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A.R.C. Technical Report

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Further Experiments with a Slotted-Wall Test Section

By

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Further Experiments with a Slotted-Wall Test Section

- By -

F. Vandrey

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Abstract

As shown by previous experiments (ref. (1)), a slotted-wall test section is especially suitable for a water tunnel intended for the testing of long models. The present report deals with the transition from this type of test section to the diffuser.

The main results are: The optimum diameter of the diffuser entry is about 10% greater than the diameter of the nozzle (for 30% losses in the test section, less for smaller losses). A gap should be left between the end of the slotted-wall and the diffuser entry. A model in the test section has very little influence on the pressure in the diffuser entry.

Experiments both in air and water are in good agreement.

Introduction

1. In a previous report[1], a model of a slotted-wall test section for a planned water tunnel was investigated with a view to developing a long working section with the correction properties of a free jet. In a conventional open tunnel, the length of the working section is restricted by the turbulent dissipation of the free boundary to about $1\frac{1}{2}$ diameters of the jet. In order to obtain a longer test section, the jet was enclosed in a cage of longitudinal bars. It was reasoned that the bars would delay the dissipation of the free boundary, but the gaps between them would permit a compensation of pressure differences thus preserving the essential feature of a free jet[2].

2. The experiments of ref. (1) confirmed these expectations and showed that a slotted-wall test section can be used for models with a length of about 3 diameters of the jet, or possibly even longer, whilst maintaining the small corrections of a free jet[2].

3. The present report extends the experiments of (1) in which a slotted-wall test section was investigated as an isolated element, to the problems involved in joining the test section to the diffuser. The experiments were made partly in air, partly in water, the results in both cases were found to be in good agreement.

Experimental Arrangement

Experiments in Air

4. The construction of the slotted-wall section in shown in fig. 1, details of the transition from the test section to the diffuser are given in fig. 2, details of the slotted wall in fig. 3a.

5./

5. The jet J issuing from the nozzle N (diameter 5") is guided by a case of 16 wooden bars of rectangular cross-section ($\frac{3}{4}$" x 5/16") and a length of 30". At the inner side of the cage, strips of stiff paper were glued to the bars in order to obtain an opening ratio of 18% of the total boundary (fig. 3). Although the thickness of the longitudinal bars obviously has an effect on the losses in the slots, it is considered that this effect is small, and it was hoped that the use of relatively thin paper would tend to balance the slightly improved performance to be expected from the Perspex cage - in view of its better surface finish - which was to be used for experiments in water. In the last 3" of their length, the bars were tapered to a sharp trailing edge at the downstream end.

6. The upstream end of the cage was fixed to the flange F_1 at the nozzle. Near its downstream end, the cage was held together and supported by a brass ring S of 10" diameter. Four of the sixteen bolts holding the bars were fitted with long nuts (n in fig. 3) to support the ring from the wall of the reservoir R. The central part of two of the bars were removable to facilitate mounting a model into the test section.

7. The reservoir R (12$\frac{1}{2}$" diameter) surrounding the cage was joined to the nozzle by the flange F_1 and joined to the contraction C by the flange F_2. Its wall was made of 1/32" presspan sheet, it had a telescopic extension T permitting adjustment of the distance between the end of the cage and the diffuser entry. The wall of the reservoir had several small holes for introducing pitot-tubes, etc., an opening for introducing the model, normally covered by a presspan plate with a hole for the support of the model, and several observation windows of celluloid sheet. Before using the tunnel, these holes and the telescopic extension had to be sealed with adhesive cellulose tape, as the static pressure in the working section was well below the atmospheric pressure when the tunnel was running.

8. The contraction C between the flanges F_2 and F_3 was made of paraffin wax cast into the form of a slightly conical solid piece and then turned out to the desired shape. Seven pressure holes P were drilled into the contraction piece for measuring the pressure distribution of this part. Four different contractions with the end diameters 5", 5.4", 5.6" and 6" were tested, details of their design are given in fig. 2. For comparison, the contraction and the adjoining diffuser were then removed and replaced by a straight cylindrical continuation of the reservoir ("no contraction" in fig. 2).

9. The 7° diffuser D was made of presspan sheet. Its original length for the 5" contraction (a) was about 40". As the contraction was increased in diameter in the course of the experiments, the diffuser was correspondingly shortened to fit the end of the contraction. At the end of the diffuser, the flow was discharged into the open air.

10. The static pressure along the axis of the tunnel was measured by pushing a long static tube into the tunnel from the open downstream end of the diffuser. Velocity traverses were measured with a small pitot-static tube introduced through holes in the wall of the tunnel. The pressure readings were taken with a standard multitube manometer filled with alcohol.

Experiments in Water

11. A diagrammatic representation of the test section for water is given at the top of fig. 9; a cross-section through the slotted wall in the plane of the supporting ring near its end is given in fig. 3b.

12./

12. The test section (diameter of the cage 5") was mounted in the A.R.L. 12-Inch Water Tunnel with closed jet working section. It consisted of two separate parts: the nozzle with the cage and the contraction with the diffuser. The nozzle and the contraction were made of paraffin wax cast into cylinders of thin brass sheet (12" diameter) and then turned out to the desired shape. The shape of the contraction was virtually the same as the contraction for the experiments in air (fig. 2), except for the slightly smaller diameter of the reservoir (12" instead of $12\frac{1}{2}$"). Four different end diameters of the contraction were tested (5", 5.2", 5.4" and 5.5"). The cage was made of Perspex, the slots were arranged horizontally and vertically, rather than radially, to reduce their interference with optical observations of the flow inside the cage (fig. 3b). The 7° diffuser had originally a length of about 30", in the course of the experiments, it was shortened so as to fit the greater end diameter of the contraction.

13. The static pressure along the axis was measured with a long static tube with 9 pressure holes along its length. Two representative velocity traverses of the jet were taken with a pitot-static tube. The pressure readings were taken with a standard multitube manometer filled with mercury.

Experimental Results in Air

14. The experiments were carried out with a velocity of the jet $V_o = 140$ f.p.s., corresponding to a Reynolds number $Re = V_o . D_o / \nu = 370,000$. With the exception of the last test (section 31 below), all experiments were made in the position 1 of the contraction leaving a gap of $2" = 0.4\ D_o$ between the end of the cage and the smallest diameter section of the contraction.

Static Pressure Along the Axis

15. The most important result of the present investigation is the dependency of the static pressure in the contraction on its minimum diameter D. The results are given in fig. 4 for various ratios D/D_o. Along the axis of the cage, p_{st} is constant in all cases. For $D/D_o = 1$, p_{st} drops towards the end of the cage to a minimum of -32% of the head in the narrowest part of the contraction, recovers quickly and rises continuously along the axis of the diffuser to the outside atmospheric pressure at its end. This sudden local pressure drop is undesirable in a water tunnel, where the lowest pressure should be in the working section in order to prevent the beginning of cavitation elsewhere in the tunnel.

16. The cause of the pressure drop in the narrow throat of the diffuser entry is obvious. If D equals D_o, the continuity of the flow requires equal average velocity in the nozzle and in the diffuser entry. The losses of energy in the working section can then only appear in the form of a loss of pressure energy which is the observed pressure drop of $-0.32 \frac{\rho}{2} V_o^2$. If this pressure drop is undesired, it can only be removed by widening the diffuser entry and so transforming the losses of potential (pressure) energy into losses of kinetic energy.

17. Using for a rough estimation a linearised one-dimensional theory, the pressure drop of 32% would correspond to a rise of the effective velocity (= velocity in the central parts of the diffuser entry) of 16%. In order to compensate for this, the cross-section has to be increased by 16%, or the diameter by 8%.

18./

18. The curve D/D_o = 1.08 in fig. 4 shows that this widening of the diffuser entry has in fact almost the desired result, the minimum pressure in the contraction being now only -4% of the head instead of -32% before. The curve shows a slight rise of the pressure at the end of the cage which appears in all the subsequent curves and is probably only hidden in the first curve D/D_o = 1 by the much greater pressure drop in the contraction. The explanation for this may be that if the jet is no longer constrained in the cage, this is equivalent to a widening of its cross-section, which causes a rise of the pressure.

19. Another significant feature of the curve D/D_o = 1.08 is that it is below the curve D/D_o = 1 further downstream in the diffuser. This holds equally for all the subsequent curves, it means that the efficiency of the diffuser decreases as the diameter of its entry is increased. It is easy to understand this effect: As D is increased, the velocity distribution in the diffuser entry becomes poorer (cfr. fig. 5, curves C), a good velocity distribution at its entry is, however, essential for the maintenance of the efficiency of a diffuser.

20. Increasing D to 1.12 D_o raises the pressure in the diffuser entry above zero, at the same time the recovery of energy in the diffuser continues to decrease. The following curve D/D_o = 1.20 shows a still higher pressure in the diffuser entry combined with a further loss of efficiency of the diffuser.

21. Finally, the contraction and the diffuser were replaced by a straight cylindrical continuation of the wall of the reservoir, corresponding to the limiting case D/D_o = 2.5 (dotted curve in fig. 4). This causes the recovery of energy downstream of the working section to drop to about 25% of the energy recovered in the diffuser with the original contraction D/D_o = 1.00.

22. Summing up the above results, it can be said that the contraction of the reservoir at the diffuser entry is necessary for good efficiency of the diffuser. On the other hand, too great contraction causes a pressure drop in the diffuser entry, thus restricting the cavitation number which can be achieved in the tunnel. The diffuser entry has therefore to be greater in diameter than the cage, but only such that the static pressure at its smallest diameter is just equal to the pressure in the working section. If the diffuser entry is larger than required by this condition, this will cause unnecessary losses in the diffuser. In the present case, the diffuser entry should have a diameter of about 1.10 D_o.

Velocity Traverses

23. In order to obtain more information about the flow through the working section and the diffuser, the velocity distribution was measured at four representative stations: near the nozzle (A), near the end of the cage (B), at the beginning of the diffuser (C) and at its end (D). The results are plotted in fig. 5 for D/D_o = 1.00, 1.08, 1.12 and 1.20.

24. At A, the velocity is zero outside the cage and practically constant inside.

25. The subsequent curves B to D are slightly unsymmetrical due to imperfection of the cage. At B, 5 D_o downstream of A, the jet in the cage has still a core of undisturbed flow with a diameter between 0.5 and 0.6 D_o. Outside the cage, the velocity decreases rapidly and is very small near the wall of the reservoir. The curves B show but little difference for the various values of D/D_o in agreement with the results for the static pressure (fig. 4) which was constant in all cases upstream of B (x/D_o = 5.3).

26./

26. The curves C show the expected dependency on D/D_o. For $D/D_o = 1.00$, the velocity in the core of the flow is considerably higher (~ 10%) than the velocity of the jet in the working section. This is in reasonable agreement with the low pressure at C ($x/D_o = 7$ in fig. 4), considering the rapid variation of p_{st} in this region. Towards the wall, the velocity decreases rather rapidly to about $0.5\ V_o$ near the wall. In the curve $D/D_o = 1.08$, the core of the flow has still a slightly higher velocity than the jet, the transition from the core to the lower velocity near the wall is spread over a wider interval. The velocity distribution is therefore poorer than in the preceding case in agreement with the lower efficiency of the diffuser (fig. 4). For $D/D_o = 1.12$, the velocity in the core is slightly less than V_o, the transition interval continues to become wider creating a still poorer velocity distribution at the entry of the diffuser and consequently reducing its efficiency. These tendencies continue in the last curve $D/D_o = 1.20$.

27. The velocity distributions at the end of the diffuser (curves D) are, generally speaking, rather poor. The flow there was found to be strongly turbulent. Considering that even in the best case $D/D_o = 1$, the velocity distribution at the diffuser entry is not ideal and that a diffuser entry with an even poorer velocity distribution has to be used in order to avoid a pressure drop at its smallest section, there is possibly little prospect of improving the flow. A reduction of the diffuser angle may give some improvement, but it is unlikely that much is to be gained in this way.

Detailed Investigation for $D/D_o = 1.08$ and 1.12

28. A more detailed investigation was carried out for the two most interesting cases $D/D_o = 1.08$ and 1.12 which are likely to enclose the optimum of D/D_o for the present case, i.e., for a slotted-wall with about 30% losses in the working section. The results cover the difference of the static pressure on the axis and on the wall (fig. 6), the influence of a model in the working section on p_{st} (fig. 7) and finally the effect of the $0.4\ D_o$ gap (cfr. fig. 2) between the end of the cage and the smallest section of the contraction (fig. 8).

29. The static pressure along the wall of the diffuser is practically the same as on the axis (fig. 6). At the beginning of the contraction, p_{st} is somewhat greater than on the axis. The shape of the wall at this section is concave towards the axis, which causes a local retardation of the flow. At the smallest diameter of the contraction, p_{st} is slightly less on the wall than on the axis, but so little (1-2% of the head) that it is unlikely to be serious.

30. The influence of a model in the working section on p_{st} is shown in fig. 7. The test was made with a Rankine ovoid of length 12" = $2.4\ D_o$ and diameter 1.5" = $0.3\ D_o$, which gives a fineness ratio of 1:8 and a blockage ratio in the tunnel of 9%. The influence of the model was smaller than expected from an estimation of the drag of the model and of its support ($\Delta p_{st} \sim -3\%$ of the head). For $D/D_o = 1.08$, Δp_{st} was only ~ -1%, for $D/D_o = 1.12$, it was even slightly positive (~ +1%). Considering, however, that the wake of the model reduces the effective cross-section of the diffuser entry and that - the wake being mainly in the central part of the cross-section - the transition region between the core of the flow and the wall is likely to be reduced too, it may be that this improvement of the velocity distribution near the wall compensates for the losses caused by the drag of the model.

31./

31. So far, the experiments were made in the position 1 of the contraction, leaving a gap of 2" = $0.4\ D_o$ between the end of the cage and the beginning of the narrowest part of the contraction. In order to obtain information on the effect of this gap, on p_{st} in the critical region, the contraction was moved into the position 2 (cfr. fig. 2) so that the end of the cage coincided with the smallest section of the contraction. The results are shown in fig. 8. In both cases $D/D_o = 1.08$ and 1.12, p_{st2} is considerably lower than p_{st1} in the critical part of the diffuser entry. This indicates that a gap should be left between the end of the cage and the smallest section of the diffuser entry. Within fairly wide limits, however, its length is unlikely to be critical.

Experiments in Water

32. For comparison, part of the preceding experiments were repeated in a model slotted-wall section for water (cfr. II, 11-13 above). The experiments were made with a velocity V_o = 20 f.p.s., corresponding to a Reynolds number $V_o.D_o/\nu = 750{,}000$.

33. The results are shown in fig. 9. In the critical region of the diffuser entry, the curves of the static pressure on the axis are practically identical with the results obtained in air. Further downstream in the diffuser, the curves do not however change their order as in fig. 4. The experimental arrangement did not permit p_{st} to be measured along the whole axis of the diffuser in order to obtain reliable information on this point. From the noise emanating from the region at the end of the model diffuser, it appeared, as may be expected, that flow conditions at this section were definitely poor and that cavitation was probably taking place. It is unlikely under those conditions that reliable values of the pressure recovery in the diffuser would be obtained.

34. The two velocity traverses A and B show the stabilising effect of the slotted wall on the boundary of the jet. At B, $3.1\ D_o$ downstream of the nozzle, the jet has still a completely undisturbed core of $0.73\ D_o$; up to a diameter of $0.92\ D_o$, the velocity is greater than $0.8\ V_o$. The curve B gives the velocity distribution of a free jet at $3.0\ D_o$ distance from the nozzle for comparison (cfr. ref. (1), Fig. 3a).

Conclusions

35. In a water tunnel with a slotted-wall working section, the problem of joining the test section to the diffuser is, shortly, to combine the requirement of avoiding a pressure drop in the diffuser entry with an acceptable efficiency of the diffuser. The pressure drop can be avoided by making the diffuser entry larger than the nozzle, but this will reduce the efficiency of the diffuser. The diffuser entry should, therefore, be of such a size that the static pressure in its smallest diameter is just equal to the static pressure in the test section.

36. The optimum diameter of the diffuser entry depends mainly on the losses in the working section, for 30% losses, D should be about 10% greater than D_o. Considering the rather poor velocity distribution near the wall of the diffuser entry, the shape of the contraction is unlikely to be critical, although it should of course be a smooth curve. A long length of contraction is not necessary, about $1\frac{1}{2}\ D_o$ is sufficient. It is advisable to leave a gap of about $\frac{1}{2}\ D_o$ between the end of the slotted wall and the smallest diameter of the contraction. The influence of a model (up to 10% blockage ratio) on p_{st} in the diffuser entry is very small.

37./

37. Parallel experiments in air and water are in good agreement, confirming that the results from the experiments in air can be used as a basis for the design of a slotted-wall test section for a water tunnel.

Acknowledgements

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References

No.	Author(s)	Title, etc.
(1)	K. Wieghardt and F. Vandrey	Experiments on a slotted-wall working section in a wind tunnel.
(2)	F. Vandrey	Theoretical corrections for long Rankine ovoids in a closed or open tunnel of circular cross-section. A.R.L./R.2/G/HY/4/1. A.R.C. 14,239.

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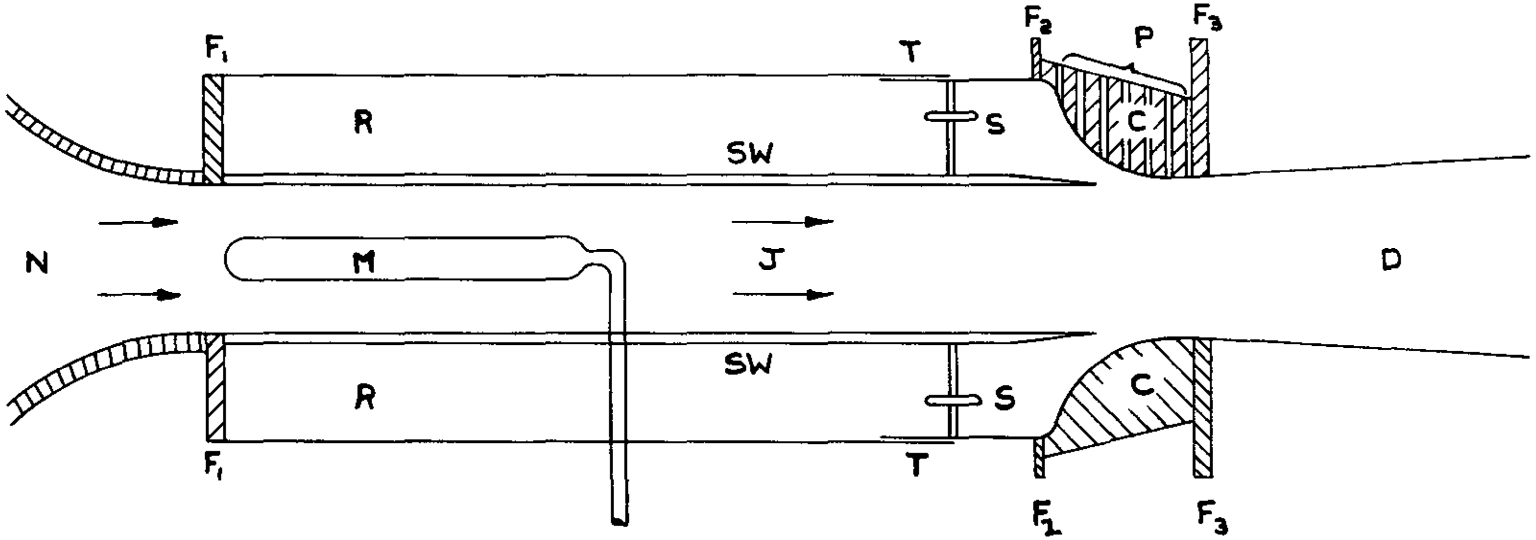


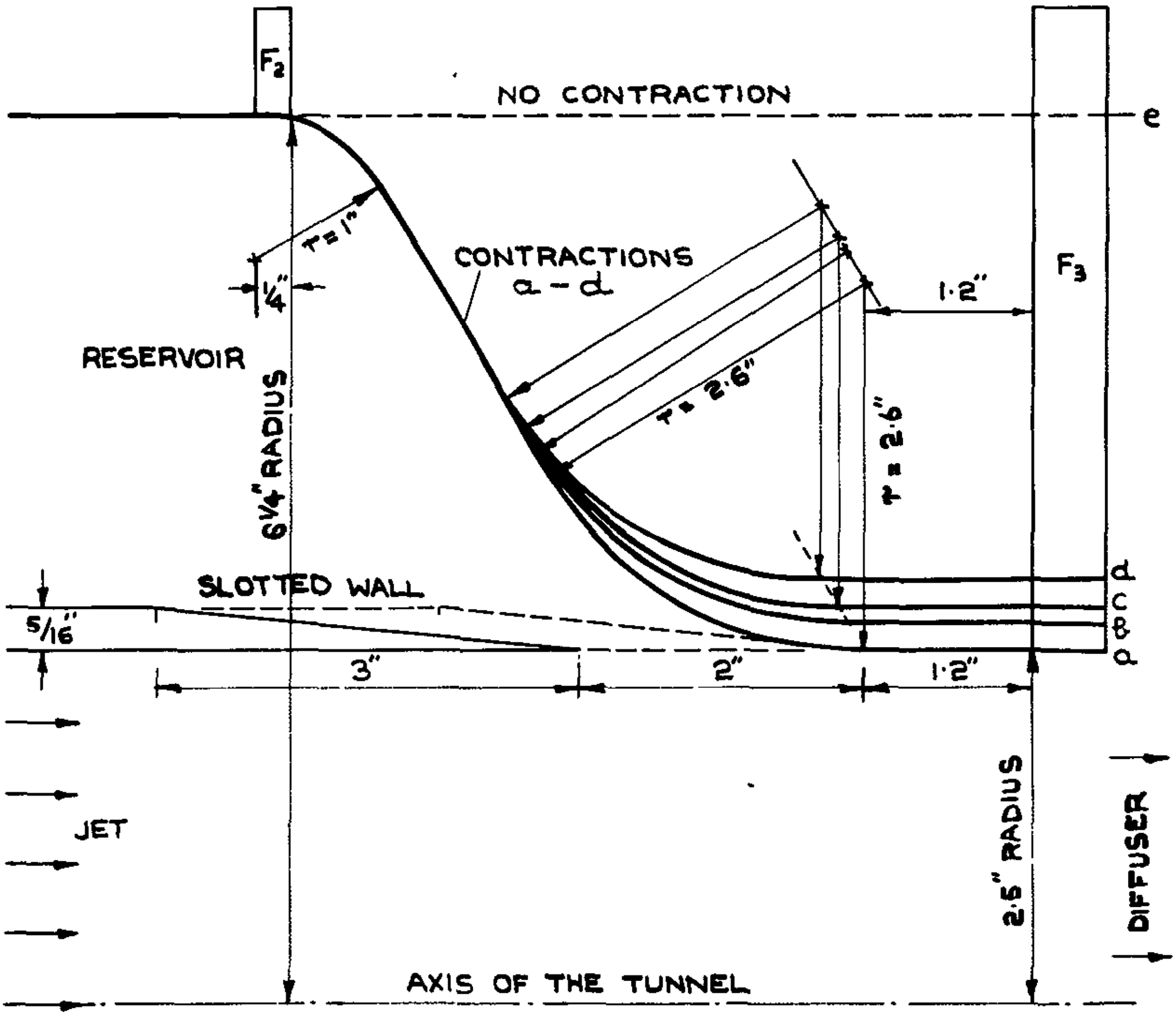
SLOTTED-WALL TEST SECTION FOR AIR.

N = NOZZLE (5" DIAMETER)
R = RESERVOIR (12½" DIAMETER)
C = CONTRACTION (FROM 12½" TO 5"–6" DIAM)
S = SUPPORT RING FOR THE END OF THE SW.
F_1 F_2 F_3 = FLANGES

J = JET
SW = SLOTTED WALL (16 BARS, 18% OPEN, 30" LONG)
T = TELESCOPIC EXTENSION
D = DIFFUSER (7°, 35" LONG)
P = PRESSURE HOLES

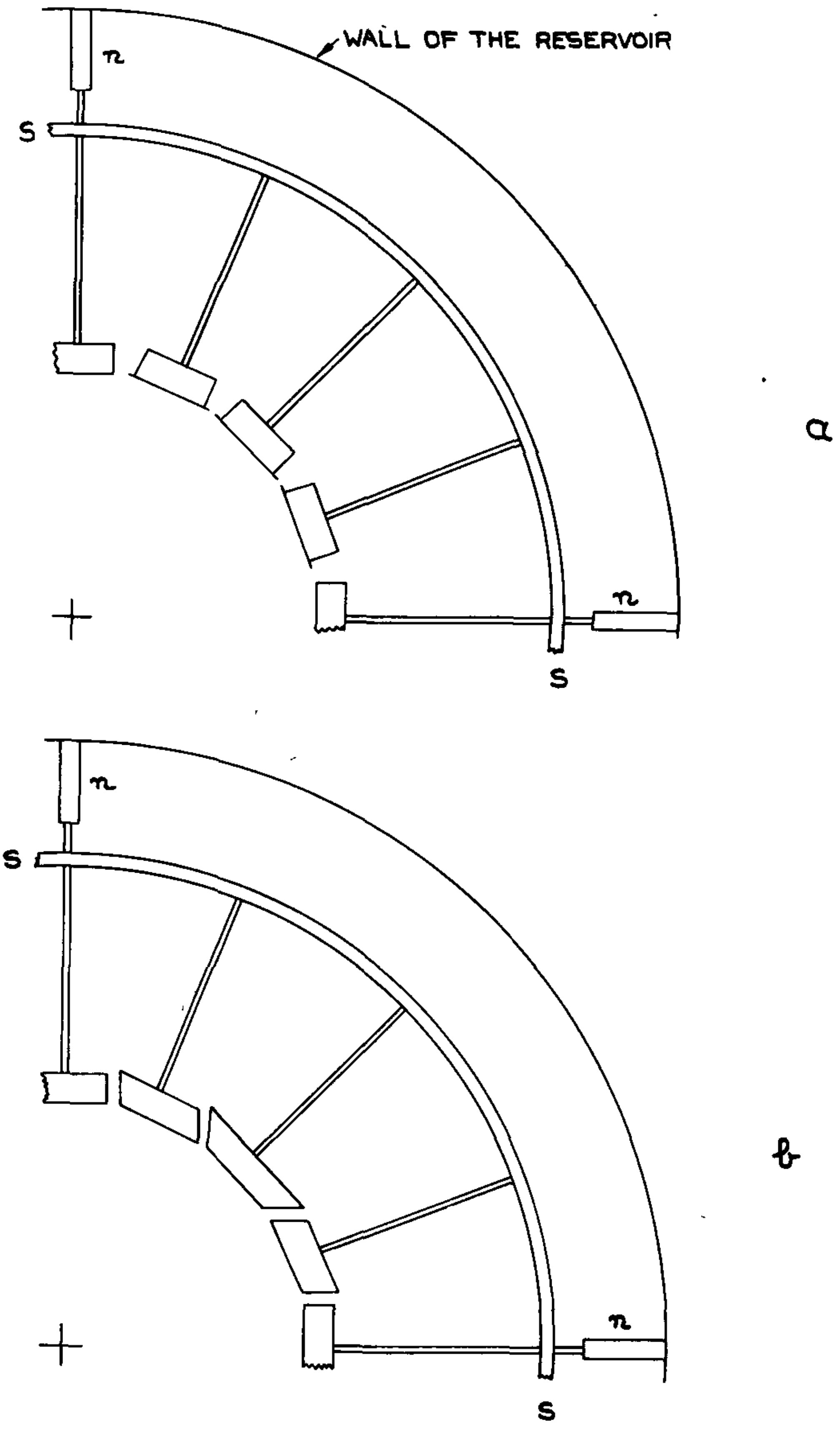
M = MODEL (1½" DIAM., 12" LONG)

FIG. 1.



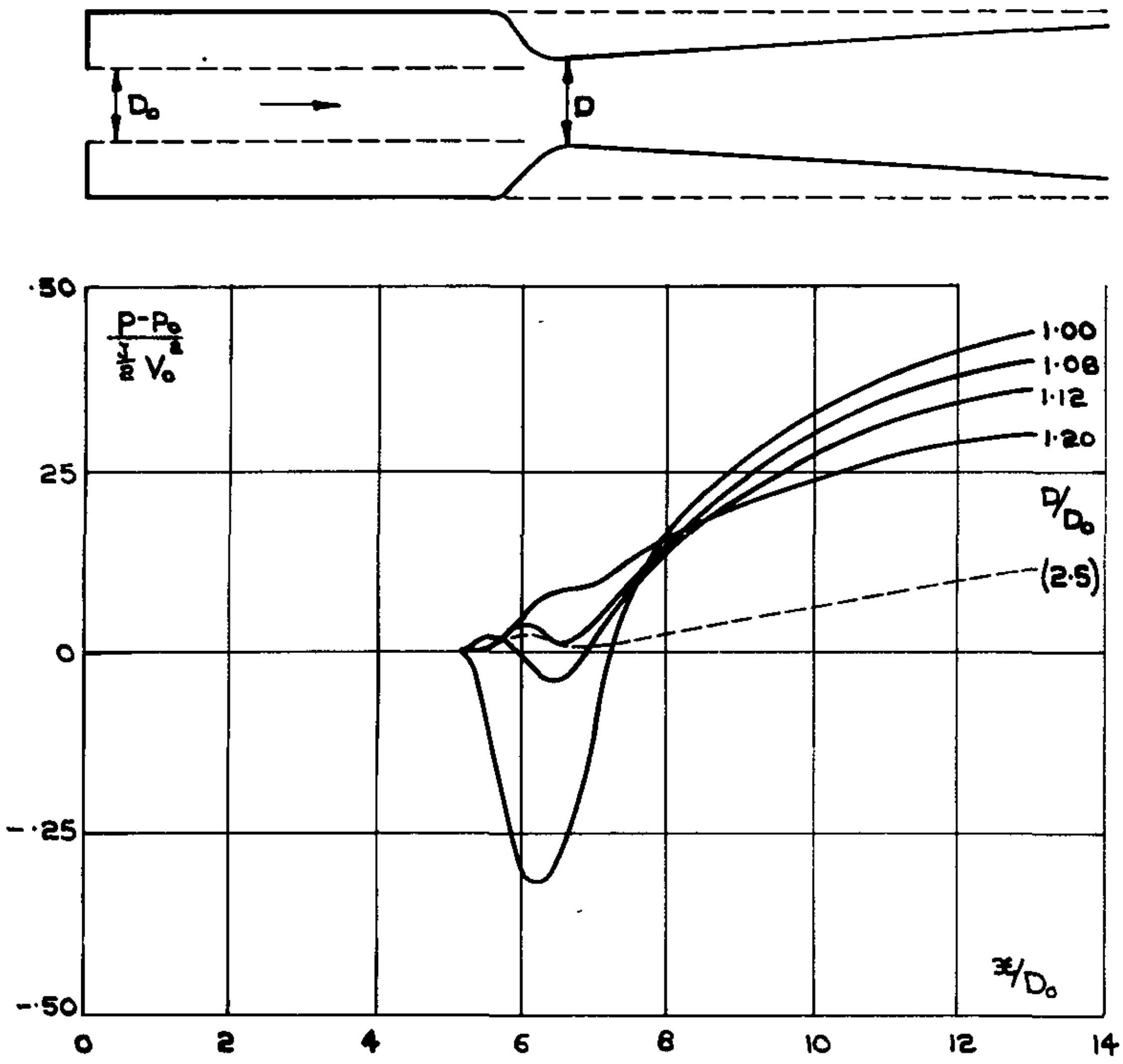
SLOTTED-WALL TEST SECTION FOR AIR.
CONTRACTIONS a – e BETWEEN THE END OF THE RESERVOIR F₂ AND THE ENTRANCE OF THE DIFFUSER F₃. POSITIONS OF THE SLOTTED WALL. 1 WITH 2" GAP(——), 2 WITHOUT GAP(- - -)
END DIAMETERS OF THE CONTRACTIONS: a = 5", b = 5·4"
c = 5·6", d = 6".

FIG. 2.



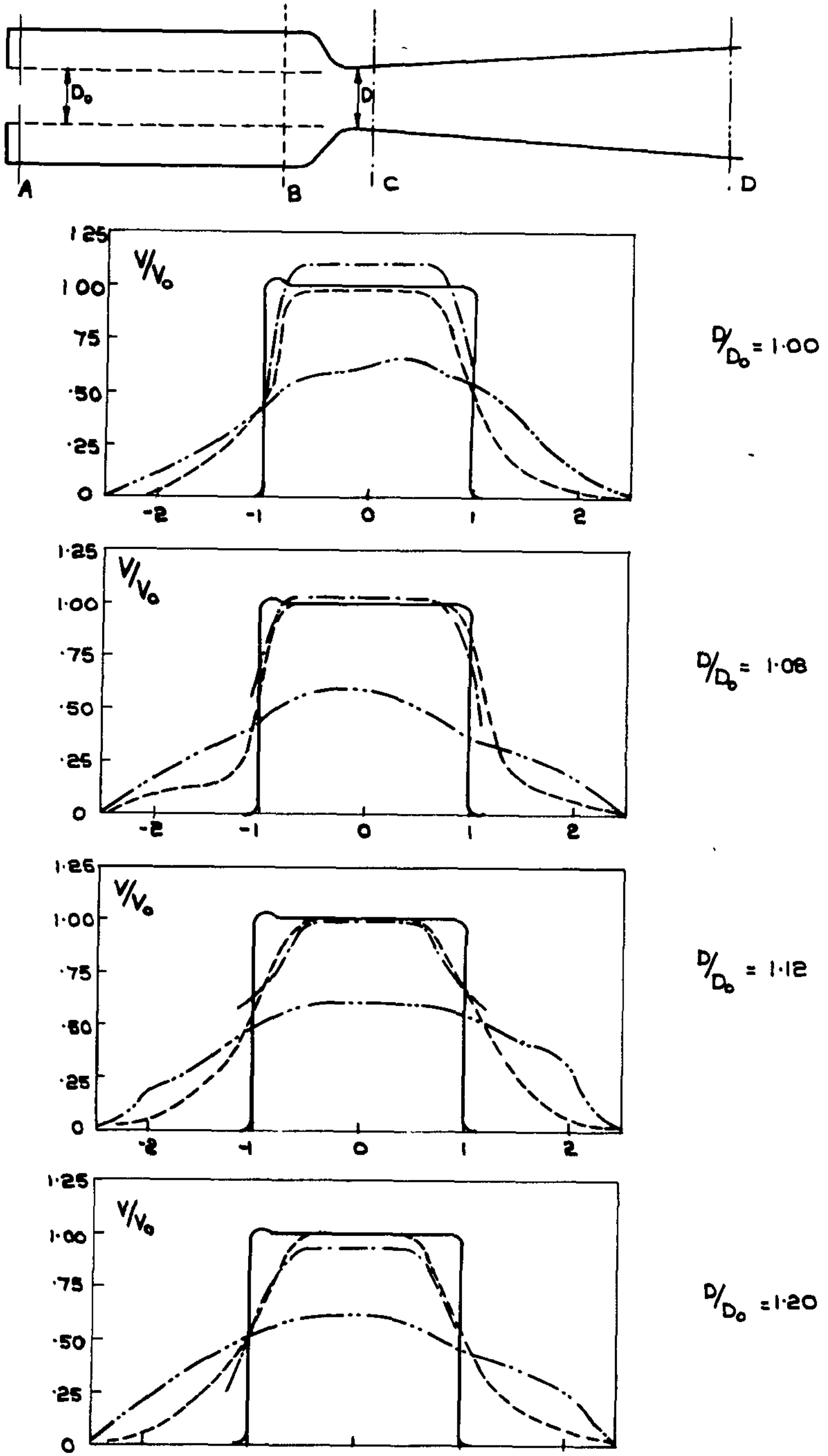
SLOTTED-WALL TEST SECTIONS FOR AIR (a) AND WATER (b)
CROSS-SECTION THROUGH THE SLOTTED WALL IN THE PLANE OF THE SUPPORT RING. (S IN FIG. 1.)

FIG. 3.



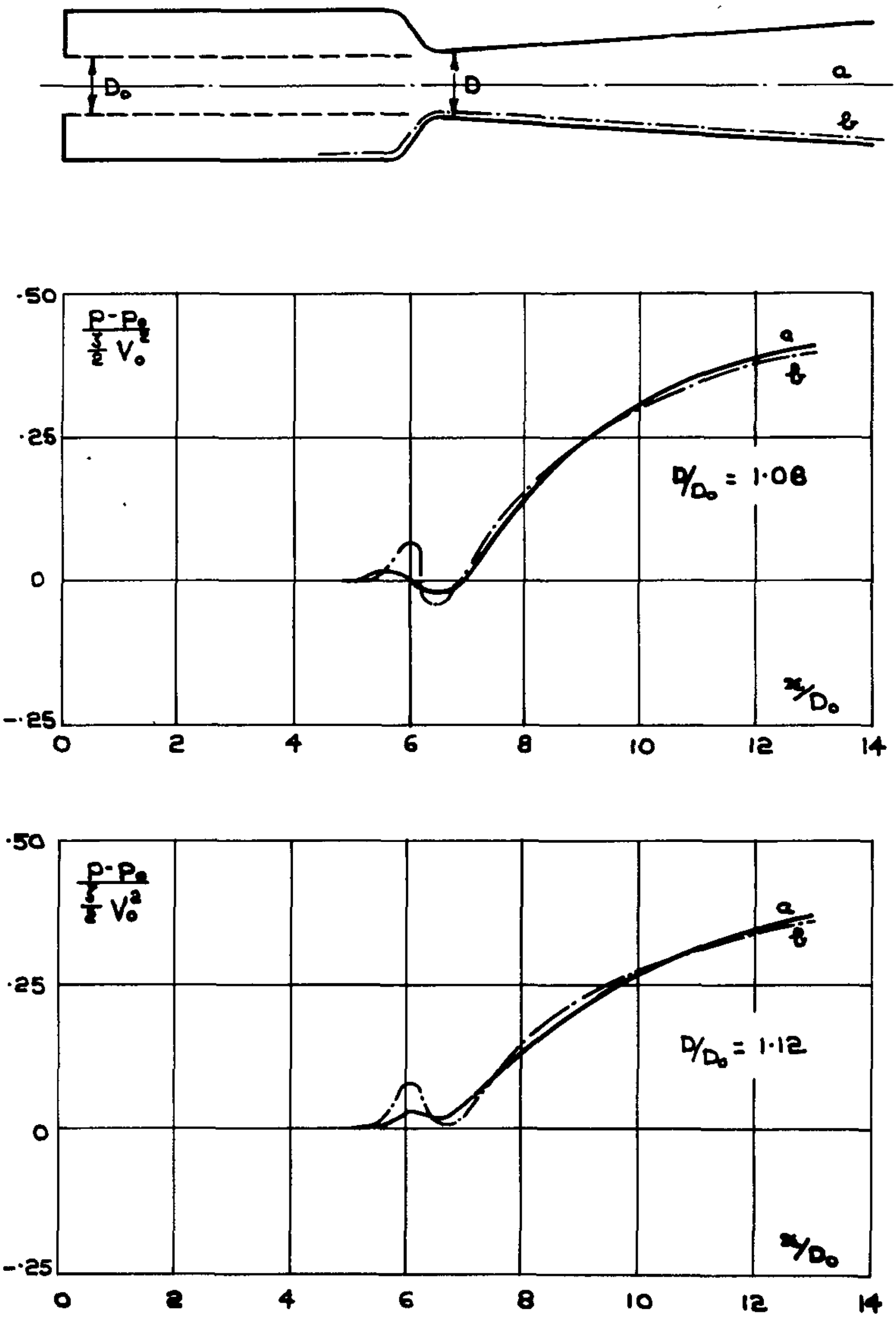
EXPERIMENTS IN AIR: STATIC PRESSURE ALONG THE AXIS OF THE TUNNEL FOR VARIOUS RATIOS D/D_0

FIG. 4.



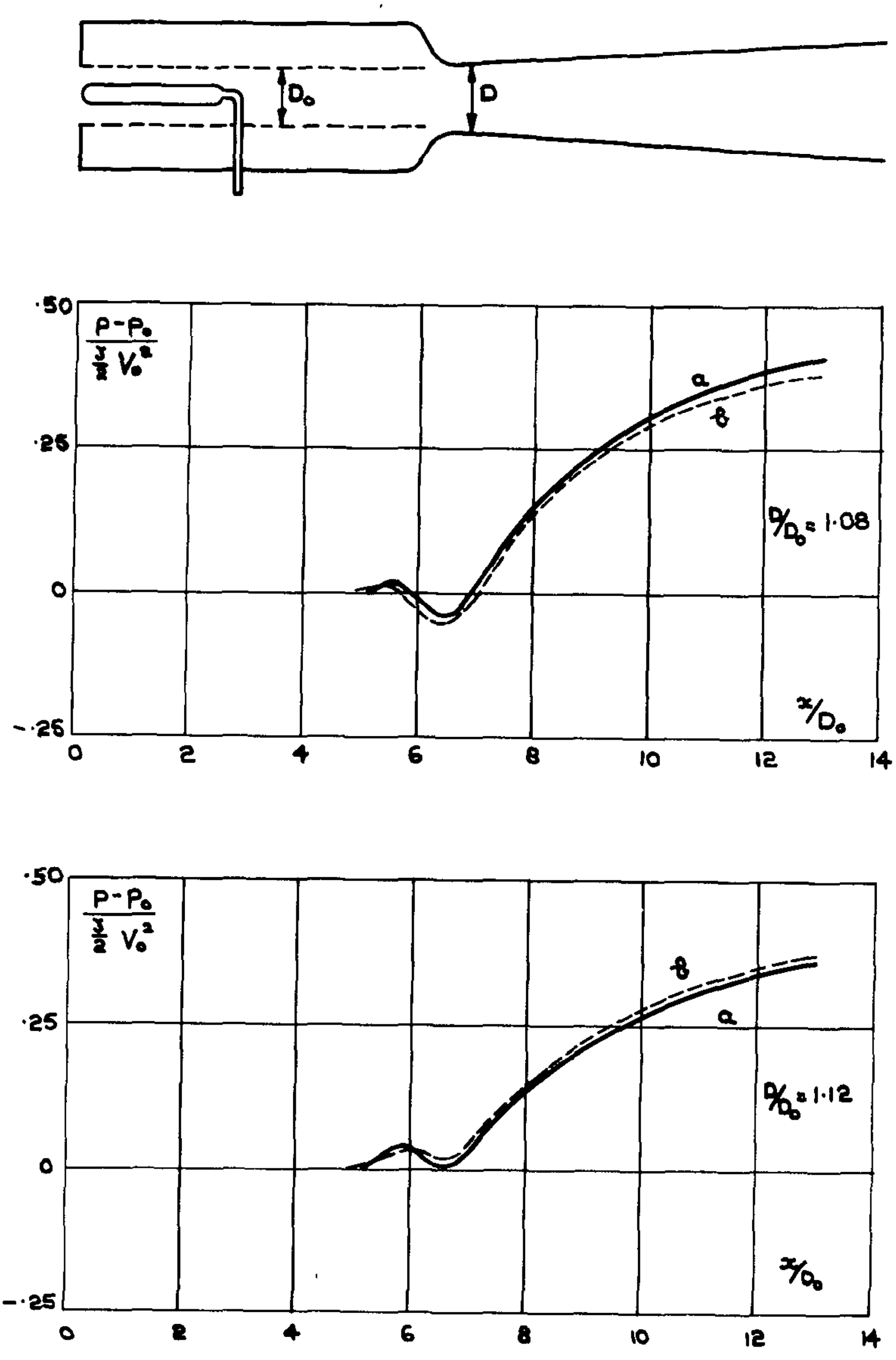
EXPERIMENTS IN AIR: VELOCITY TRAVERSES 'A'–'D' FOR VARIOUS RATIOS OF D/D_o

FIG. 5.



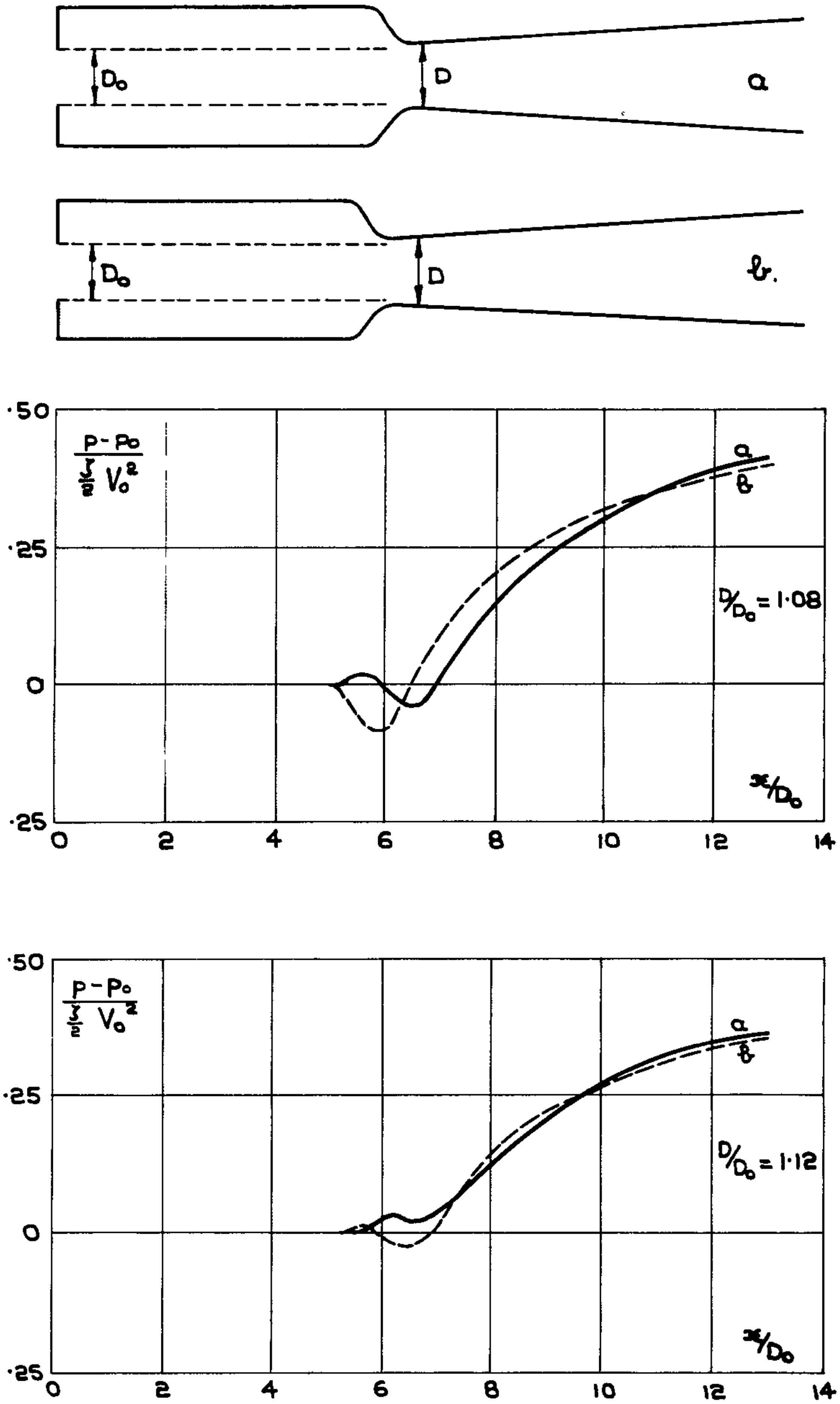
EXPERIMENTS IN AIR: STATIC PRESSURE ALONG THE AXIS AND ALONG THE WALL OF THE TUNNEL. 2" GAP, D/D_o 1·08 & 1·12.

FIG. 6.



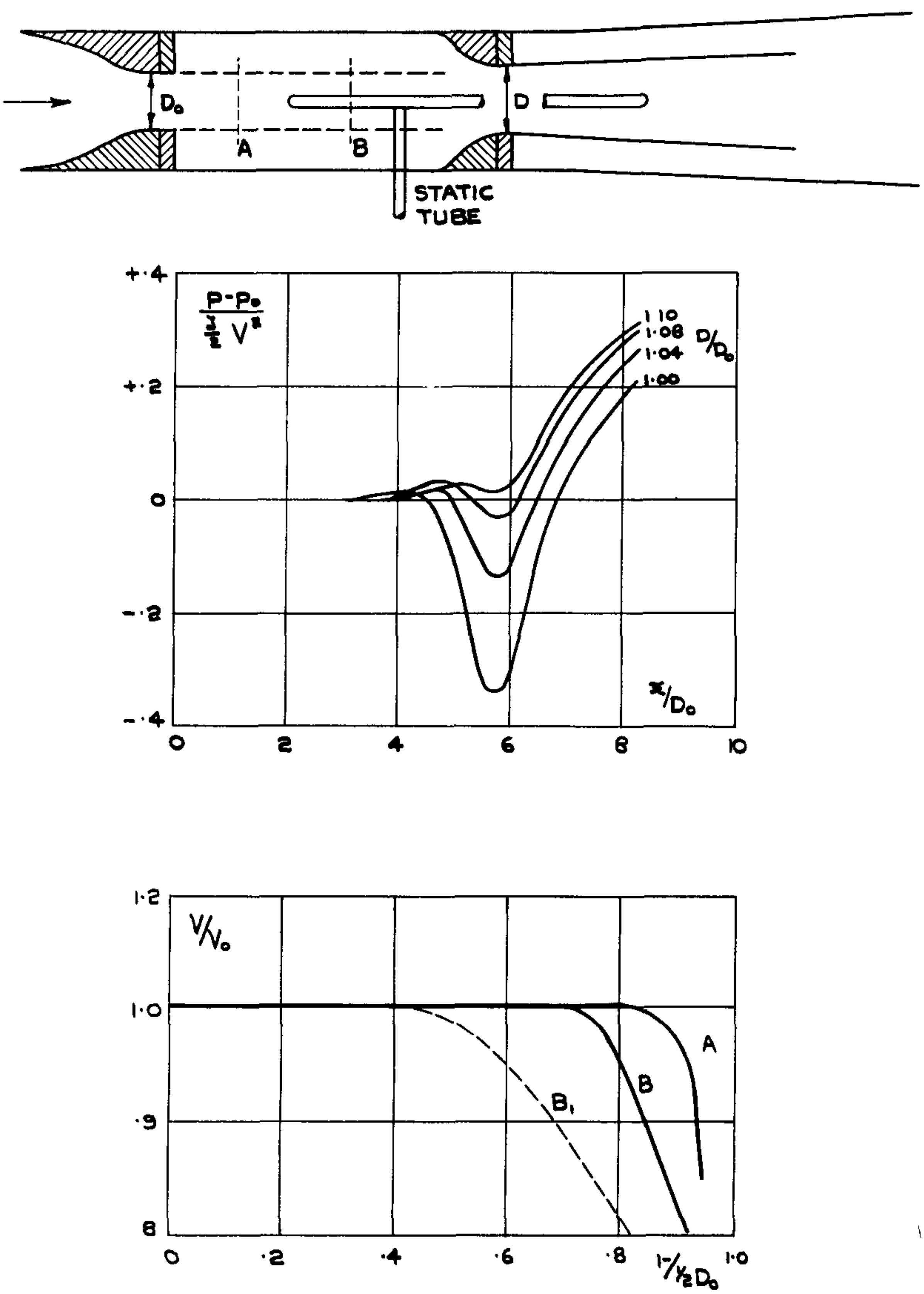
EXPERIMENTS IN AIR: STATIC PRESSURE ALONG THE AXIS WITHOUT (a) AND WITH MODEL (b). 2" GAP, $D/D_0 = 1{\cdot}08$ AND $1{\cdot}12$

FIG. 7.



EXPERIMENTS IN AIR: STATIC PRESSURE ALONG THE AXIS WITH AND WITHOUT A GAP BETWEEN THE END OF THE CAGE AND THE ENTRANCE OF THE DIFFUSER.

FIG.8.



EXPERIMENTS IN WATER: STATIC PRESSURE ALONG THE AXIS OF THE TUNNEL FOR VARIOUS RATIOS D/D_0 AND VELOCITY TRAVERSES AT 'A' AND 'B'. 'B_1' = VELOCITY DISTRIBUTION AT SECTION 'B' OF A FREE JET.

FIG. 9.

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