Vortex amplifier internal geometry and its effect on performance

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Consideration of the internal geometry of a vortex amplifier reveals eight geometrical ratios that describe the device. The effects of each of these ratios on the performance of a vortex amplifier are considered and experimental results presented. The most significant ratios when designing for vortex amplifier performance are identified

Keywords: *power fluidics, vortex amplifier, performance, design*

Power fluidics may be defined as the engineering art of controlling process fluid flows without using moving parts. The kinetic and potential energies of the process fluid itself are employed to control the flow using vortex amplifiers, vortex diodes, beam deflection amplifiers etc. The techniques of fluid/fluid and fluid/containing-geometry interaction are powerful and elegant. The main advantage of power fluidics over conventional controllers is the absence of moving parts and the complete reliability and lack of maintenance requirements that this implies. The main disadvantage is the 'off' state or leakage flow required for a pure fluid device to operate.

Fig 1 shows a conceptual radial vortex amplifier. The supply flow enters the vortex chamber radially via the supply inlet(s), passes radially inward through the vortex chamber, turns and leaves axially via the exit throat and exit diffuser. The resistance to flow is varied by the introduction of control flow tangentially via the control inlet(s). The angular momentum of the control flow is imparted to the total flow and the flow forms a free vortex. The vortex amplifier has its effect by generating high levels of kinetic energy in the vortex chamber through the high tangential velocities reached at the exit throat. This kinetic energy is destroyed in the complex and highly turbulent flow in the exit diffuser. Varying the level of control flow generates varying levels of kinetic energy and hence of total pressure drop across the device.

The work described here formed part of the United Kingdom Atomic Energy Authority's programme of research into power fluidics. It is concerned with the effects of internal geometry on the performance of radial vortex amplifiers. Previous investigations of vortex amplifier (va) performance had been for use in signal fluidics and it was considered that much of that work was not strictly applicable to the radial vortex amplifier geometries used for power fluidics by the UKAEA, or that the previous work had not been carried out in a sufficiently systematic manner to enable engineering design algorithms to be developed.

A review of published work on the effects of internal geometry reveals that much of it, although useful pioneering work, was not carried out in a systematic way. In some instances more than one variable was changed at once[1,2] and in others the chamber outlet diameter was changed[3,4], thus varying all of the important geometrical ratios at once. The steady-state turndown performance of radial vortex amplifiers was therefore systematically investigated.

Choice of performance criteria

To measure the performance of a vortex amplifier it is necessary to define some criteria for measurement. In some applications vortex amplifiers are used for pressure control so a pressure difference or a pressure ratio should form one of the criteria. The va, like any fluidic device, has a leakage flow when in the 'off' state and so some measure of this leakage flow relative to the maximum operating flow is also a sensible criterion. Tippetts[5,6] has pointed out that a vortex amplifier can be treated as a three terminal device having six characteristic variables (Fig 2). Kirchoff's laws apply and:

$$P_{cs} = P_c - \Delta P \tag{1}$$

$$Q_0 = Q_s + Q_c \tag{2}$$

Thus there are only four independent variables to consider. These could be chosen as:

(i) P_c the pressure drop from control inlet to outlet
(ii) ΔP the pressure drop from supply inlet to outlet
(iii) Q_s the flow into the supply inlet
(iv) Q_c the flow into the control inlet

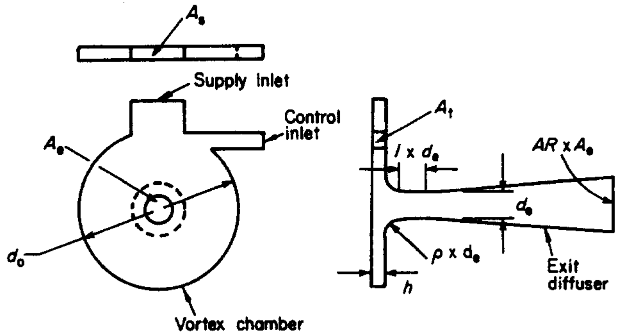

Fig 1 Conceptual vortex amplifier showing critical internal geometry

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To determine characteristics for the va it is necessary to hold at least one of the four constant and examine the relationship between the others. Since pressure is to be controlled we should hold either P_c or ΔP constant. In this work ΔP was held constant although Tippetts has shown[6] that if a va is considered as an Eulerian flow machine it is possible to scale the characteristic to any of the 108 possible characterisation formats and so any one of the variables may be held constant.

It was decided to adopt performance criteria that have been widely used in the past[1]. The measure of pressure adopted was the so called 'control pressure ratio' defined as:

$$\text{control pressure ratio } (G^*) = \frac{P_c}{\Delta P} \quad \text{for } Q_s = 0$$

The measure of maximum throughput relative to the leakage flow adopted was the so called 'turn down ratio' defined as:

$$\text{turn down ratio } (T) = \frac{Q_{s(Q_c=0)}}{Q_{c(Q_s=0)}} \quad \text{for constant } \Delta P$$

The criteria G^* and T have also been adopted for reasons other than tradition. G^* represents the drop in static pressure in the tangential inlets. When $Q_s = 0$ the pressure seen at the supply inlets depends on the acceleration of the control flow as it passes through the tangential inlets. Thus G^* is a measure of the effectiveness of the tangential inlets in creating a vortex of a given strength.

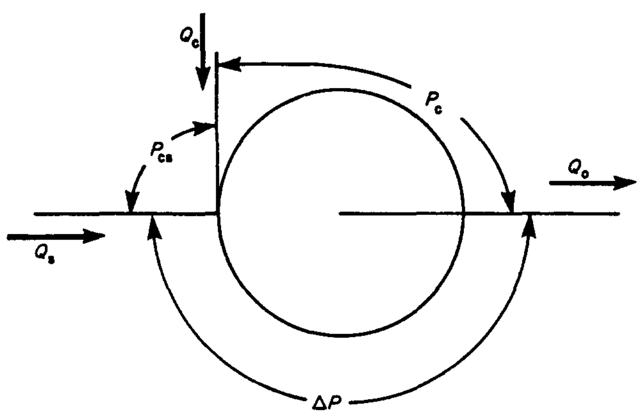

Fig 2 Characteristic variables of vortex amplifiers

It is possible to redefine T as ξ_c/ξ_s where ξ_c is the Euler number, at $Q_s = 0$ and ξ_s the Euler number at $Q_c = 0$. Thus the turn down ratio represents a ratio of the resistance to flow of the va in its two extreme states. High values of T are relevant in any application since it is necessary to raise the value of ξ_c as high as possible and to push ξ_s as low as possible in order to minimise the quiescent power drain.

A further measure of performance can be defined, the performance index T/G^*. High values of T are usually achieved at the expense of high values of G^*; hence the ratio T/G^* gives an indication of the ability of the va to create a high turn down ratio at low control pressure ratios.

Choice of parameters for optimisation

Having decided on the criteria to be used in the measurement of the performance of a vortex amplifier, it is necessary to consider the optimisation of the internal geometry of the va to maximise these performance criteria. Wormley and Richardson[3] suggested that if the fluid was considered incompressible and the effects of surface tension and heat transfer were neglected, four geometrical ratios, together with the Reynolds number, were sufficient to describe the transfer characteristics of a va. The four geometrical ratios they recognized were:

$$\frac{A_c}{A_e} = \frac{\text{control port area}}{\text{exit port area}}$$

$$\frac{A_s}{A_e} = \frac{\text{supply port area}}{\text{exit port area}}$$

$$\frac{r_e}{r_0} = \frac{\text{exit port radius}}{\text{chamber outer radius}}$$

$$\frac{h}{r_0} = \frac{\text{chamber height}}{\text{chamber outer radius}}$$

In the course of the investigation reported here it became apparent that other geometrical factors were important to the performance and the behaviour of vortex amplifiers.

Notation

$A_c = A_t$	Area of tangential inlets	Q_0	Outlet flow, volume flow rate
A_e	Area of exit throat	Q_s	Supply flow, volume flow rate
A_s	Area of supply inlets	Re	Reynolds number, $V_e d_e/\nu$
AR	Diffuser area ratio	r_e	Radius of exit throat
d_e	Exit throat diameter	r_0	Chamber outer radius
d_0	Chamber outer diameter	T	Turn down ratio, $Q_{s(Q_c=0)}/Q_{c(Q_s=0)}$
G	Control pressure ratio, $P_c/\Delta P$	T/G^*	Performance index
G^*	Control pressure ratio at $Q_s = 0$	V_e	Exit throat 'top hat' velocity, $(Q_s + Q_c)/A_e$
h	Chamber height	ξ	Euler number, $\Delta P/\rho V_e^2$
l	(Parallel outlet length)/d_e	ξ_c	Euler number for $Q_s = 0$
P_c	Control pressure relative to outlet	ξ_s	Euler number for $Q_c = 0$
P_{cs}	Control pressure relative to supply inlet	ρ	Density; Blending radius from chamber to exit throat
ΔP	Supply pressure relative to outlet	ϕ	Hole diameter/d_e
Q_c	Control flow, volume flow rate		

Here behaviour is used to mean static and dynamic phenomena. Since the effects of any geometrical parameter are seen in both behaviour and performance, certain modifications that were made to the va in an attempt to change its behaviour are also reported in this paper.

Considerations of vortex flow structures[7] led to a belief that the flow in a va would be affected by the geometry of two different sections of the outlet, firstly the region immediately surrounding the exit throat and secondly the region downstream of the exit throat. Syred[1] suggested that radiusing and blending the walls of the vortex chamber to the exit throat was advantageous to performance and that diffusers downsteam of the outlet could have considerable effects on both performance and characteristics. Saunders[2] gave results for an outlet throat geometry specifically designed to carry flow from the vortex chamber to the outlet with as low a loss as possible, in the pure radial flow condition. To achieve this end he placed a 'pip' in the form of a body of revolution on the back wall of the vortex chamber opposite to and coaxial with the outlet port. The importance of such pips was questioned and so it was decided to compare a flat back wall with one carrying a pip typical of those in va's currently in use. Saunder's geometry was also compared.

McNeil and Curtet[9] removed flow from the vortex chamber by suction at a hole in the centre of the back wall. Preliminary investigations of a hole in the back wall carried out by the author suggested that considerable effects could occur due to holes of differing sizes fed by positive pressure from the supply plenum, which in the designs of radial va investigated is situated behind the back wall of the vortex chamber. The extra flow introduced on the centre line due to the hole in the back wall appeared to affect both performance and behaviour.

Zobel[10] indicated that a parallel section of diameter equal to that of the exit throat for one diameter downstream of the exit throat was necessary for optimum flow restriction in the swirling flow condition. The effect of varying the length of this parallel section on the performance and behaviour of va's was investigated. It was also realized that recovery of static pressure in a diffuser downstream of the exit throat would have a significant effect on the vortex amplifier's maximum throughput for a given ΔP and so the area ratio of an outlet diffuser was also considered.

In a well designed va the exit throat is the maximum restriction to pure supply flow ($Q_c = 0$). Thus all the geometrical features were, where possible, expressed in terms of non-dimensional ratios related to the vortex chamber outlet (Fig 1). The non-dimensionalising unit of length was taken as the exit throat diameter d_e and thus the eight geometrical ratios investigated became:

$$\frac{A_s}{A_e} = \frac{\text{supply inlet area}}{\text{exit throat area}}$$

$$\frac{A_e}{A_t} = \frac{\text{exit throat area}}{\text{tangential inlet area}}$$

$$\frac{d_0}{d_e} = \frac{\text{chamber outer diameter}}{\text{exit throat diameter}}$$

$$\frac{h}{d_e} = \frac{\text{chamber height}}{\text{exit throat diameter}}$$

$$l = \frac{\text{parallel outlet length}}{\text{exit throat diameter}}$$

$$\rho = \frac{\text{outlet blending radius}}{\text{exit throat diameter}}$$

$$AR = \text{diffuser area ratio} = \frac{\text{diffuser outlet area}}{\text{exit throat area}}$$

$$\phi = \frac{\text{diameter of hole in back wall}}{\text{exit throat diameter}}$$

These eight non-dimensionalised parameters have been identified for optimisation in terms of performance.

A survey of the literature showed that certain of these ratios had been considered previously[1-4,8-12] but that for design purposes the information available was satisfactory for only three of the eight ratios, A_s/A_e, d_0/d_e and h/d_e. The results of previous investigations of these three ratios and their effect on va performance are reviewed below. The remaining five ratios were investigated by the author using the va shown in Figs 6–8; the experimental procedure is described in the Appendix.

Previous investigations of performance

Much theoretical prediction and a large amount of experimental work was carried out on vortex amplifiers during the 1960's. Unfortunately much of this work is irrelevant to the type of power fluidic device considered here. In almost all cases the devices considered were very small, many having outlet throats of the order of a few millimetres in diameter. Such small devices were often operated at high supply pressures in order to overcome the large friction losses. The chamber height was often large relative to the outlet diameter and, in many of the investigations, more than one parameter was changed at once, eg when chamber height was changed the area of the inlets also changed.

Wormley[4] reviewed much of this earlier work in 1976 and, in summary, he found:

Reynolds number

The va is relatively insensitive to the pure supply flow Reynolds number certainly over the range $750 < Re < 3300$ and characteristics may be Euler scaled from one supply pressure value to another. At low Reynolds number the va is sensitive to the value of Re.

A_s/A_e

The va is insensitive to the supply port resistance for $A_s/A_e > 3$.

A_e/A_t

As A_e/A_t increases T and G both increase.

$d_0 d_e$

This was found to be the parameter that had the strongest influence on device performance and behaviour, the shape of the characteristic being found to alter as d_0/d_e changed. As d_0/d_e decreased both G and T increased.

h/d_e

T increases with increasing h/d_e for small h/d_e (ie $h/d_e < 1$) and is insensitive to h/d_e for $h/d_e > 1$.

A survey of work on vortex devices reveals Zobel's classic publication[10] on the vortex diode, which has some relevance to the current investigations, and work at Sheffield University[1,11,12] in the late 1960's and early 1970's that began investigation of thin chamber vortex devices for power fluidic applications. These latter publications indicated that the adoption of low chamber heights, profiled outlets and diffusion of the exiting flow could lead to substantial improvements in performance, while the use of multiple inlets led to a more symmetrical flow pattern that improved both performance and behaviour. From this work came the radial geometry investigated in this paper. Recent work at Cardiff University and elsewhere[13,14] aimed at high performance applications in other fields, has led to the development of more sophisticated inlet and chamber geometries which are beyond the scope of this paper.

Syred[8] reviewed the work that had been carried out on thin chamber vortex devices and, together with his other papers[1,11,12], this has given a basis from which to work. It is evident from the literature that no large scale systematic approach has been made to the optimisation of vortex amplifiers, particularly thin chamber devices. The work that has been carried out in the past has been of an exploratory nature, revealing the important parameters without, in most cases, systematically investigating the optimisation of these parameters for performance or behaviour. From the literature it was possible to draw conclusions about three of the geometrical ratios identified above (A_s/A_e, d_o/d_e and h/d_e) which then formed the basis for the design of vortex amplifiers used to investigate the other five ratios and also the effects of ΔP (Reynolds number).

Influence of A_s/A_e

Both Syred[1] and Wormley[2] indicate that the effect of the supply inlets on device performance is negligible where $A_s/A_e > 3$. Syred[1] found that if $A_s/A_e > 4$ performance begins to deteriorate and suggested that this was due to the degree to which the vortex chamber wall was cut away. It was found that, as might be expected, G^* was unaffected by A_s/A_e. Vortex amplifiers used by the author were designed with $A_s/A_e = 4.07$.

Influence of d_0/d_e

Wormley[4] suggested that as d_o decreased T and G^* increased. It should however be noted that Wormley was altering d_o/d_e by changing d_e while leaving all other factors constant. Thus, his explicit changes in d_o/d_e involved implicit variation of A_e/A_t, h/d_e, A_s/A_e etc. His results should therefore be treated with caution. The effects on T and G^* that he observed were that T and G^* increased as d_e increased while d_o remained constant. Considered in this light it can be seen that T and G^* were increasing as A_e/A_t increased, and as A_s/A_e and h/d_e decreased at the same time as d_o/d_e decreased. Others have observed the effect of d_o/d_e on flow ratios but no investigations of the effect on G^* are apparent. Wormley's results for G^* are thus quoted in Table 1 with reservations. Syred[1] found that the effect of d_o/d_e was not as important as that of h/d_e or A_e/A_t, a change of d_o/d_e from 3.5 to 9.5 having small effect on T with low A_e/A_t (≤ 1), but an increase to $d_o/d_e = 19$ reduced T by 40%.

Zobel's comprehensive work[10] on vortex diodes suggests that there may be an optimum value of d_o/d_e for a given value of A_e/A_t. High values of resistance in the pure control flow state (ξ_c) yield high values of turn down ratio. For any given control inlet geometry, if the variation of some other geometrical ratio increases the value of ξ_c this will result in a reduction of G^*. This is because the improvement occurs in the vortex chamber and not in the control inlets and so for the same pressure drop across the control inlets, a higher pressure drop occurs in the vortex chamber and G^* decreases. Thus an increase in ξ_c is a desirable phenomenon in terms of both T and G^*. When some of the data presented by Zobel[10] are reworked and presented in the form of Fig 3 it appears that there is a definite optimum value of d_o/d_e for ξ_c particularly at high values of A_e/A_t. When these optima are plotted against A_e/A_t and the 95% of optimum lines are drawn, Fig 4 results.

Clearly, for small values of A_e/A_t (<1) there is considerable latitude in the value of d_o/d_e; for $A_e/A_t > 1$ the peak is narrower. In Wormley's tests[3] the values of A_e/A_t were in the range $3.1 < A_e/A_t < 47.3$ and $4 < d_o/d_e < 14$. It can be seen that much of Wormley's work was well down from the optimum of the curve in Fig 4 and thus his device performance would be susceptible to both d_o/d_e and A_e/A_t which he was varying simultaneously by varying d_e. Syred was working on the left of Fig 4 where the peak is broad and thus d_o/d_e is not too crucial.

Fig 4 shows that d_o/d_e is an important ratio in va design but that it must be chosen with the value of A_e/A_t in mind. In the experimental work reported in this paper d_o/d_e was set at 6.4 thus giving near optimum values at low A_e/A_t, where most of the interest was centred, but also about 70% of optimum at higher values of A_e/A_t.

Influence of h/d_e

The effect of h/d_e on device performance and behaviour has been shown by Syred[1], Saunders[2] and Wormley[3]. Wormley worked in an incompressible flow regime. He found that for $h/d_e > 1$ the performance was independent of chamber height and specifically recommended $h/d_e > 1$. The work of both Syred and Saunders was for $h/d_e < 1$. Saunders found that turn down ratio (T) increased with decreasing h/d_e until a limit was reached beyond which T began to fall off again. The value of h/d_e at which maximum T was achieved depended on factors other than h/d_e (roof shape, A_e/A_t) but was about $h/d_e = 0.2$ to 0.3. Saunders gave no information regarding instability and noise but Syred showed that as T increased with decreasing h/d_e so also the noise and instability increased. Syred found no maximum; his values of T went on increasing with decreasing h/d_e.

In the work of both Syred and Saunders the value of A_e/A_t was changing as h/d_e changed. This was caused by the lowering of the chamber back wall reducing the size of the tangential inlets. Some more recent work by Sidhu[15] on thin chamber vortex diodes varied h/d_e without varying A_e/A_t and showed a clear optimum value of $h/d_e \simeq 0.19$ for pure tangential flow Euler number. This is equivalent to the pure control flow Euler number of a va and has been plotted as such in Fig 5.

Table 1 Influence of various parameters on vortex amplifier performance

Independent variable	Dependent variable: T	Dependent variable: G^*	Dependent variable: T/G^*
A_s/A_e	Rises with $A_s/A_e<4$ then falls for $A_s/A_e>4$	Independent of A_s/A_e	Rises and falls with A_s/A_e increasing as T
A_e/A_t	Increases with increasing A_e/A_t Fig 9	Increases with increasing A_e/A_t Fig 9	Rises then falls with Increasing A_e/A_t Fig 9
d_0/d_e	Rises then falls, with increasing d_0/d_e for a given A_e/A_t Figs 3,4	Falls with increasing d_0/d_e?	Rises then falls with increasing d_0/d_e for a given A_e/A_t
h/d_e	Rises then falls with increasing h/d_e Fig 5	Independent of h/d_e?	Rises then falls with increasing h/d_e
l	Falls with increasing l Fig 10	Falls with increasing l Fig 10	Falls with increasing l Fig 10
ρ	Increases with increasing ρ Fig 11	Increases slowly with increasing ρ Fig 11	Increases with increasing ρ Fig 11
AR	Increases with increasing AR	Independent of AR	Increases with increasing AR
Pip	Pip increases T relative to flat at $A_e/A_t>1.0$ Figs 9,12	Pip increases G^* relative to flat at $A_e/A_t>1.0$ Figs 9, 12	Pip increases T/G^* relative to flat at $A_e/A_t>2.0$ Figs 9, 13
ϕ	Rises then falls with ϕ at low A_e/A_t, inversely dependent at high $A_e/A_t>2.5$ Fig 12	Increases with increasing ϕ Fig 12	Rises then falls with ϕ at low A_e/A_t, inversely dependent at high A_e/A_t Fig 13
ΔP	Independent of ΔP for $Re>10^4$, $M<0.3$	Independent of ΔP for $Re>10^4$, $M<0.3$	Independent of ΔP for $Re>10^4$, $M<0.3$ Fig 14

If T were dependent on ξ_c alone it would be reasonable to expect T to have the same relationship to h/d_e. However, T depends also on the pure supply flow Euler number ξ_s. In a well designed va the exit throat is the major restriction to flow but if the radius to the exit is not kept sufficiently large as the chamber height is reduced another restriction to flow may dominate. This is the so called 'curtain' area, ie the minimum cylindrical surface area through which flow passes radially inwards before making its turn to the exit. A condition is reached when the 'curtain' area equals the exit throat area, ie:

$$\pi(d_e+2\rho d_e)h=N\pi\frac{d_e^2}{4}$$

for a va with N outlets where ρd_e is the blending radius

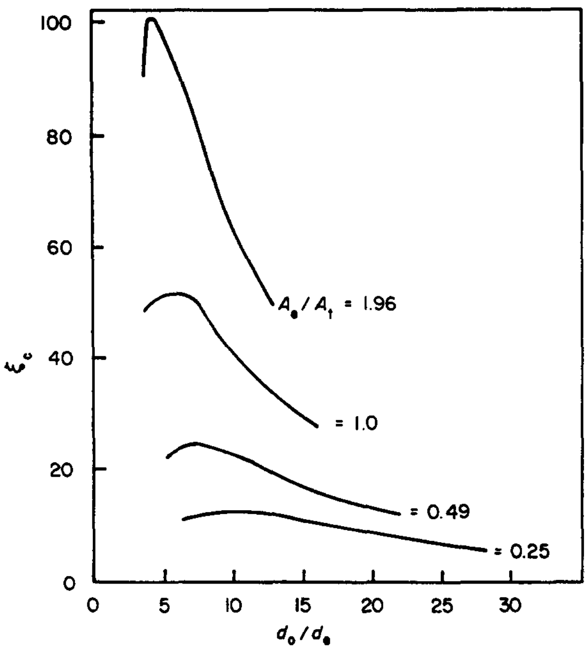

Fig 3 Swirling flow Euler number (ξ_c) versus d_o/d_e *(after Zobel[10])*

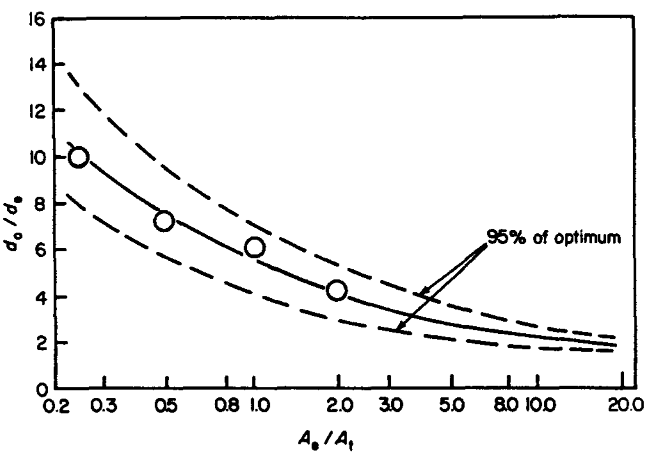

Fig 4 d_o/d_e *optimum versus* A_e/A_t *(after Zobel[10])*

from chamber front wall to exit throat. Hence it can be seen that when:

$$\frac{h}{d_e}=\frac{N}{4(1+2\rho)}$$

the area of the 'curtain' equals the area of the exit throat. Further reduction in h/d_e leads to the 'curtain' area controlling the flow instead of the exit throat.

If for example $\rho=0.1$, the limiting value of $h/d_e=0.21$ and so this factor would affect T to shift the peak of the curve in Fig 5 to the right. In all the results presented in this work for comparison of other variables $h/d_e=0.23$, $\rho=0.375$.

No mentioned is made in the literature of the effect of h/d_e on G^* except that Syred[1] indicates that G^* is independent of h/d_e. He also states that reducing h/d_e below about 0.3 substantially increases the amplitude of noise generated within the amplifier. This is borne out by the author's observations. The value of $h/d_e=0.23$ adopted in this work is a compromise between performance and noise level.

Influence of A_e/A_t

As A_e/A_t increases the size of the tangential inlets decreases for a fixed d_e. This was achieved in the experiments by successively reducing the width of the tangential inlets by inserting plasticine fillets symmetrically into the inlets and moulding them to retain the same general geometry both at the outer end of the inlets where the flow passes through from the plenum chamber, and at the chamber wall. In this way the centre line of the tangential inlet was left in the same place and the chamber geometry was disturbed as little as possible (Fig 6).

In general it can be said that increasing A_e/A_t increases both T and G^*, but the value of T/G^* has a marked maximum at values of A_e/A_t between 2 and 5 depending on the device configuration (Fig 9). The results plotted in Fig 9 are averaged over a series of values of ΔP, and show that the relationships between T and A_e/A_t and G^* and A_e/A_t are similar for all the outlet back wall geometries shown in Figs 7 and 8. The rate of change of T decreases with increasing A_e/A_t whereas the rate of change of G^* increases. This leads to clear maxima of T/G^*. For virtually all geometries, the maximum T/G^* value lies close to $A_e/A_t=3$.

Influence of the parallel outlet length

Following Zobel's work[10] on parallel sections downstream of the exit throat, a series of parallel sections of

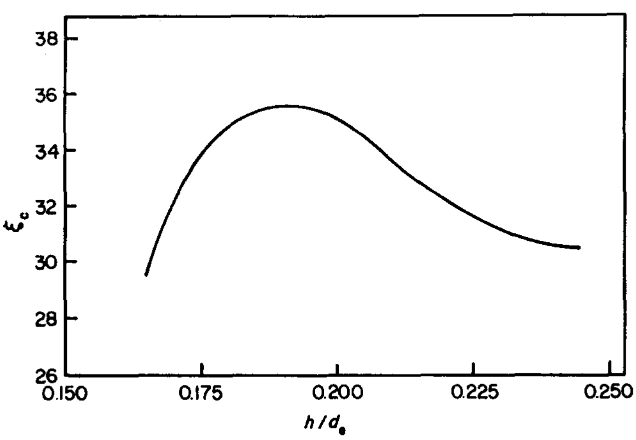

Fig 5 Pure tangential flow Euler number (ξ_c) versus h/d_e *(after Sidhu[15])*

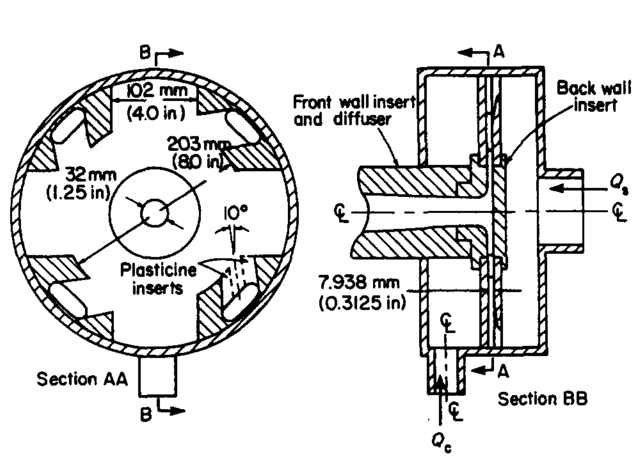

Fig 6 Radial vortex amplifier used in performance investigations

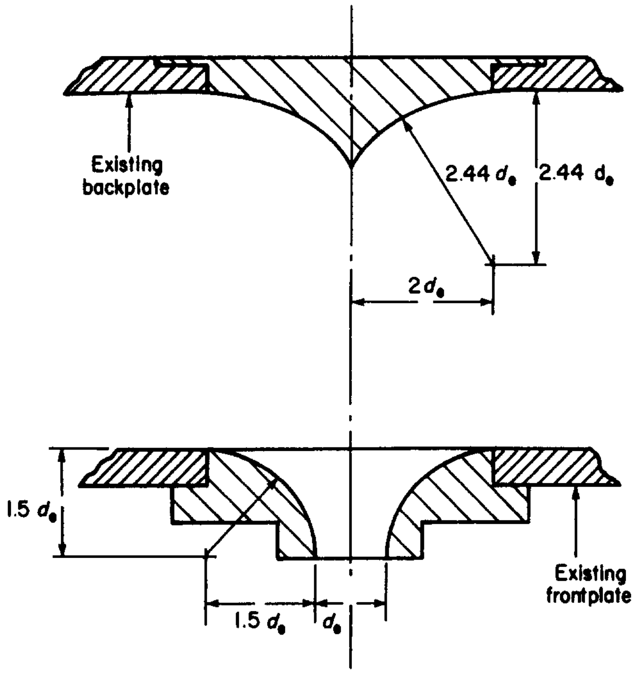

Fig 7 Saunders' geometry inserts

varying length were tried and their effect on both performance and behaviour noted. It was found (Fig 10) that, averaged over a range of values of ΔP, the general effect was for both G^* and T to decrease as the length of parallel section was increased and for the amplitude and severity of noise to be reduced. The decrease in T is largely caused by the increase in the resistance of the device under pure supply flow conditions. Zobel found an increase in ξ_c with increasing l. The results obtained here show an increase in ξ_c by 10% as l increases from $0.5d_e$ to $2.5d_e$; over the same range of l, however, the value of ξ_s increases by 25% thus giving an overall reduction in T.

Influence of outlet blending radius

The effect of outlet radius on va performance is shown in Fig 11 where averaged values of T, G^* and T/G^* for a series of ΔP values are plotted against outlet radius non-dimensionalised in terms of exit throat diameter. The outlet radius has its major effect on radial/axial flow rather than on swirling flow. It would appear that outlet radii of $0.2d_e$ and above allow the pure supply flow leaving the vortex chamber to make the transition from radial to axial with minimum flow separation. For $\rho < 0.2$ the transition is too sharp and the flow separates, creating non-uniform velocity profiles at the diffuser entrance leading to loss of diffuser efficiency. Outlet radius affects swirling flow when $\rho > 0.1$. The swirling flow Euler number is reduced, indicating a decrease in resistance of the vortex flow. The optimum value of ρ for performance would seem to be $0.25 < \rho < 0.35$.

Influence of outlet diffusers

The more general field of the outlet loading of a va has been looked at elsewhere. Saunders[2] loaded va outlets and observed the effect on the shape of the characteristic. A more extended investigation of outlet loading in the form of both restrictions and diffusers forms part of the work for a PhD thesis[16]. The concern here is rather with the effects of diffusers on the performance of a va. Diffuser area ratio is important to vortex amplifier performance. Under pure radial flow conditions the efficient recovery of pressure at the exit increases the flow rate at a given pressure drop across the device. It has been found that for conical diffusers of 7° included angle, an increase in diffuser area ratio from 4 to 6.25 can add 10% to the value of T and a further increase from 6.25 to 9 can add as much again. Expectations of the performance of conical diffusers, based on Sovran and Klomp[17] for example, would suggest that such improvements were unlikely to come from the pure supply flow end of the characteristic alone. There is some evidence of a slight reduction in the pure control flow as diffuser area ratio increases but it is true that although there is an undeniable increase in T with increasing diffuser area ratio, the difference between the values is close to the limits of accuracy of the measuring rig.

The effect of the diffusers on G^* has been found to be negligible, as might be expected.

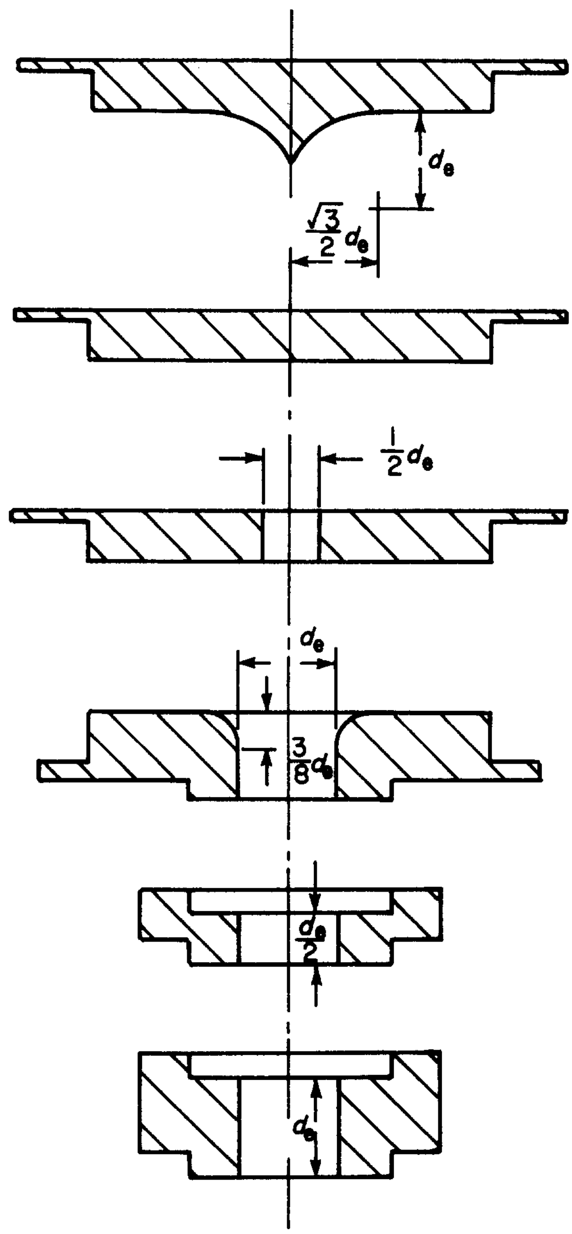

Fig. 8 Pip, hole and parallel section inserts

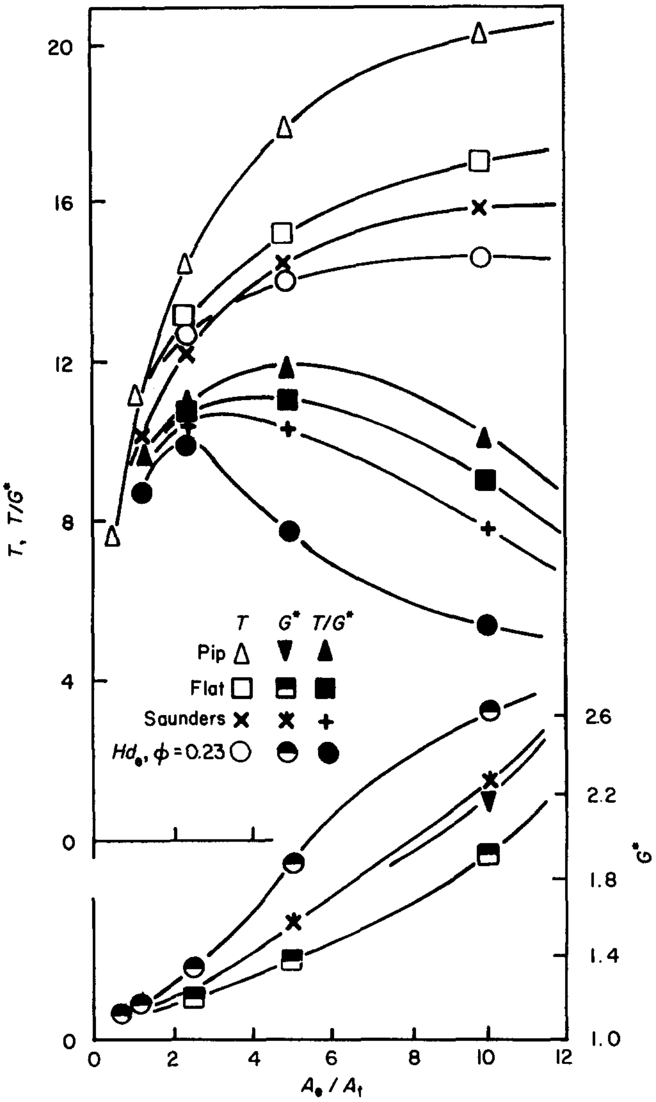

Fig. 9 Effect of A_e/A_t *on* T, G* *and* T/G*

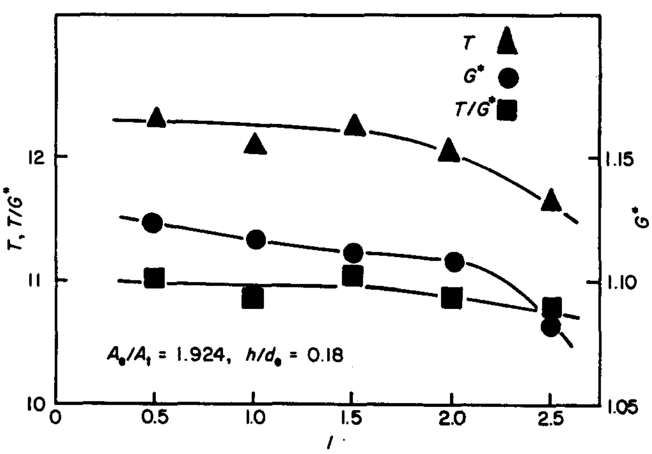

Fig 10 Effect of parallel outlet lengths (l) *on* T, G* *and* T/G*

Influence of back wall geometry

Work by McNeil and Curtet[9] shows that a hole in the back wall (ie upstream end) of a vortex chamber can have considerable influence on the flow in the chamber. In McNeil's work, flow was abstracted from the chamber via a hole on the centre line. The size of the hole and the rate of extraction were varied and note taken of the effect on the flow structure. With this and certain theories concerning va behaviour in mind[7] the effect of allowing extra air to flow into the vortex chamber from the supply plenum via a hole in the back wall was examined. Various sizes of hole were tried and also combinations of holes. The main purpose of the investigations was to determine the effect on device behaviour and noise, but the holes had an effect on the va performance as well.

Since it was felt that the region of the flow in the central portion of the vortex amplifier was probably crucial to the operation of a va[7,18] the effect of pips on the back wall was also investigated. Saunders[2] claimed that the design of pip and outlet radius that he investigated gave a flow that continually contracts as the flow direction is changed from radial motion in the vortex chamber to axial motion in the outlet. Similarly many of the pips used in plant are claimed to 'help' the flow around the transition from radial flow in the chamber to axial flow in the outlet. Both pips were designed to affect the pure supply flow operation.

Measurements of the variations of *T*, *G** and *T/G** with non-dimensionalised hole size (ϕ) were made at a number of different values of ΔP. As a control a flat back wall (labelled Flat in Figs 9, 12 and 13) was also examined as were the pip (labelled Pip in Figs 9, 12 and 13) and a replica of Saunders' geometry.

Fig 12 shows the influence of the hole in the back wall on device performance. At low values of A_e/A_t the hole makes little effect on *T* or *G** but at high values of A_e/A_t there is a markedly detrimental effect. The pip has little effect at low A_e/A_t but gives considerable improvement in *T* at the cost of an increase in *G** at high A_e/A_t. In Fig 13 the overall influence on the performance index can be seen. It becomes noticeable that at low A_e/A_t the hole can achieve a slight improvement of the device performance.

It might be expected that the presence of the hole in the back wall would permit more flow to pass through the va in the pure supply flow condition since the hole is connected to the supply plenum. It might also be supposed that the effect of the hole would be detrimental to the pure control flow condition since the introduction of flow without swirl would weaken the vortex. However, the improvements in *T* produced by both holes and pips were largely due to their effect on the pure control flow

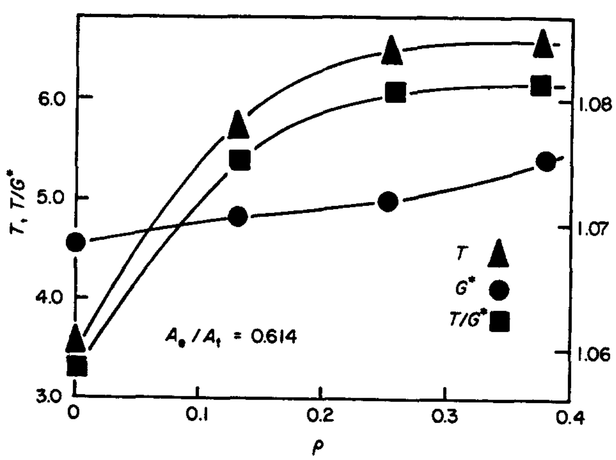

Fig 11 Effect of outlet blending radius (ρ) *on* T, G* *and* T/G*

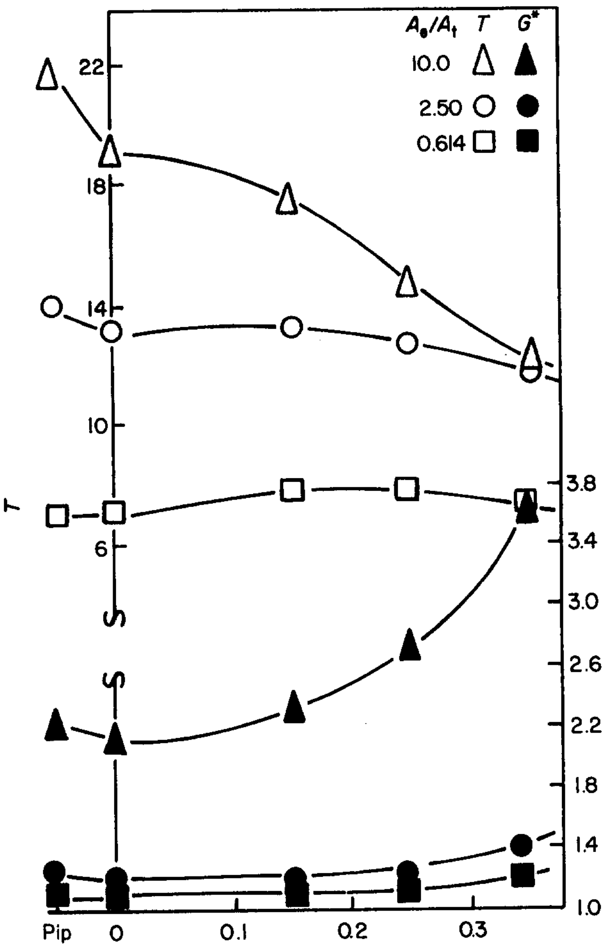

Fig 12 Effect of back wall geometry on T *and* G*

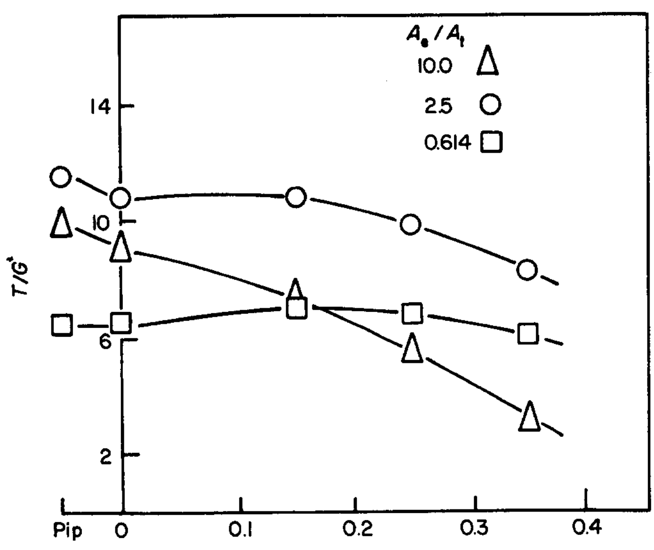

Fig 13 Effect of back wall geometry on T/G*

condition. The presence of the pips and holes made a variation in the pure supply flow Euler number ξ_s of about 12% of the value with a flat back wall. This was within the range of scatter from the various values of ΔP used. The general trend was that ξ_s decreased as ϕ increased but by no more than 12% for $\phi = 0.3$ relative to $\phi = 0$. The presence of the pip made very little difference to ξ_s and as can be seen in Fig 9 the effect of the Saunders' geometry on performance is generally detrimental. The effects of the holes and the pip were much more marked in the pure control flow conditions. The effect of ϕ is detrimental to ξ_c at high A_e/A_t. However, at low A_e/A_t (<2.5) there is evidence that the presence of a small hole actually increases the value of ξ_c by up to 25% for $\phi \approx 0.15$. For $A_e/A_t = 10$ the pip makes up to 50% improvement in ξ_c. The pip has negligible effect for $A_e/A_t < 1.23$.

These results are serendipitous since the original intention of the pip was to affect pure supply flow by reducing losses due to expansion in the chamber followed by the contraction of the throat. It is thought that the effect of the pip and of the hole on the swirling flow case ($Q_s = 0$) may be due to an interference with the recirculation of flow within the vortex chamber. Since this recirculation effect only occurs at higher values of A_e/A_t it would be reasonable that the effects of the pip should only be seen at higher A_e/A_t. This is discussed further elsewhere[18].

Influence of ΔP (Reynolds number)

As the value of ΔP for a device is changed so the flow rate alters and the Reynolds number of the flow varies. In all references to Reynolds number in this work the value of Re is based on an average or 'top hat' velocity at the throat of the va and the diameter of the exit throat:

$$Re = \frac{V_e d_e}{\nu} \qquad V_e = \frac{Q_s + Q_c}{A_e}$$

The vortex amplifiers reported here are all operating well into the turbulent regime with $5 \times 10^3 < Re < 5 \times 10^5$. Although Wormley[4] found that his va's were independent of Reynolds number, it has been found[19] that the performance of vortex diodes exhibits dependency on Re and so this effect was investigated. For all the results presented here the maximum velocity in the va was 100 m/s and so the Mach number was less than or equal to 0.3 and the flow may be considered incompressible.

It was found that T is relatively independent of ΔP but the value of G^* decreases with increasing ΔP for all values tested. Since the value of A_e/A_t affects the Reynolds number of the pure control flow quite markedly, it is beneficial to consider these results in terms of Re for pure control flow. As shown in Fig 14, T/G^* rises fairly steeply until $Re \simeq 2 \times 10^4$. Above this value T/G^* becomes increasingly insensitive to pure control flow Reynolds number. That there is some slight continued increase was

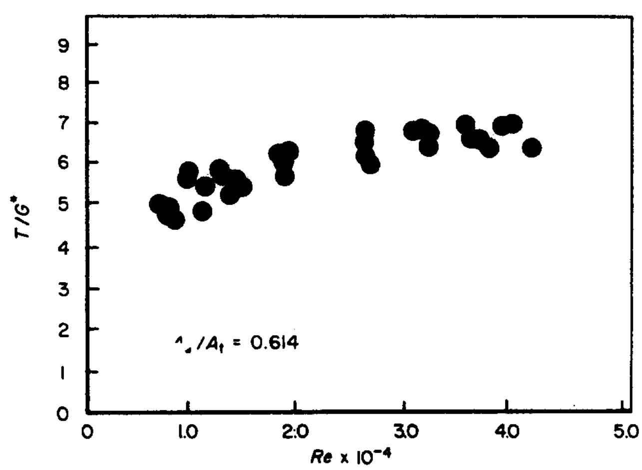

Fig 14 Dependence of performance index (T/G*) *on Reynolds number*

shown when a larger scale device with a pure control flow Reynolds number of 6×10^4 showed a 26% increase in T/G^* over a geometrically similar device with $Re\simeq2\times10^4$.

Conclusions

Three criteria have been selected for the evaluation of the performance of a vortex amplifier. These criteria are the turn down ratio T, control pressure ratio G^*, and the performance index T/G^*. These criteria are measures of the resistance of the va to flow in the two end states of its characteristic ie $Q_{s(Q_c=0)}$ and $Q_{c(Q_s=0)}$.

Eight geometrical ratios have been identified as having an effect on va performance and these ratios have been investigated, together with the effect of Reynolds number on the va. The results have been presented and discussed and the findings are collated in Table 1. From these findings it can be said that provided the flow through a va is incompressible, the most significant geometrical ratio affecting the performance of a vortex amplifier is the ratio of exit area and tangential inlet area (A_e/A_t). Once that is known, the outer diameter of the chamber relative to the exit throat (d_o/d_e) may be optimised to suit. The chamber height (h/d_e) may be selected for maximum performance or for minimum noise or some compromise and the blending radius to the outlet throat from the chamber (ρ) may be chosen to suit. The length of parallel section downstream of the diffuser throat (l) is relatively unimportant although for optimum performance it should be kept short. Within plant constraints, the greater the diffuser area ratio (AR) the better, but since large AR comes with increasing length it may be necessary to compromise for plant design. The size of the supply inlets relative to outlet throat (A_s/A_e) is not crucial but a value of $A_s/A_e\simeq4$ gives best performance. Further improvement of performance index may be achieved when $A_e/A_t>2.0$ by putting a pip on the back wall of the vortex chamber; at values of $A_e/A_t<2.0$ it may be beneficial to put a hole in the back wall.

Acknowledgements

The author gratefully acknowledges the support and inspiration of Dr N. Syred who supervised this work, which was submitted as part fulfillment of the author's PhD thesis. The work received generous financial support from UKAEA, part of whose programme of investigation of power fluidics it formed. UKAEA holds patents on certain aspects of vortex amplifier design.

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Appendix

The five geometrical parameters felt not to have been sufficiently well covered by other researchers were investigated for their effects on the performance and behaviour of vortex amplifiers. To build up a body of material for design purposes one of the parameters was varied at a time, in a systematic way, the other parameters being held constant. In this way the effects of altering one parameter were not masked by those of another that was altering simultaneously.

A vortex amplifier was constructed (Fig 6), the geometry of which could be varied by means of inserts. One set of inserts was made to reproduce the geometry given by Saunders (Fig 7), another to reproduce the most common internal geometry of the vortex amplifiers in use as ventilation controllers (Fig 8). This latter had a set of different chamber back wall configurations:

(a) Flat – for control
(b) Pip
(c) A flat plate with various hole sizes.

Provision was also made to fit a series of parallel sections of various lengths immediately downstream of the exit throat (Fig 8).

A series of readings was taken for each of the flat, pip and a series of hole diameters. Each geometrical configuration was tested at a series of A_e/A_t ratios spanning the normal operating range. Each of the 5 geometrical ratios was varied over a sufficiently large range to indicate any optimum values that might exist or the general trend where such optima were not apparent.

The value of the pressure drop across the va was also varied in order to determine whether there was any dependence of performance or behaviour on Reynolds number. The effects of diffusion were tested by using varying diffuser area ratios.

The vortex amplifier was tested in a purpose built test rig. The flow was moved by a Becker 1000 blower capable of delivering up to 0.3 m^3/s (600 cfm) at pressures up to 22 kN/m^2 gauge (3 psig). Static pressure readings were made using an inclined multimanometer filled with water and the flow readings were taken from a bank of rotameters. Each rotameter was used over the mid part of its range only, to avoid the inaccuracies occurring at the extreme ends of the range. Where more than one rotameter was used in parallel, each was used in the middle of its range. Checks were made of the consistency of readings from various groups of rotameters and it was found that errors due to the parallel use of more than one rotameter were of the same order as those quoted for individual rotameters by the manufacturer (ie up to 6% of full scale).

All the readings concerning the performance of va's were made with positive gauge pressures at the inlets. The va was connected to the rig and for each configuration a set of readings of pure supply flow rate $Q_{s(Q_c=0)}$ and pure control flow rate $Q_{c(Q_s=0)}$ were taken over a range of values of ΔP from $\Delta P=1$ iwg (1 in = 25.4 mm) to $\Delta P=10$ iwg and then a full characteristic curve for $\Delta P=6$ iwg was taken. To obtain the maximum information from each experiment, a record was made of the behaviour of the va throughout the characteristic as described elsewhere[18]. It was found that due to the compressing action of the Becker blower, the air warmed up and a settling period was required to permit the system to come to equilibrium. Since the blower extracted its air supply from the laboratory and the va exhausted into the laboratory, it was found that after a period of about 10 min the air in the laboratory had grown noticeably warmer and an equilibrium temperature was reached after about 10 to 15 min. It was usually found that once this equilibrium had been achieved the readings of flow rate obtained altered very little with continued running.

Values of A_e/A_t used were 0.614, 1.23, 2.5, 5.0, 10.0 (20.0).
Values of l used were 0.5, 1.0, 1.5, 2.0, 2.5.
Values of ρ used were 0.0, 0.125, 0.25, 0.375.
Values of ϕ used were 0.16, 0.22, 0.31.

BOOK REVIEW

Heat Transfer in Heat Rejection Systems

Eds S. Sengupta and Y. G. Mursalli

This volume is a compilation of 12 papers presented at the 1984 ASME Winter Annual Meeting. The papers address the general topics of heat transfer in steam power plant condensers, performance of several types of cooling towers and cooling ponds, and heat transfer from imbedded tubes in a semi-infinite medium. Included is a paper by Bartz, Johnson and Adams that discusses the results of three types of heat rejection systems, namely evaporative cooling towers, cooling lakes, and water-conserving cooling towers. The authors make clear the potential for research in these systems. Studies dealing with condenser operations examine primarily tube enhancement and biofouling based on performance and economic justification. They show that considerable gains can result from enhancement both on the water and steam sides. A new approach to monitoring biofouling is described by Characklis and Mussalli. A paper by Beckett and Davidson describes a new modelling procedure for power station condensers. The problem of modelling isolated air pockets, however, still exists.

The cooling tower studies are analytical, experimental and numerical. The paper by Majumdar, Mukerjee, Bartz and Micheletti introduces a new heat transfer model to better account for evaporative heat transfer in wet cooling towers as compared to the models of Merkel and Poppe. A numerical study by Pin and Long shows good comparison of their simulation of cooling tower plumes with four different data sets. The model is three-dimensional, but two-dimensional results only are presented.

The information presented in this volume is timely and provides interesting reading for both practising engineers and specialists developing advanced heat rejection systems. The papers are grouped to provide insight for both industrial applications and the kernel of fundamental investigations. The performance data and new modelling concepts that are introduced provide direction for the necessary developments to improve heat rejection and condensing systems.

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