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AIR-ENTRAINING WATER FLOWS UNDER A REDUCED AMBIENT PRESSURE

by

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S U M M A R Y

The aim of this work was to investigate the effect of a reduction in ambient atmospheric pressure on the flow of water in which air is entrained.

It was known that the flow through a vertical pipe is a powerful entrainer of air over a particular range of supply level. Accordingly this flow was observed in a decompression chamber over a range of ambient pressure from 50 to 760 mm mercury.

It was observed that there were three major types of air entrainment and that the air flow diminished with decreasing ambient pressure.

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INTRODUCTION

One aim of this work was to describe the effect of a reduction in ambient atmospheric pressure on the flow of water in which air is entrained. It was prompted by the suggestion, frequently expressed (see for example BINNIE & SIMS (1)), that the properties of such a flow might be more accurately modelled if the effective atmospheric pressure were scaled appropriately.

It was noted by BINNIE (2) that the flow of water down a vertical pipe is a powerful entrainer of air over a limited range of supply head. Accordingly this flow was studied and a second aim of this work was to describe its air entraining processes.

Air entrainment is, of course, strongly influenced by other factors such as surface tension and viscosity, but in the small scale experiments to be described attention was concentrated on the consequences of altering the ambient pressure within the wide range 50 to 760 mm mercury. The work was carried out with water at a sensibly constant temperature.

APPARATUS

The experiments were performed in a decompression chamber, indicated schematically in side elevation in figure 1. Access was at one end through a rectangular door about 850 mm high and 600 mm wide. The chamber was divided by a bulkhead, the original door in which was removed. There were two portholes in the outer chamber and six in the inner. Through a connexion at the top, the chamber was evacuated by a pump that in 10 minutes could reduce the absolute pressure to 50 mm on a mercury gauge. Air was readmitted by a 38 mm (1½ in.) valve.

The water was circulated by a centrifugal pump sited outside the chamber. The pump was designed to operate under a very low suction head, and it was driven by a d.c. electric motor fitted with conventional speed controls. A fresh charge of water was circulated for many hours under the highest attainable vacuum in order to remove dissolved air. The flow was measured by a standard orifice plate connected to mercury-water and air-water manometers. It was feared that its action might be vitiated by the emergence of dissolved air on the downstream side, where the pressure in the system was lowest. So the horizontal piping there was made of Perspex, and air which did in fact collect at this point was sucked out by a water-driven ejector. The arrangement proved invaluable also for detecting leaks.

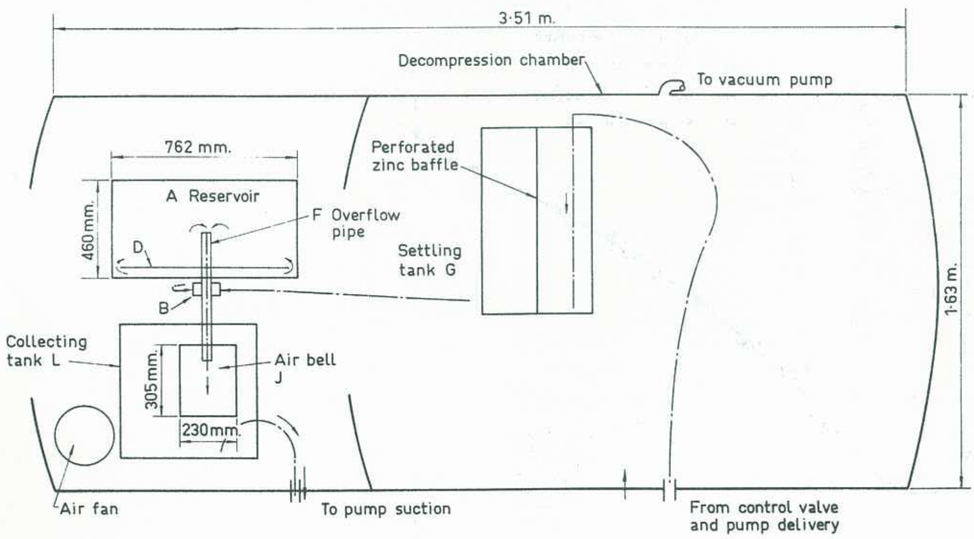


Figure 1 *Arrangement of Apparatus*

The water entering the chamber was carried first to the settling tank G in the inner part, whence it passed to the vertical-pipe apparatus housed in the outer chamber. To avoid swirl in the water approaching the top of the vertical pipe F, the supply came in by two pipes diametrically opposed in the component B which was bolted over a hole in the bottom of the circular tank A. It then moved up into the tank past vertical fins to reduce the swirl, and was guided out towards the wall of the tank by the circular baffle D which was supported on three small feet. The pipe F was fixed to the plate that was bolted over the base of component B.

This arrangement had been found effective by BINNIE (2) and it was improved by adding radial fins to the underside of the baffle D. The vertical pipe was of stainless steel 450.8 mm long, with inner and outer diameters 28.6 and 31.8 mm; its top, placed 114 mm above the baffle, was machined flat. For photographic purposes a Perspex extension 50 mm long was sometimes pushed over the top of the pipe.

The water level in the tank was measured by means of a vertical graduated glass tube visible through a porthole. The collecting tank L for the water was placed below the vertical pipe, and the Perspex bell J was clamped round the pipe outlet with its open bottom sealed by the water in the tank. To assist their separation, the water and the air emerging from the pipe struck a piece of wood floating within the bell. The water passed from the tank to the suction side of the pump, while the air was taken from the top of the bell through a stilling box and a dry gasmeter to an electric fan, controlled from outside so that the pressure difference, read on a water manometer, between the interior and exterior of the bell was negligible. Both the gasmeter and thermometer could be seen through a porthole. It was confirmed that the airbell did not alter the flow: the head-water flow relation shown in figure 2, the gulping behaviour and the transition between regimes were not influenced by its presence. The action of the gasmeter at reduced ambient pressures was checked by inflating through it a polythene bag of capacity about 0.04 m^3. This trial was done at various rates, and no discrepancies were found.

DESCRIPTION OF THE AIR-ENTRAINING FLOW THROUGH THE PIPE

Figure 2 shows the relation between the head Y over the pipe crest and the water flow W plotted non-dimensionally for an ambient pressure of 760 mm mercury. The ordinate h is Y/D where D is the pipe internal diameter and the abscisse Q is W/X where X is the flow (14.16 l/s here) at which the pipe just ran full of water, identified on figure 2 by the sharp discontinuity at Q = 1.00. Although five regimes may be distinguished in figure 2 attention is limited here to regime 2, defined as the range of conditions in which a measurable quantity of air was drawn through the pipe. Regime 2 excludes the air entrainment associated with vortices.

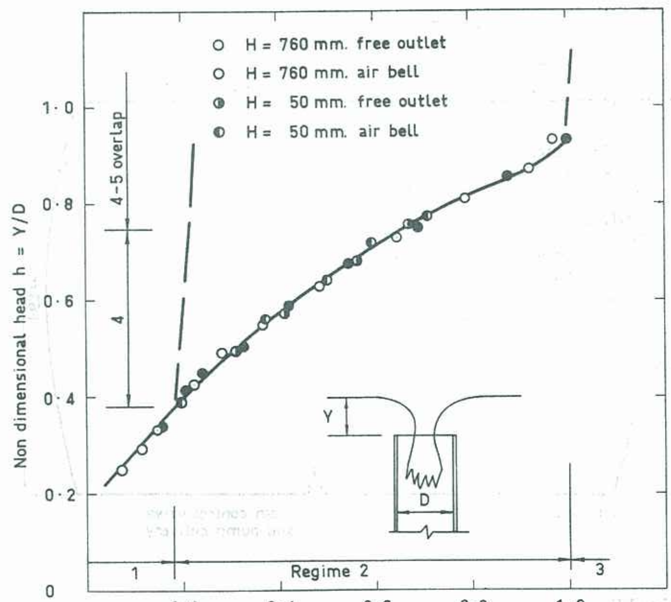
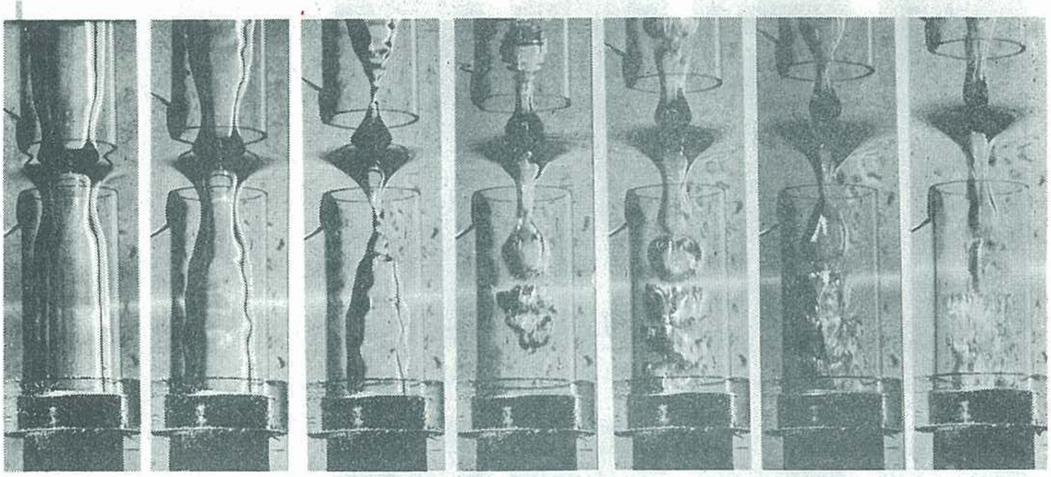


Figure 2 *Vertical pipe. Relation between head and air-entraining flow*

Under a rising head regime 2 began when the smooth weir-like flow of regime 1 suddenly became unstable. The series of photographs in figure 3 shows how the flow pattern changed with head. Figure 3 (i) illustrates the flow with a smooth air core in regime 1 at h = 0.27. The surface of the air core was slightly disturbed at h = 0.35 (figure 3 (ii)). Gulping was about to start in the next photograph, h = 0.44, and the core was distorted, particularly at its narrowest part. Regular gulping was observed in the range of h from 0.37 to 0.50 in which the period of the gulping cycle increased from 0.2 to over 1.0 second.



h = 0·27	0·35	0·44	0·52	0·62	0·70	0·79
Q = 0·08	0·15	0·24	0·34	0·47	0·58	0·75
q = 0	0	1·10	0·70	0·59	0·44	0·25

Figure 3 *Vertical pipe. Air-entraining flow*

When viewed from above gulping appeared as a radial oscillation of the air core surface, making it open and close. It clearly played an important role in the entrainment of air and it will be described in detail - Figure 4 shows the flow at various times during one gulping cycle when h = 0.43. At this head the gulping was regular with a period of 0.36 sec. Two series of photographs were used to construct figure 4: a 16 mm cine film, taken at 64 frames per second, and a series of random exposures illuminated by a 1/1000 second electronic flash. A selection of the latter have been used arranged in the correct sequence and with an approximate time scale added after a close comparison with the relevant cine film frames.

Photograph 4 (i) shows the symmetrical flow just before a gulp starts. Photograph 4 (ii) (t = 0.02s), taken 0.02s after photograph (i), shows the air core separated. The pointed ends of the upper and lower remnants of the air core suggest that the break occurred at or near to the point of minimum air-core diameter. The separation pocket, revealed by the dye filament, appears to be slightly larger than in (i). In both pictures the surface of the air core was slightly disturbed. The situation at t = 0.03s (iii) is that the ends of the two parts of the air core have become flatter. The bubble moving down the pipe was further from the inlet and the dye trace suggests that the flow of water into the pipe was steady and that it was not much altered by whether the air core was open or closed at the reservoir surface. In photograph (iv) the ends of the separated parts of the air core have become further apart and their ends were flatter still. Photograph (v) was taken soon after the air core reformed. The surface dimple had deepened quickly and developed six capillary waves on its surface. As the dimple extended into the pipe it began to disintegrate and assume the appearance of a jet of air forced into the pipe from the free surface. As soon as the core was established in the flow it became apparent, figure 4 (iv), that its surface was disturbed by steep and irregular waves, the amplitude and wavelength of which were about 0.3 and 1 times the diameter of the core. The waves died slowly and a little over half way through the cycle, figure 4 (vii), t = 0.25s, the surface of the core was nearly as smooth as it was at the beginning of the cycle. The core surface remained relatively smooth for about 0.15s, until at t = 0.36s the cycle suddenly started again with the parting of the air core. As h rose through the regime the gulping period not only lengthened but it also became more irregular. The importance of this mode of air entrainment therefore decreased to

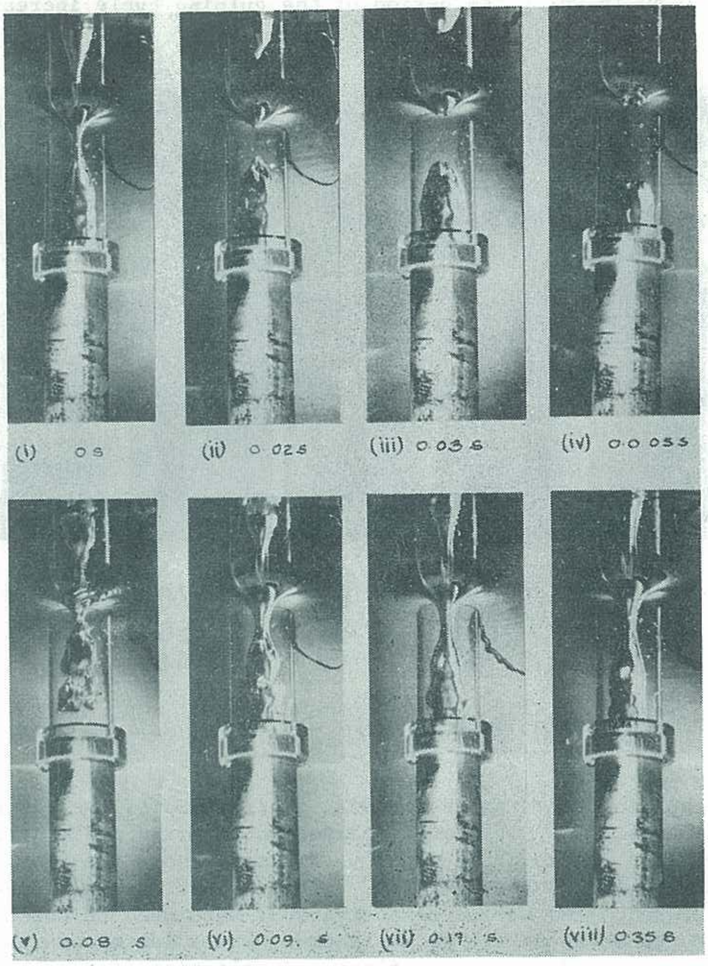


Figure 4 *Vertical pipe. A single gulping cycle.* $h = 0.43$, $Q = 0.23$, $q = 1.15$

insignificance at h = 0.45.

In the lengthening intervals between gulps at h > 0.5 the flow began to growl with a frequency which rose with head, and figure 3 (iv) - (vii) suggests (in agreement with BINNIE(2)) that the growling originated in the movement of the surface of the air core. As the head rose, the amplitude of the protuberances on the core surface increased until at h = 0.52 (figure 3 (iv)) they met across the core to enclose bubbles of air about one diameter long. Figure 3 (v) and (vi) confirm that the wavelength of the disturbance is approximately constant with rising head.

The appearance of the air core remained sensibly unchanged from h = 0.52 until h = 0.75 when its structure broke down owing to the asymmetry of the flow at the pipe inlet. Increasingly as h increased above 0.60 one side of the air core bulged more than the other to produce a radial "rib" on the convex water surface at the beginning of the air core. The rib is shown in figure 3 (vi) and (vii) and is described more fully in SIMS (3): it is sufficient for the present purpose to record that the air core was seriously and increasingly distorted by the rib as h rose to 0.92. Indeed, figure 3 (vii) suggests that the air could scarcely be said to be in a core, having become widely distributed across the pipe section after only one pipe diameter.

With increasing head through the regime it was observed that the time mean value of the geometricaly minimum area of the air core decreased steadily to a minimum at h = 0.45. As shown in figure 5 it then increased to a maximum at h = 0.65, thereafter falling to zero at the submergence head, h = 0.92.

When the flow was examined under reduced ambient pressures the perspex extension piece had not been fitted to the pipe and so the details of the flow inside the pipe were not observed. However, figure 2 shows that the head-discharge relationship was not affected by the ambient pressure in the absence of the effects of cavitation and experiment confirmed that the gulping behaviour was similarly insensitive.

AIR ENTRAINMENT

Figure 5 includes the relationship between the air flow q and head h at an ambient pressure H of 760 mm mercury. Here q is defined as the air flow indicated by the gas-meter divided by the coexistent water flow. Figure 5 reveals that immediately gulping started q achieved its maximum of 1.32 at h = 0.40 and then rapidly decreased, as the gulping intensified, to a pronounced change of slope at h = .50 which was perhaps associated with the sudden increase in the area of the air core. The air flow thereafter declined slowly, despite the increase in air core area, until h = 0.60. As h increased above 0.60 the water flow increasingly choked the pipe inlet and the air flow diminished linearly towards zero at the submergence head, h = 0.92.

There appear to be three mechanisms by which air is entrained into the water flow through the pipe in regime 2.

(A) The entrainment associated with gulping.

(B) The entrainment caused by irregular waves on the surface of the air core.

(C) The entrainment which occured when the rib was present.

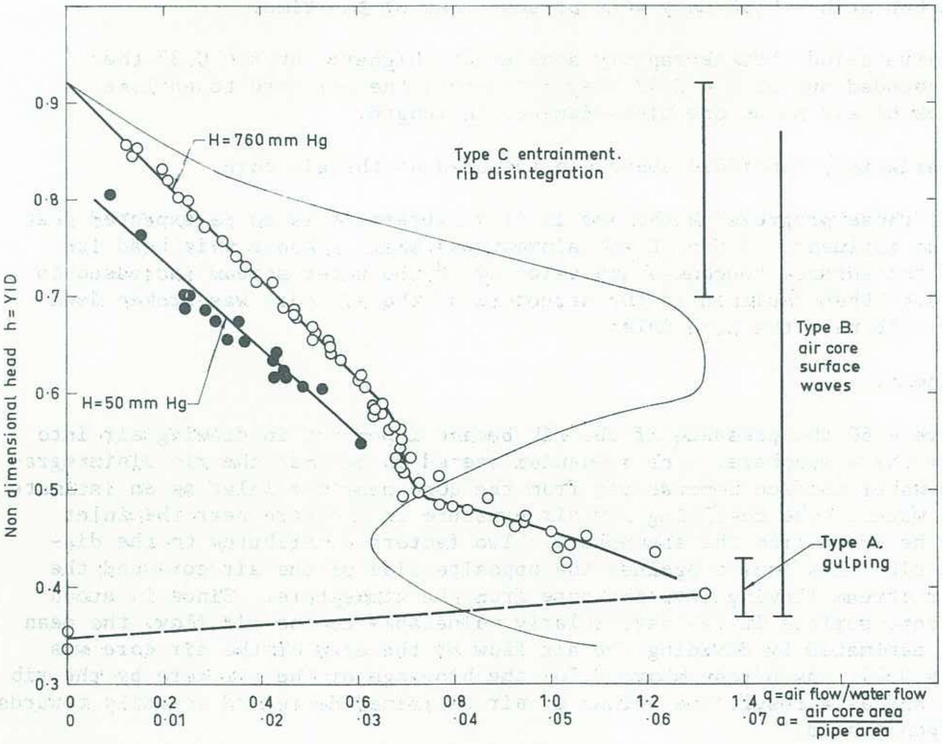


Figure 5 *Vertical pipe. Relation between air entrained, air core area and head*

Type A entrainment

It is possible to construct a simple model of the gulping flow and to correlate the water flow, the air flow, the gulping period and the mean velocity of the flow through the pipe inlet. The assumptions made are (a) that the air was entrained in large bubbles that were drawn into the flow while the air core was open, and separated by blocks of water (b) that air is incompressible and the bubbles travelled through the pipe at the average water velocity. The model is successful only qualitatively for it predicts the location of the air flow maximum near h = 0.40. This location coincides with the gulping period (0.48 sec) at which only one water block was present in the pipe at a time, presumably the situation in which the air flow was a maximum. Both model and experiment agree that as the gulping period increases with rising h above 0.40 the air flow falls rapidly away, but the model underestimates the air flow by about 30%.

Type A air entrainment thus coincided with the start of gulping at h = 0.37 and fell away rapidly once h rose above the head at which the gulping period was greater than 0.48 sec, h = 0.43 approximately.

Type B entrainment

It will be recalled that during a gulping cycle a pattern was observed in the behaviour of the surface of the air core. The surface was considerably disturbed by relatively large waves during about a quarter of the gulping cycle after the reformation of the core. Further, as the head rose, the frequency of the gulping decreased and it became less regular. In the lengthening periods between gulps the air-core surface was found (figure 3) to be permanently disturbed with large, irregular waves that are considered to be the source of the growling emitted by the flow. The waves on the air core surface were responsible for type B air entrainment: the air being drawn down the pipe by the drag between it and the corrugations on the core surface.

Type B air entrainment began at h = 0.37, when gulping started and under a rising head the entrainment was affected in three ways.

(i) The air core corrugations appeared for a greater proportion of the time: at h = 0.37 they were present only briefly during a gulping cycle but at h = 0.50 they were present most of the time.

(ii) The corrugations became rapidly steeper and higher: at h = 0.37 they were rounded but at h = 0.52 they met across the air core to enclose bubbles of air about one pipe diameter in length.

(iii) The variation, described above, in the area of the air core.

As a result of these progressive changes in flow pattern it is to be expected that for h up to 0.43 the influence of type B entrainment was small. Above this head its importance rose as the surface roughness and velocity of the water stream increased to the maximum at h= 0.67 then declined as the structure of the air core was broken down increasingly by the rib near the pipe inlet.

Type C entrainment

When h is above 0.60 the presence of the rib became important in drawing air into the water flow from the atmosphere. The mechanism seemed to be that the rib disintegrated and the broken water surface removed air from the core near the inlet as an intimate mixture of air and water. The resulting low air pressure in the core near the inlet caused more air to be drawn from the atmosphere. Two factors contributed to the disintegration of the rib: its impact against the opposite side of the air core and the velocity of the air stream flowing into the core from the atmosphere. Since it stood well clear of the core surface it was particularly vulnerable to the air flow, the mean velocity of which, estimated by dividing the air flow by the area of the air core was about 10 m/s at h = 0.70. As h rose above 0.70, the blockage of the air core by the rib became more severe and as a result the volume of air entrained decreased steadily towards zero at the submergence head.

The air flow was found to depend on the ambient pressure H and the results for H = 50 mm mercury given in figure 5 reveal that the air flow was reduced by about 20% throughout. It will be noticed that the curve for H = 50 mm mercury is truncated at both ends. Over the missing range at the bottom the gulping activity was so greatly curtailed that the flow changed of its own accord to Borda flow before the readings for figure 5 could be obtained. This phenomenon together with the truncation on the top was caused by cavitation and is not dealt with further here: they are more fully discussed in SIMS (3). Apart from these truncations, the flow was not visibly influenced by cavitation and an explanation of the reduction in entrained air must be sought elsewhere.

Measurement of the air flow at other ambient pressures confirmed that the reduction in ambient pressure down to 250 mm mercury had little effect, and the change down to 50 mm was responsible for the whole of the diminution in the measured air flow.

DISCUSSION AND CONCLUSION

Major air entrainment in the flow through a vertical pipe takes place, with considerable overlap, in three modes:

(a) Through the periodic disturbance of the air core termed gulping.

(b) Through the drag associated with large irregularities on the surface of the air core.

(c) By the disintegration of the lower end of the radial asymmetry of flow at the inlet called the rib.

In the absence of cavitation the reduction of ambient atmospheric pressure H has no noticeable effect on the relation between the head and the water discharge, or on the gulping, although the air flow is lessened. The reduction in H diminishes the stiffness of the air bubbles and it is concluded that the transient vibrational behaviour of the bubbles has an unimportant influence on the water flow.

The air flow diminishes as the ambient pressure falls. The diminution remains small until the pressure reduction is large: when H is 50 mm mercury the air flow is about 20% less than when H is 760 mm.

A partial explanation of the reduction in air discharge may be the fact that at normal atmospheric pressure bubbles drawn through the apparatus, although broken up, suffered only a small change in total volume. In contrast, when measured on a water manometer the lowest ambient pressure employed was of the same order of magnitude as the vertical dimensions of the apparatus, and bubbles in the critical low pressure region near the inlet occupied a larger volume than at entry to the pipe. Since the water discharge remained unchanged, so did the air discharge across the critical section. Hence at small ambient pressure the demand for air at the critical section was met by a smaller flow through the gasmeter.

However, it is not clear why the reduction mH from 760 to 150 mm mercury had such a small effect compared with that from 150 to 50 mm.

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The views expressed in this paper are not necessarily those of the Snowy Mountains Engineering Corporation.

REFERENCES

1. BINNIE, A.M. & SIMS, G.P. Air entrainment by flowing water under reduced atmospheric pressure. Jl. Hydraul. Res. Vol. 7 No.3 p.279, 1969.

2. BINNIE, A.M. Proc. Roy. Soc. Series A. Vol.168 p.219, 1938.

3. SIMS, G.P. Hydraulic modelling of air entraining processes. Ph.D. thesis, University of Cambridge, 1967.