An Experimental Study of the Tangential Velocity Profile in the Ranque-Hilsch Vortex Tube

Linderstrøm-Lang, C.U.

Publication date:
1965

Document Version
Publisher's PDF, also known as Version of record

Risö Report No. 116

Risö Report No. 116

Danish Atomic Energy Commission

Research Establishment Risö

An Experimental Study of the Tangential Velocity Profile in the Ranque-Hilsch Vortex Tube

by C. U. Linderstrøm-Lang

September, 1965

Sales distributors: Jul. Gjellerup, 87, Sölvgade, Copenhagen K, Denmark
Available on exchange from: Library, Danish Atomic Energy Commission, Risö, Roskilde, Denmark

An Experimental Study of the Tangential Velocity Profile in the Ranque-Hilsch Vortex Tube

by

C. U. Linderstrøm-Lang

The Danish Atomic Energy Commission
Research Establishment Risö
Chemistry Department

Abstract

In connection with a study of the gas separation taking place in the vortex tube, a series of pressure determinations has been carried out. These, together with data from the literature, permit an evaluation of the magnitude and shape of the tangential velocity profile in the type of tube tested. It is indicated how these results may be interpreted in terms of the strength of the radial and axial velocity components.

In a previous publication[1)] a number of experimental data were presented, showing the gas-separation ability of the vortex tube. It was concluded that the driving force behind the observed effects is the centrifugal field.

In the present investigation additional information about the conditions prevailing in the type of tube tested (fig. 1 and ref. 1), fig. 1) has been obtained by measuring static pressures at the wall, along the periphery and elsewhere. More extensive measurements have been made by other authors, and by taking such data into account a fairly complete picture of flow conditions inside the tube has been obtained.

Experimental. Measurements of static pressure were made through 0.5 mm holes in the walls. Their positions are shown in fig. 1. The vortex tubes employed were made from perspex.

Differential pressure measurements were carried out between seven points simultaneously to within 1 mm Hg, while absolute pressure values were obtained to within one to five cm Hg at pressures from one to four atmospheres.

Results

Figs. 2-4 show typical pressure data for tubes with different orifices.

In tubes with narrow orifices and sonic velocity in the ducts, the total flow varies in a characteristic way as shown in fig. 5, while it attains its limiting value (approx. 37 l/min for an inlet jet diameter of 1 mm and a gauge pressure of 3.6 ato.) in tubes with wider orifices.

A plot of the total flow as a function of peripheral pressure indicates that the latter is almost identical with the true back pressure of the jet, with sonic velocity at lower peripheral pressures. There is a small discrepancy, which is probably caused by an irreversible pressure drop between the nozzle and the first pressure point.

The relation between orifice diameters and peripheral pressure is shown in fig. 6, where, in order to obtain monotonous functions, only data measured with one or the other orifice closed are given. With sonic velocity in the jet, this relation is determined on the one hand by the pressure build-up near the axis that provides for the necessary acceleration of the flow into the orifice, on the other hand by the radial pressure gradient created by the rotation of the gas. At smaller orifice diameters the peripheral pressure is determined by the magnitude of the total flow, which, as mentioned, is limited because sonic conditions are created in the exit duct. This critical flow is, however, not directly deducible because, as before, the pressure in the duct is a function of the radial and the axial pressure drop in the vortex tube.

It will be noted in fig. 6 that the pressure-orifice relation depends significantly on the length of the tube; see below for a discussion of this point.

It is possible to obtain a fairly complete picture of the tangential velocity distribution from pressure data such as those given in figs. 2-4. In order that this approach may be successful it is necessary first to select a limited number of functions which experience has shown to be physically relevant.

A number of papers have appeared which give detailed information on the tangential velocity distribution in special types of vortex tubes. It is characteristic that they fall into two rather well-defined groups (table 1). Group a contains the data of Scheller and Brown[2] and of Hartnett and Eckert[3] and clearly shows the existence of a forced vortex almost from the centre to the periphery near the jet; further away the velocity maximum moves somewhat in. Group b contains data measured by Keyes[4] and by

Ter Linden (for a gas cyclone)[5] which indicate the existence of a semifree vortex in the outer region, i.e. $v \propto r^n$ where n is negative, which changes to a forced vortex near the centre. The data of Reynolds[6], belong chiefly to this group.

The two-dimensional theory by Einstein and Li[7] and by Deissler and Perlmutter[8] accounts fairly well for the general trend in these results. According to this theory the radial Reynolds number $Rey_{rad} = \rho ur/\mu$ (where μ may be the molecular or the eddy viscosity, depending on the type of flow in the tube) determines the velocity profile in such a way that group a results are to be expected when Rey_{rad} is small compared with one and group b results when it is somewhat greater than one.

In tubes with a large radial inflow (group b) the theory has a limited applicability, as pointed out by Keyes[4] and by Kendall[9], because a major part of the radial flow is carried by the end-wall boundary layers. This has the double effect of reducing the effective Rey_{rad} in the main tube while giving rise to strong axial flows, at certain intermediate radii, originating from the end-wall radial flow.

As shown by Kendall, these flows may not have lost much of their angular momentum and may therefore contribute considerably to the measurable tangential velocity distribution in the main part of the tube.

Furthermore, a discrepancy between theory and experiment is to be expected because of the assumption that μ is a constant. The flow in the vortex tube has been found to be turbulent (see refs. 9) and 4)), but it is probable that the turbulence will diminish as the gas moves towards the centre (see refs. 4) and 9)); thus a reduction in eddy viscosity must result.

Experiments show (see refs. 4) and 5)) that the overall result of these modifying effects is that, in the expression for $v \propto r^n$, n has a constant negative value in the outer part of the tube (Keyes' results show n = 3/4), changing fairly suddenly to n = 1 at a radius approximately 2/3 of the orifice radius.

In long tubes with little radial flow (group a) the two-dimensional flow picture breaks down, and there is a considerable reduction in peripheral tangential velocity along the tube. It is clear that, connected with this change, there must be a tendency of the radial flow to be displaced away from the jet. If we apply the theory of Deissler and Perlmutter to the two ends of the tube separately, it becomes clear why the tangential velocity changes under these conditions from a forced vortex near the jet to a semifree vortex at the other end.

This change in velocity profile may create an axial pressure gradient at intermediate radii, which will produce a reversed flow towards the jet, resulting in an outward radial flow at the jet. Such a flow has been stated by Sibulkin[10] to exist in a similar tube, and its existence in both cases quoted above may be inferred since the velocity profile at the jet is shown to be concave upwards, i.e. n in the expression for v is here greater than +1 (cf. the experimental results below).

It is interesting to note that tangential Mach numbers near one have been obtained only in group a tubes. The rapid reduction in tangential velocity along the tube in these cases thus becomes understandable. Furthermore the cause of the velocity stabilization at the jet may conceivably be the establishment of the outward radial flow there.

Calculation of the Velocity Profile

The following assumptions, based on the discussion above, were made: A forced vortex always exists in the region limited by a cylinder with a radius 2/3 that of the orifice; outside this region v is proportional to r^n, where n is a constant that may have any value between -1 and +1 (or possibly greater).

The data include measurements at the periphery (r = 5 mm), at the hot end wall (at r = 4 mm), at the cold end wall (at r = 3 mm), and finally measurements in the exit ducts and beyond (see fig. 1). When there is no net flow through one of the orifices, i.e. when the valve there is completely shut, the pressure along the wall of that duct is somewhat lower than the pressure at the corresponding radius in the main tube, but higher than that at the centre. Thus a certain amount of gas is allowed to be accelerated into the duct at its periphery and turned back along the axis. It follows that at an intermediate radius the pressure in the main tube must be the same as the wall pressure in the exit. A probable value for this intermediate radius would appear to be about two thirds of the orifice radius. In this way additional points on the pressure distribution curves have been obtained. These points are reasonably reliable if the orifice at the closed-off exit duct is not too wide.

The best data, as shown in figs. 2-4, give directly the type of velocity profile that exists in the tube, i.e. the value of n in the expression for v, and also provide the magnitude of the peripheral tangential velocity.

In table II the most likely values for v_p and n are given (in cases of equal probability two values are shown) for a number of orifice diameters and two different tube lengths. The inlet or jet velocity as calculated from the flow volume and the peripheral pressure is shown for comparison.

The difference between the long and the short tube, which was already evident in fig. 6, appears clearly in table II. In the short tube the velocity distribution is essentially independent of the axial position, as shown by the fact that changes of the v_p and n values are monotonous with changes in orifice diameter even though the configuration of the tube alternates between open-cold/closed-hot orifice and vice versa. This result, together with the negative n-value, shows that the short tube belongs to the group b tubes discussed above.

In the long tube, on the other hand, there is a marked difference between the two configurations. This means that the flow cannot be approximated by a two-dimensional model: The flow picture strongly resembles that obtained with group a tubes, i. e. there is a forced vortex near the jet at all radii, changing to a semifree vortex in the outer part of the tube towards the far (hot) end of the tube, and probably a considerable reduction of v_p along the periphery. In addition, an outward flow near the jet is highly probable, especially so since the pressure data might have been better fitted with an n-value greater than one.

It is readily seen (table II) that the hypothesis made above concerning the difference between group a and group b tubes predicts a difference between the long and the short tube of the same kind as that found experimentally.

A comparison of the peripheral tangential velocity with the expected jet velocity shows that a considerable reduction takes place at or near the jet, as was to be expected. The data for the long tube are not accurate enough to decide whether there is a stabilization of the jet velocity in this case.

The actual values of total flow and peripheral pressure are selected by the tube in such a way that the pressure distribution in the centre region of the tube is suitable for accelerating the flow into the exit duct. In agreement with this it is found by calculation that the absolute magnitude of the pressure in the centre region is fairly insensitive to changes in tube length at large orifice diameters, where the jet limits the flow volume. The finding (fig. 6) that the peripheral pressure is lower in long tubes than in short thus reflects the fact that the pressure gradient is steeper the shorter the tube.

Similar results have been obtained by Kendall, who explains this trend in terms of a varying contribution of the end-wall boundary flow to the total inflow.

When the orifice limits the flow, a similar relation holds, but the pressure at the centre should be lower the shorter the tube (for a given orifice) because the gas volume will decrease with an increase in pheripheral pressure. Thus the pressure gradient in the 1 cm tube, which has not been measured directly, is probably greater than indicated by the differences in fig. 6.

The Flow through the Open Exit

The pressure measured at the wall of an open exit duct and the flow volume through the exit may be used for the calculation of the axial velocity of the gas in the exit when it is taken into account that the pressure at the centre of the vortex tube represents the stagnation pressure of this flow. The calculation has a meaning only for narrow orifices, where the radial pressure difference is small compared with the pressure drop from the centre of the tube to the surroundings.

The velocities calculated on this basis for the position in the duct nearest the orifice are still far below sonic. On the other hand the pressure corresponding to choking caused by friction in a narrow orifice duct may still be much greater than the pressure of the surroundings (see fig. 7); thus it follows that the gas leaves sufficiently narrow orifice ducts with sonic velocity. Fig. 7 shows that the critical pressure at the point of choking, i.e. at the end of the narrow exit duct, is in certain cases much lower than the pressure predicted by a linear extrapolation of the measured pressure values along the duct. It is therefore necessary that a considerable pressure reduction takes place between the last pressure point and the mouth of the duct. This reduction may well be caused by a sudden breaking-up of the superimposed rotational motion in this region, leading to a so-called hot spot there.

References

1. C. U. Linderstrøm-Lang, Gas separation in the Ranque-Hilsch vortex tube. Int. J. Heat Mass Transfer 7, 1195 (1964).

2. W. A. Scheller and G. M. Brown, The Ranque-Hilsch vortex tube. Ind. Eng. Chem. 49, 1013 (1957).

3. J. P. Hartnett and E. R. G. Eckert, Experimental study of the velocity and temperature distribution in a high-velocity vortex-type flow, Transact. A. S. M. E., p. 751 (May 1957).

4. J. J. Keyes, Jr., Experimental study of flow and separation in vortex tubes with application to gaseous fission heating. J. Amer. Rocket Soc. 31, 1204 (1961).

5. A. J. Ter Linden, Untersuchungen an Zyklonabscheidern. Tonindustrie Z. 77, 49 (1953).

6. A. J. Reynolds, A note on vortex-tube flows. J. Fluid Mech. 14, 18 (1962).

7. H. A. Einstein and H. Li, Steady vortex flow in a real fluid (Heat Transfer and Fluid Mechanics Institute) (Stanford Univ. Press, 1951).

8. R. G. Deissler and M. Perlmutter, Analysis of the flow and energy separation in a turbulent vortex. Int. J. Heat Mass Transfer 1, 173 (1960).

9. J. M. Kendall, Experimental study of a compressible viscous vortex. Techn. Report No. 32-290, Jet Propulsion Laboratory, California Institute of Technology (1962).

10. M. Sibulkin, Unsteady, viscous circular flow, Part 3: Application to the Ranque-Hilsch vortex tube. J. Fluid Mech. 12, 292 (1962).

Table I

	D cm	L/D	d_c cm	d_h cm	No. of jets	p_o atm	p_p atm	Total flow l/min	θ	Relative axial flow	Average radial flow l/cm min	$\frac{\rho ur}{\mu}$	$\frac{\rho ur}{\mu_e}$	Mach number at jet	group
Hartnett Eckert	$7\frac{1}{2}$	10	0	annu-lar	8	1.7	1	10^4	1	200	0	0	1	$\frac{8}{9}$	a
Scheller Brown	$2\frac{1}{2}$	43	0.9	1.0	4	5.4	1.5	620	$\frac{1}{2}$	100	3	40	$\frac{1}{4}$	$\frac{8}{9}$	a
Present exp.	1	$13\frac{1}{2}$	0.2	0.2	1	4.6	2	35	-	35	2.6	34	$\frac{1}{4}$	-	a
Present exp.	1	1	0.2	0.2	1	4.6	2	35	-	(35)	35	450	10	$\frac{1}{5}$	b
Keyes	5	-	1.2		-	6	3	-	-	0	18	240	10	$\frac{1}{3}$	b
Reynolds	$7\frac{1}{2}$	16	3.2	3.2	8	2.3	1	2300	-	40	20	265	2	1/2.5	b

p_o: pressure of the compressed air

Relative axial flow: total flow/D^2

$\rho ur/\mu_e$: from a comparison with the velocity profiles given by Deissler and Perlmutter[8].

Table II

Tangential velocity. 10 mm tubes (D = 10 mm). $v \propto r$ for $r < r_f = \frac{2}{3} r_i$; $v \propto r^n$ for $r_f < r < r_p$

L	$2r_i =$ d_c	d_h	$r_p^{*} = r_p/r_f$	v_{jet} m/sec	v_p m/sec	n	v_f	p_p cm Hg	p_f cm Hg
6	0.75		20	105	20/14	$-\frac{1}{4}/-\frac{1}{2}$	42/52	310	300
		1.0	15	165	45/30	$-\frac{1}{4}/-\frac{1}{2}$	89/116	282	240
	1.5		10	250	65/45	$-\frac{1}{4}/-\frac{1}{2}$	116/143	212	173
		2.0	7.5	315	75	$-\frac{1}{2}$	206	158	103
	3.0		5.0	315	80	$-\frac{1}{2}$	179	114	86
		4.0	3.75	315	105	$-\frac{1}{4}$	146	99	78
$13\frac{1}{2}$	0.75		20	110	17/13	$+1/+\frac{1}{2}$	1/3	308	307
		1.0	15	195	40	$+1$	3	263	261
	1.5		10	315	20	$-\frac{1}{4}$	36	162	158
		2.0	7.5	315	90	$+1$	12	112	106
	3.0		5	315	20	$-\frac{1}{4}$	30	91	90
		4.0	3.75	315	115	$+1$	31	85	79

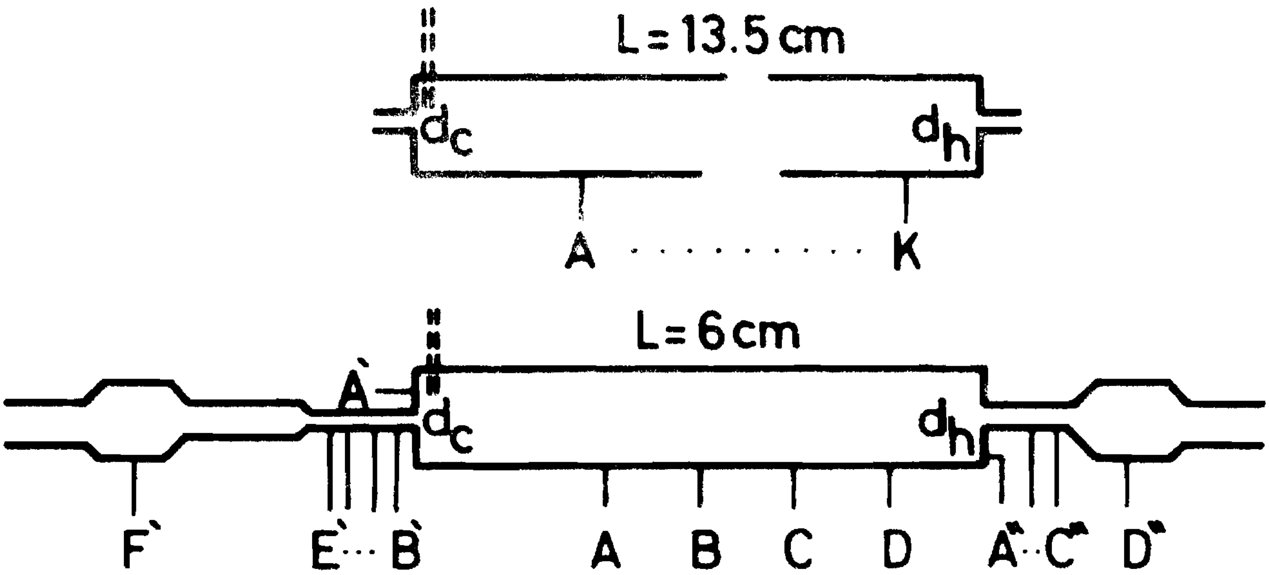


Fig. 1. Diagram of the vortex tube. The letters indicate pressure points.

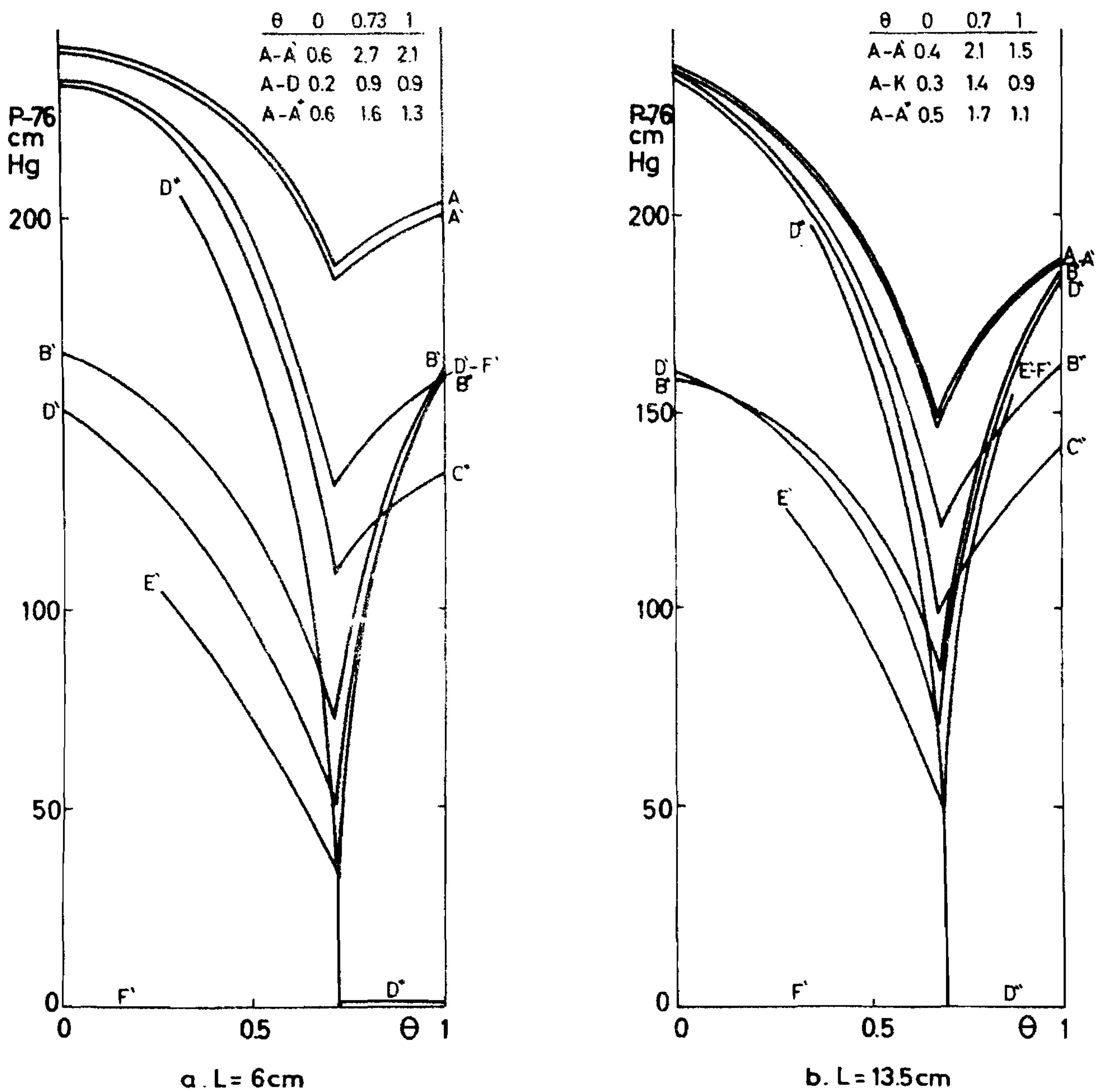


Fig. 2. Wall pressures as functions of hot-flow fraction, θ, i.e. flow through d_h over total flow. $d_c = 0.75$ mm, $d_h = 1$ mm.

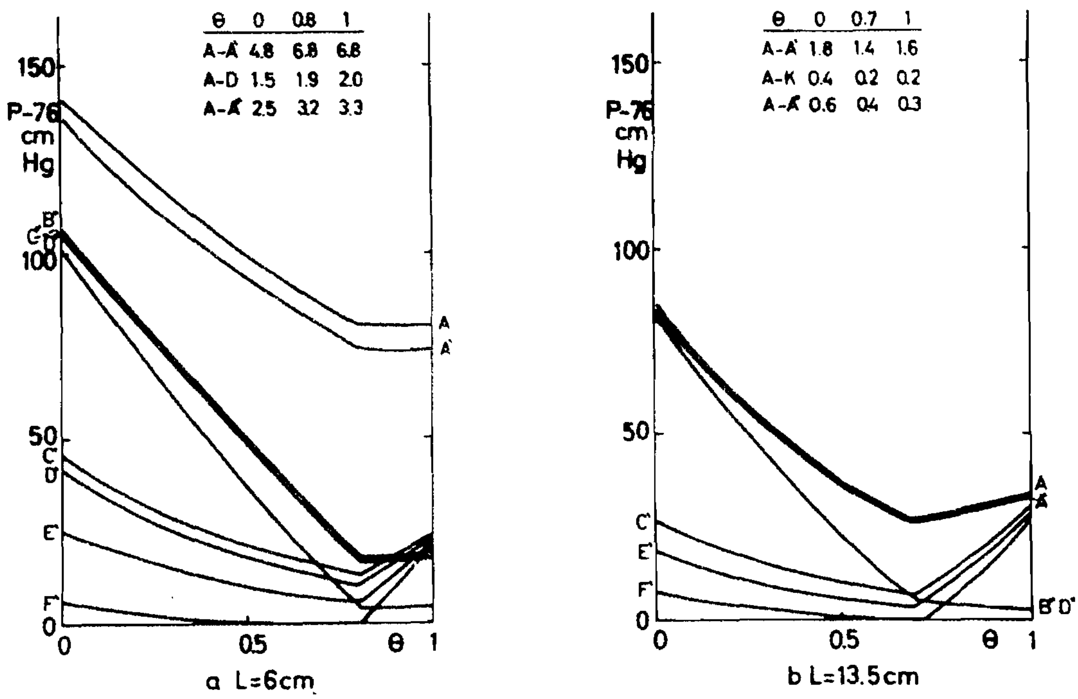
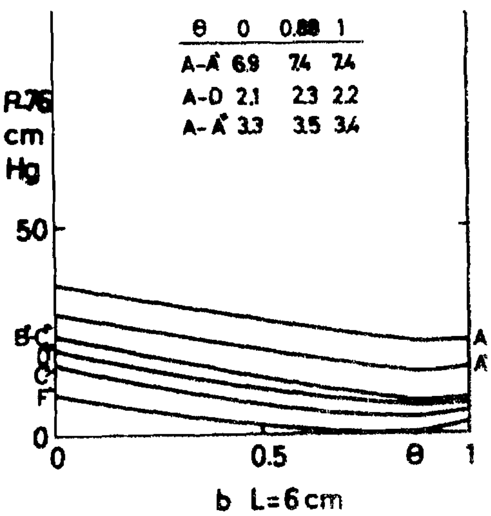


Fig. 3. Wall pressures as functions of θ. $d_c = 1.5$ mm, $d_h = 2$ mm.



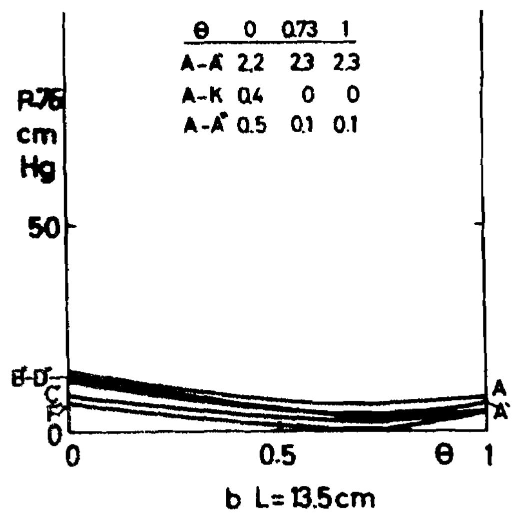


Fig. 4. Wall pressures as functions of θ. d_c = 3 mm, d_h = 4 mm.

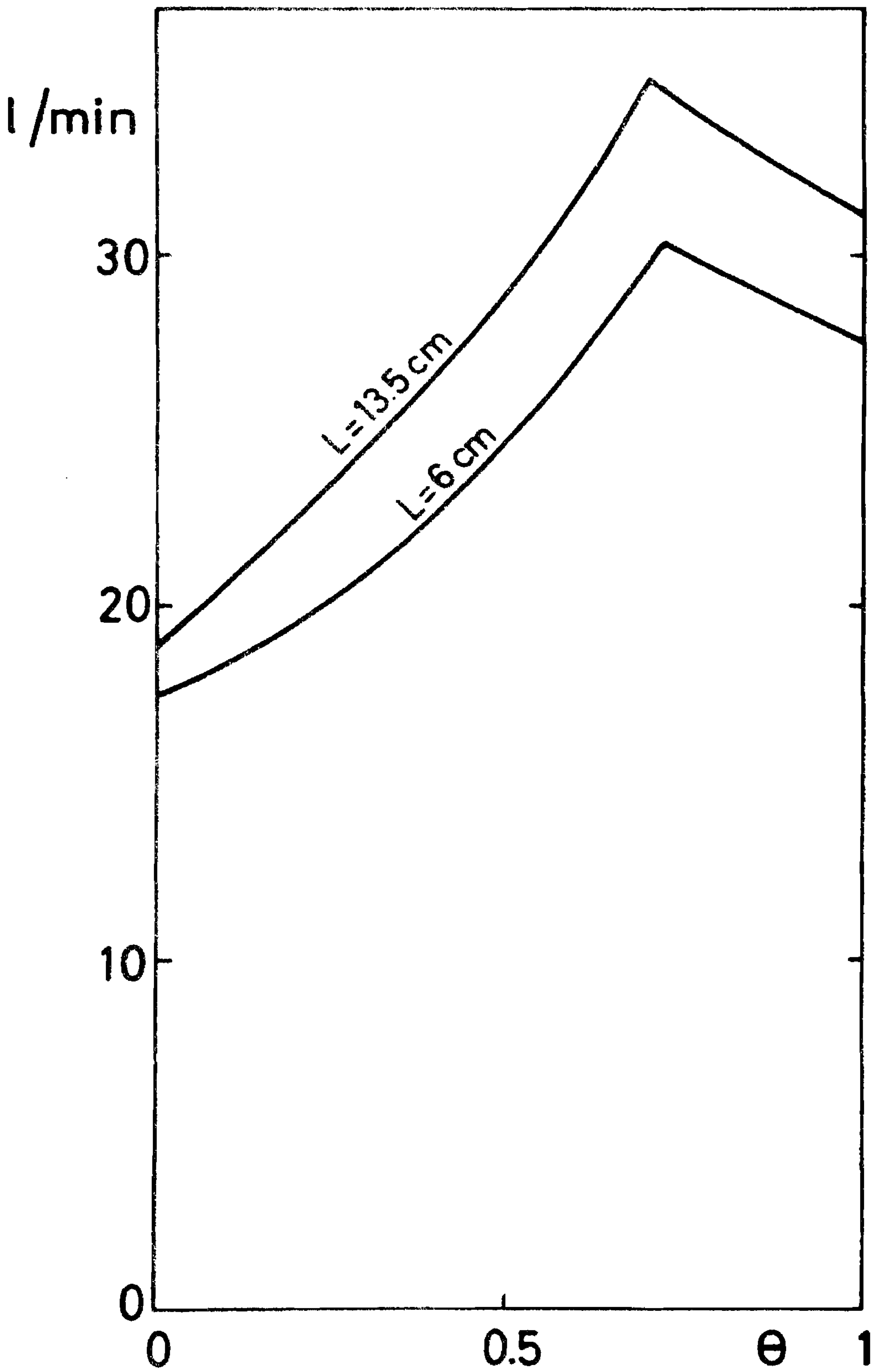


Fig. 5. Volume of air through vortex tubes as a function of θ. d_c = 0.75 mm, d_h = 1 mm.

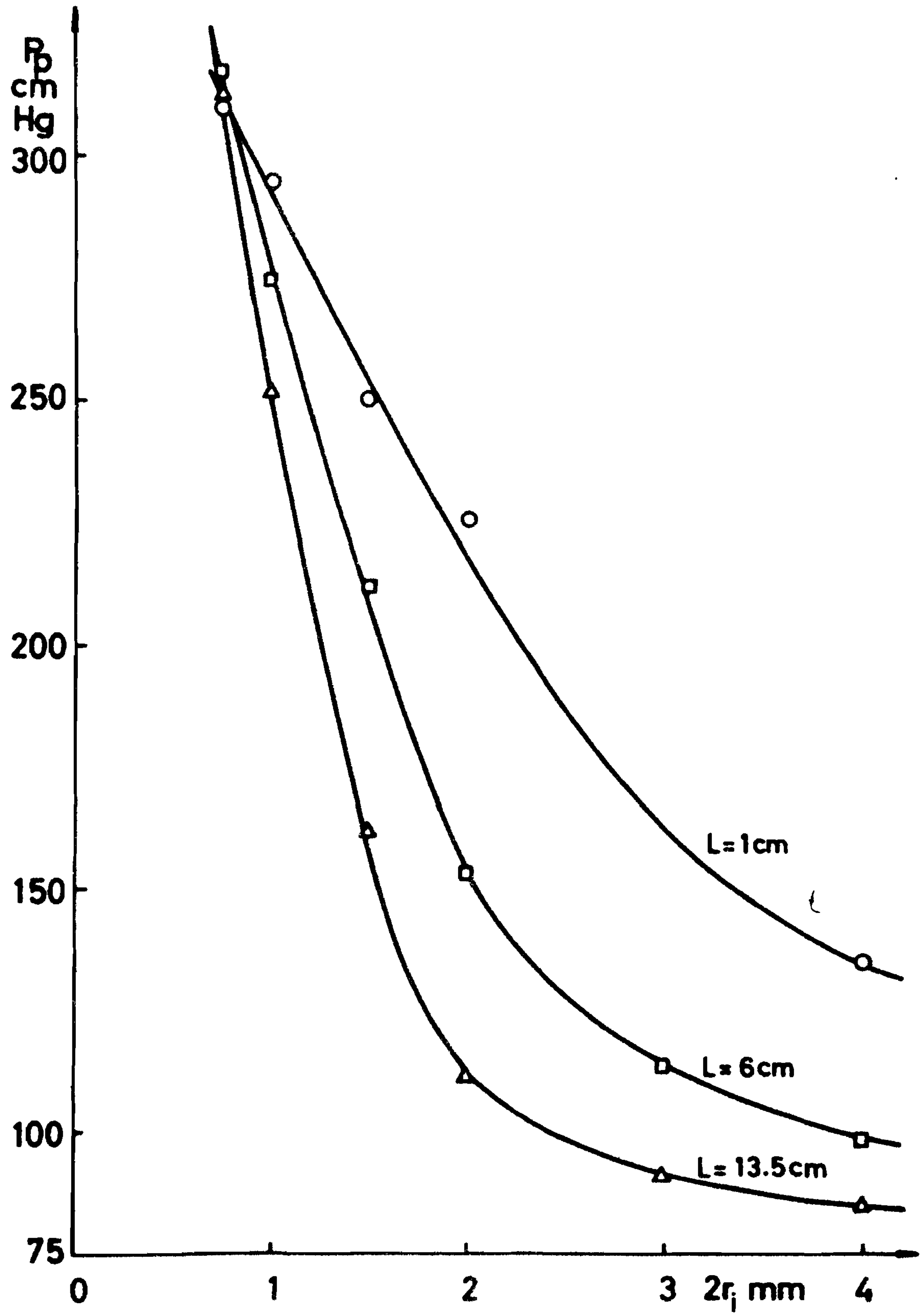


Fig. 6. Peripheral pressure as a function of orifice diameter. $2r_i = d_c$ or $2r_i = d_h$.

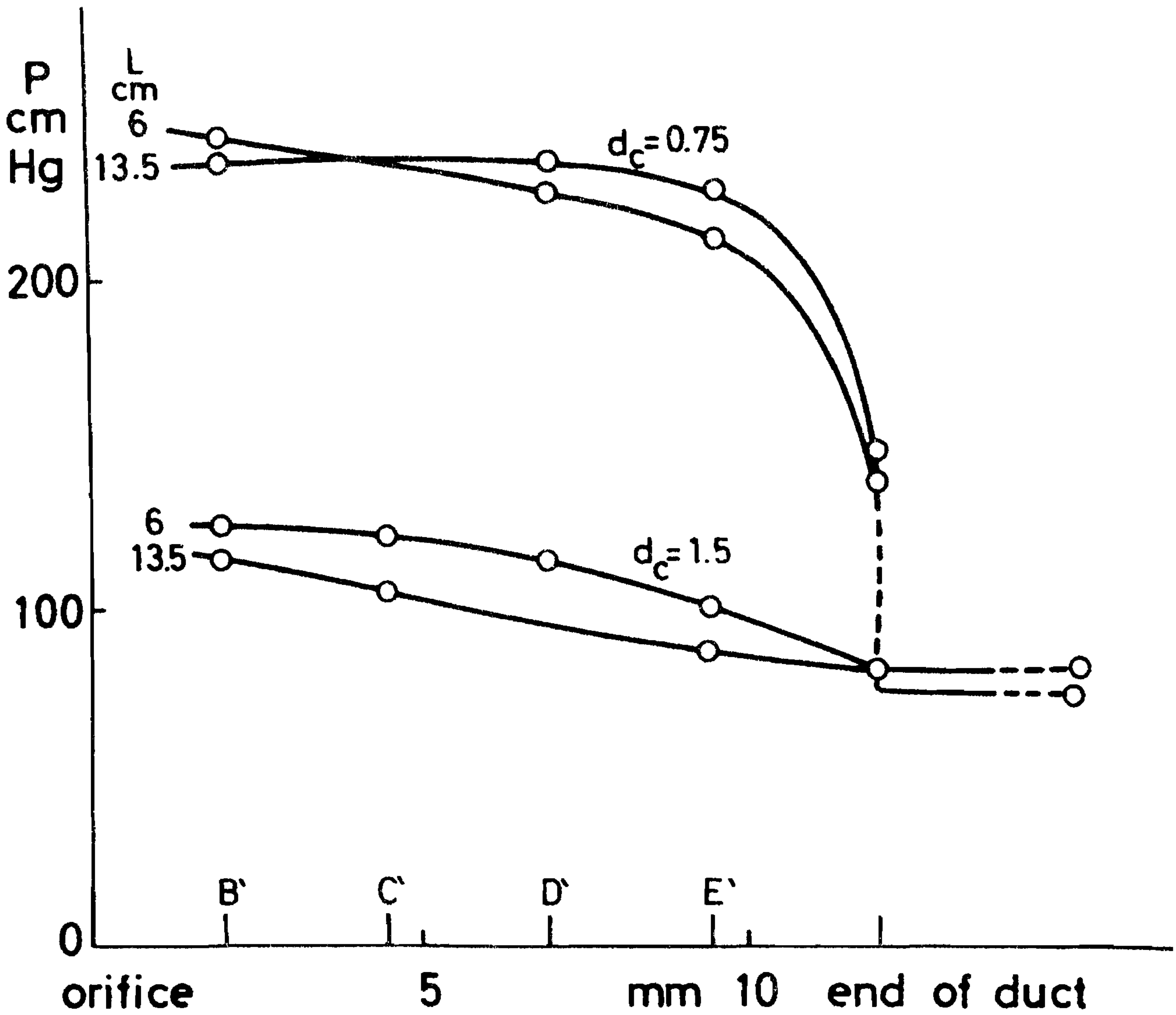


Fig. 7. Wall pressures in open exit duct (cf. fig. 1).