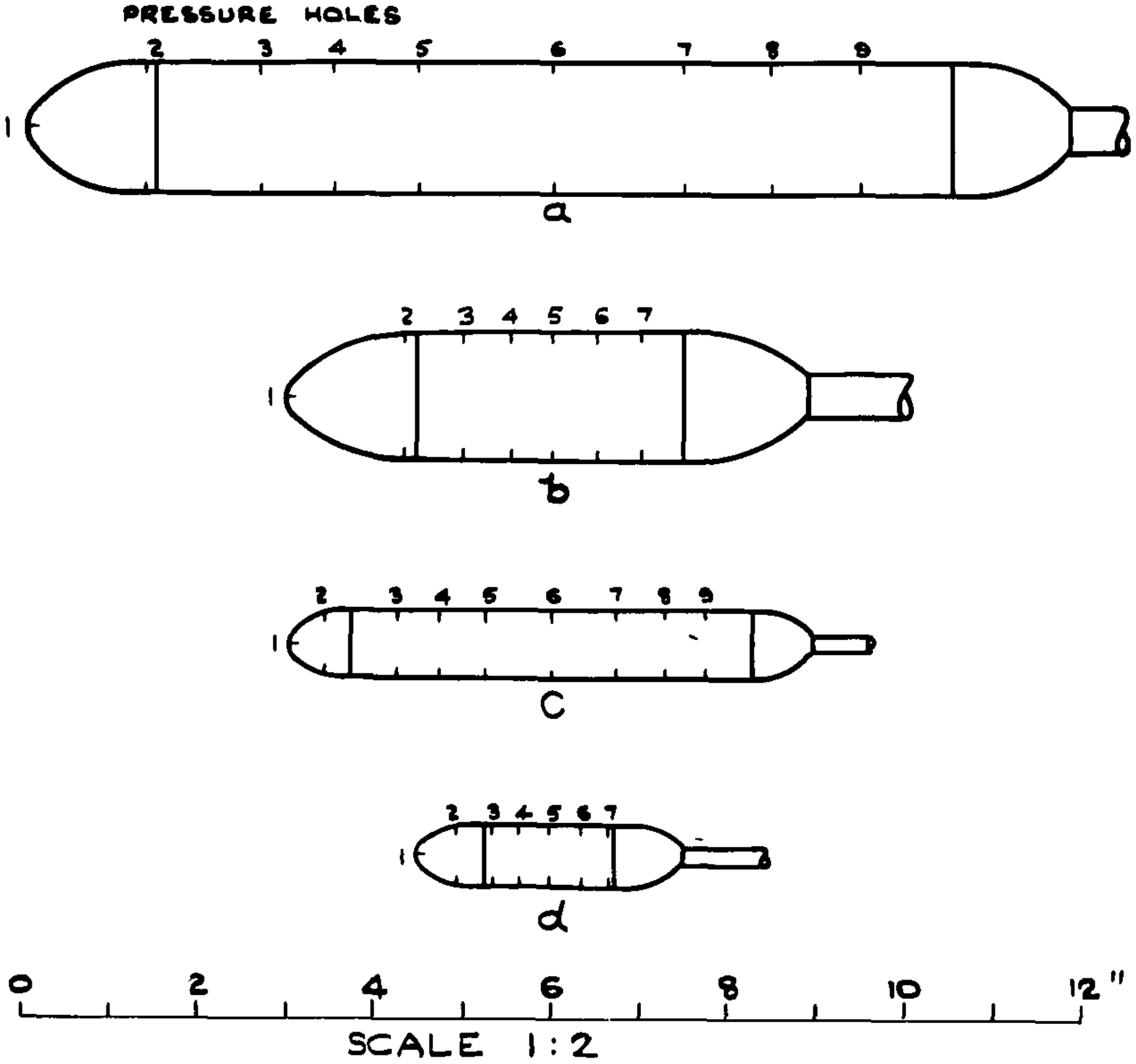


FIG. 4

STATIC PRESSURE ALONG THE AXIS OF THE EMPTY TEST SECTION.

a : NO CONTRACTION
b : SHORT CONTRACTION
c : LONG CONTRACTION
d : SHORT CONTRACTION, DOUBLE THICKNESS BARS

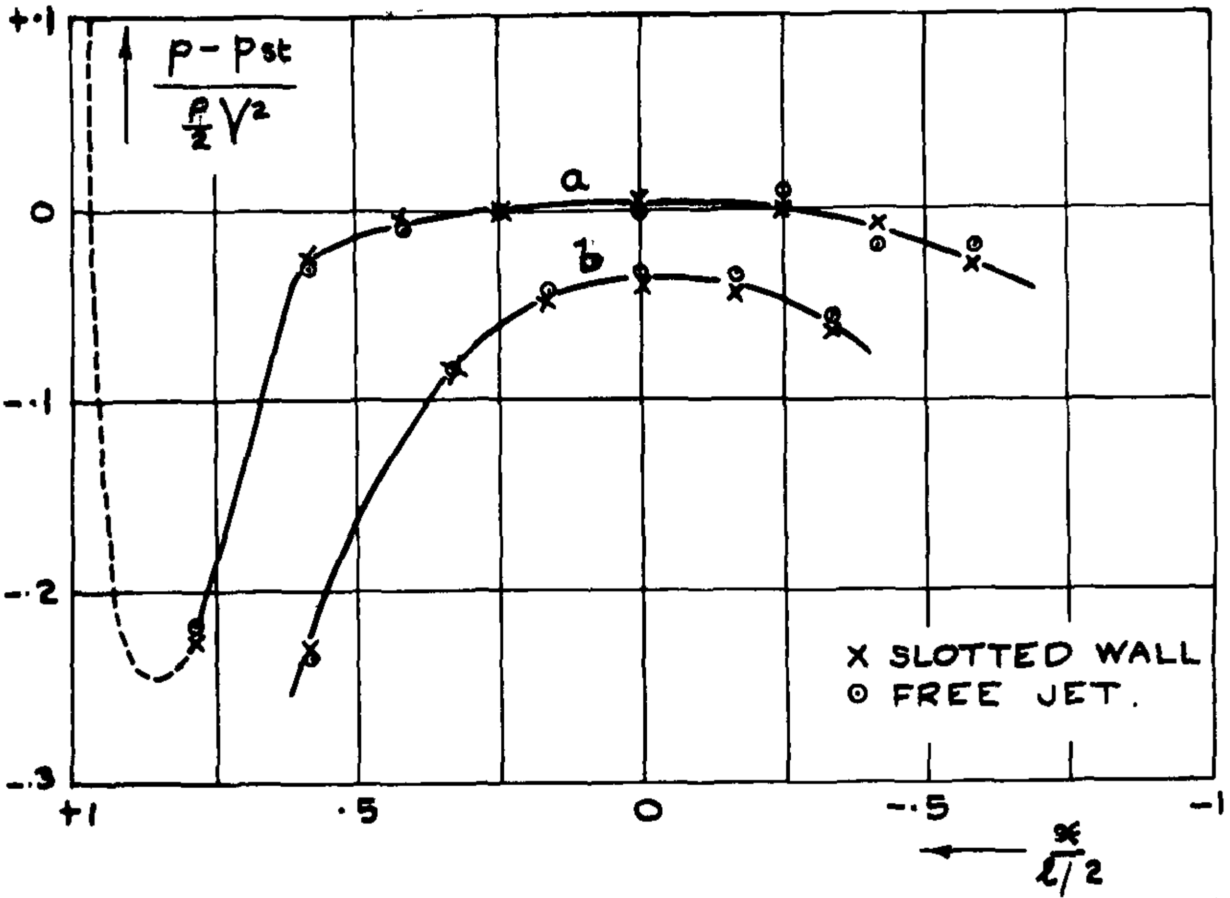


a : LARGE LONG MODEL
b : LARGE SHORT MODEL
} BLOCKAGE RATIO 9%

c : SMALL LONG MODEL
d : SMALL SHORT MODEL
} BLOCKAGE RATIO 2·25%

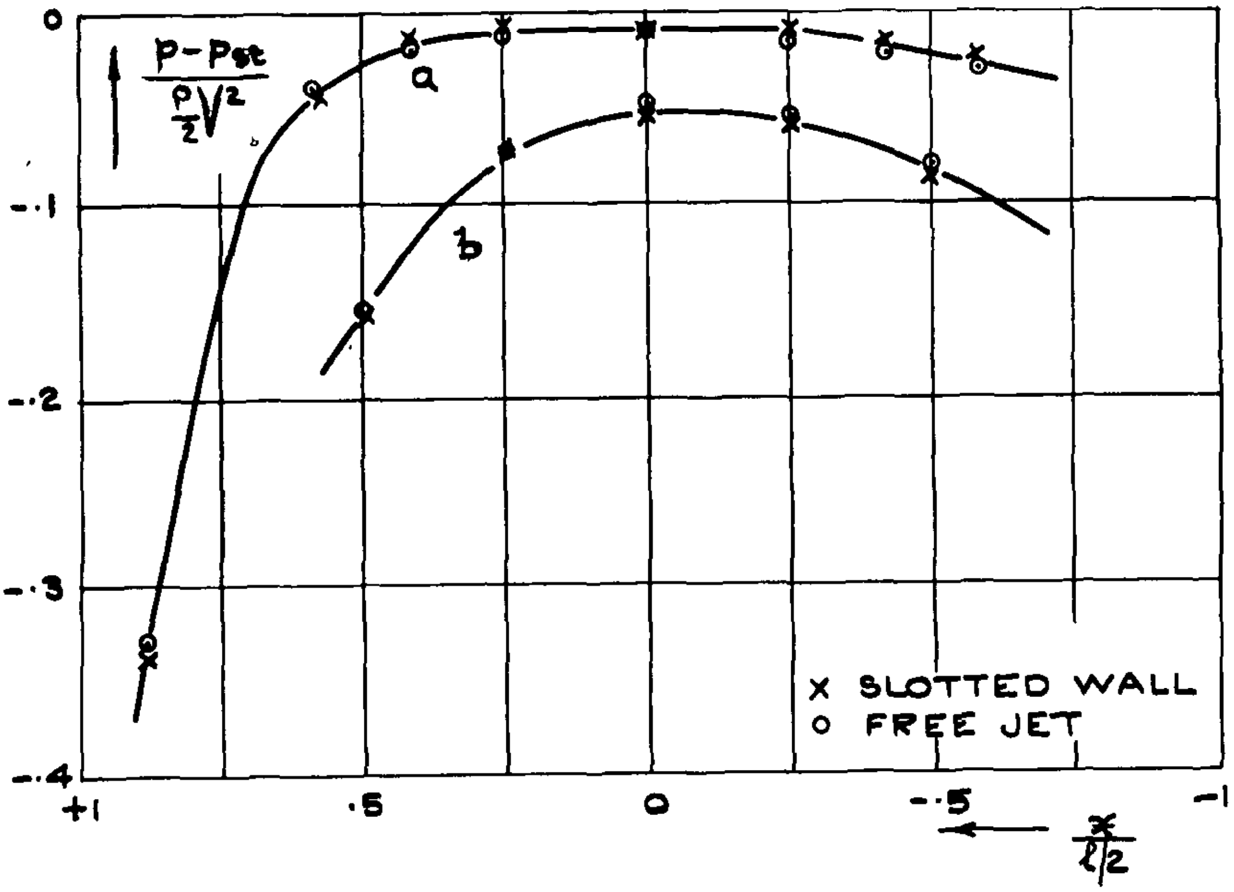
MODELS TESTED IN THE SLOTTED WALL.

FIG.5.



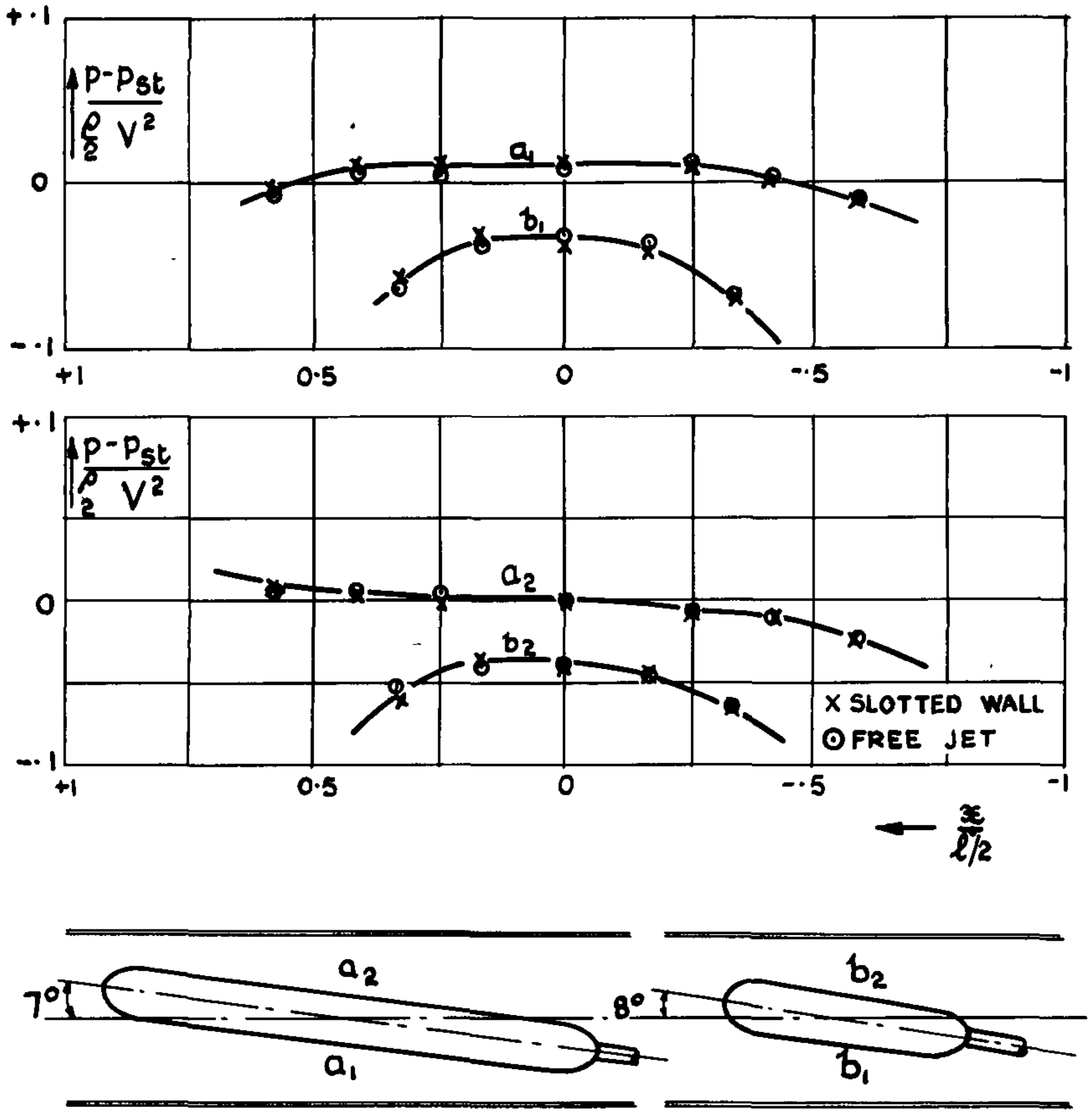
PRESSURE-DISTRIBUTION OF THE LARGE LONG (a) AND OF THE LARGE SHORT MODEL (b) AT 0° INCIDENCE.

FIG. 6



PRESSURE DISTRIBUTION OF THE SMALL LONG (a) AND OF THE SMALL SHORT MODEL (b) AT 0° INCIDENCE.

FIG. 7.



PRESSURE DISTRIBUTION OF THE LARGE LONG MODEL (a) AT 7° INCIDENCE AND OF THE LARGE SHORT MODEL (b) AT 8° INCIDENCE.

FIG. 8

C.P. No. 206

(14,871)

A.R.C. Technical Report

PRINTED AND PUBLISHED BY HER MAJESTY'S STATIONERY OFFICE
To be purchased from
York House, Kingsway, LONDON, W C 2 423 Oxford Street, LONDON, W 1
P O Box 569, LONDON, S.E 1
13a Castle Street, EDINBURGH, 2 109 St Mary Street, CARDIFF
39 King Street, MANCHESTER, 2 Tower Lane, BRISTOL, 1
2 Edmund Street, BIRMINGHAM, 3 80 Chichester Street, BELFAST
or from any Bookseller

1955

Price 2s 0d net

PRINTED IN GREAT BRITAIN

S.O. Code No. 23-9009-6

C.P. No. 206