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THE EXPANSION OF WET STEAM THROUGH A COMPRESSIBLE CONFINED VORTEX IN A FLUIDIC VORTEX DIODE

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Abstract—The pressure-flow characteristics of a Zobel-type vortex diode have been measured using a working fluid of compressible wet steam. Tests using superheated steam with inlet/outlet pressure ratios across the diode of up to 30 have shown clearly the effects of compressibility and choking on the diode characteristics. Repeating the tests using wet steam, with known dryness fractions, has shown separately the effects of wetness on the diode performance.

When the diode was installed into the pipwork in the high-resistance direction, excessive steam wetness (quality <0.93) led to a build-up of water and when this was eventually swept through to the diode the resistance was seen to fall substantially as the strong internal vortex was destroyed.

INTRODUCTION

Wet steam flows such as those encountered in a steam main of a chemical or process plant can be considered as a high quality two-phase flow. Consequently, the pressure losses in wet steam flows, whether they be frictional or singular, are usually assumed to be the same as would be measured for the gas phase alone. This is because in a well-drained main the quality will normally be of the order of 95% and will rarely be <90%. For two-phase flows such as these the gas phase is practically unaffected by the liquid phase, which exists both as drops entrained in the flow and as a film/rivulet on the pipe wall. The liquid is simply swept along by the gas and has little effect upon the loss-causing mechanisms. Thus, the pressure drop measured across a length of pipe (frictional pressure drop) or across a valve (singular pressure drop) will be much the same in a dry steam flow as in a typical wet steam flow.

Whereas in a conventional valve the pressure drop is achieved by mechanically restricting the flow area, in a fluidic valve the pressure drop is due solely to the fluid mechanics of the flow within the body of the valve—which has a fixed geometry. A vortex diode is one of a number of different non-moving-part flow control elements (King 1983). The technology of power fluidics has been developed through a comprehensive and ongoing research and development programme principally funded and managed by UKAEA. The vortex diode, figure 1, is a device which has a low resistance to flow in one direction and a high resistance to flow in the opposite direction. When the flow enters the diode through the tangential inlet a strong confined spiral vortex is produced which causes a high resistance to the flow. However, when the flow is in the opposite direction, entering the valve through the axial port at the centre of the vortex chamber and exiting through the tangential port, the flow experiences a much lower resistance, such as it might encounter when flowing through a right-angled bend. The flow direction with high resistance is conventionally called the reverse flow direction whilst the flow direction with low resistance is known as the forward flow direction, figure 2. Vortex diodes can be used, for example, as rectifying elements in fluidic pumps, or as flow restrictors in postulated loss of coolant accidents in gas-cooled nuclear reactors; see, for example, King (1983) and Syred & Roberts (1979). It is expected that fluidic valves will be called upon to operate with wet steam and other two-phase flows, since these fluids are common in the nuclear and power industries.

Since fluidic valves are designed to operate reliably and as efficiently as possible in harsh nuclear environments, it is evident that further applications will be, and are being, found in the wider fields of chemical and process engineering. As a result of the efforts of a number of researchers the performance characteristics are now available for numerous designs of vortex diodes operating with

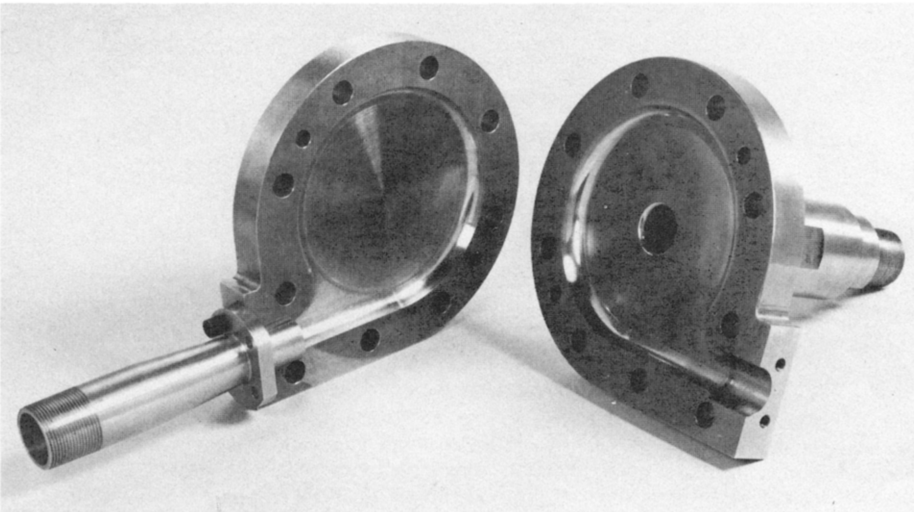


Figure 1. A vortex diode.

a variety of fluids over a wide range of conditions (Syred & Roberts 1979; Priestman & Tippetts 1982a). Much of the data is for air with moderately incompressible flow, and for water. As the pressure drop and hence flow rate through the diode is increased, so the characteristics become complicated: by the onset of cavitation in the case of liquids and by compressibility in the case of gases. For a vortex valve operating with a fluid such as saturated steam the flow will experience the effects of both compressibility and phase change. Although these effects will also be present in a conventional valve, the high pressure drop across the fluidic valve is dependent upon an effective vortex being established. The structure of the vortex, and hence the resistance characteristics of the diode, will therefore be more sensitive to fluid-dynamic phenomena. In this paper the pressure-flow characteristics of a Zobel-type vortex diode have been investigated using both superheated steam and wet steam of known dryness fractions. Thus the effects of compressibility and wetness have been studied separately. Restricting the throughput of a wet steam flow can lead to a build-up of water which, after a time, will be picked up by the vapour and swept through the pipework. The effects of such an event on the behaviour of the diode have also been investigated.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the experimental rig is shown in figure 3. The steam was supplied in a superheated condition and the flow rate was measured using an orifice plate. For the wet steam studies one, or two, fine water sprays, depending upon the amount of water required, were used to de-superheat the steam. A high-pressure reciprocating pump, fitted with a surge vessel to damp out the pressure pulses, was used to supply the water to the sprays at pressures up to 25 bar. The water flow rate was measured using rotameters. The pressure differentials across the diode and across the orifice plate were measured using differential pressure transducers. Steam temperatures before and after the diode, and at the orifice plate were measured using half-shielded thermocouples. These details, together with the fact that the steam velocities in the 77 mm bore pipe were relatively low, ensured

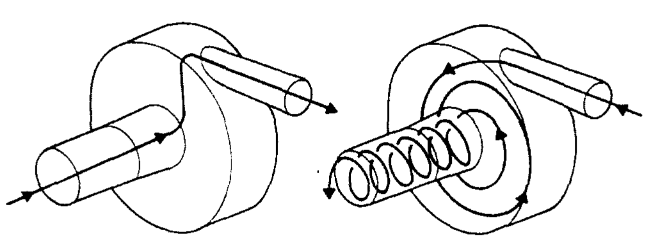
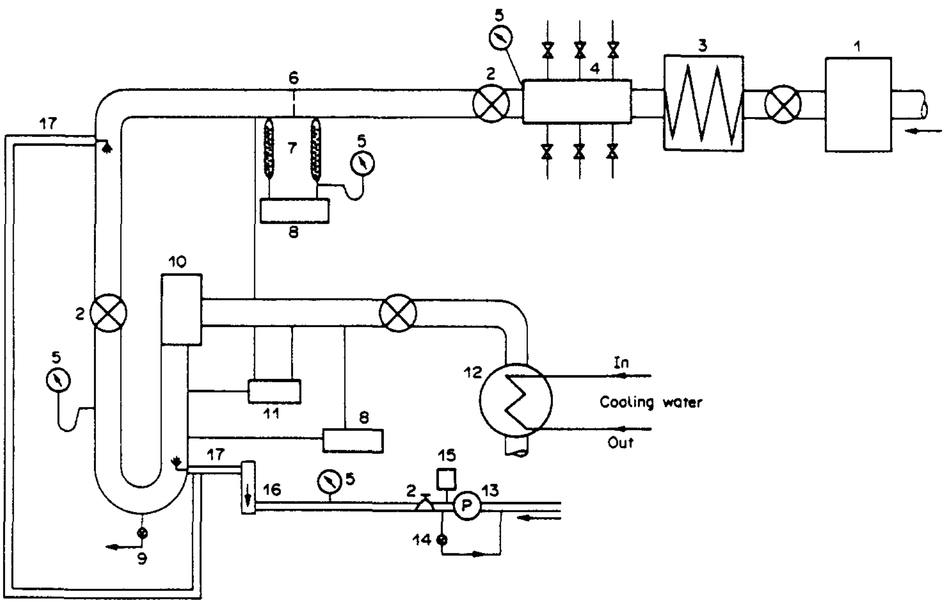


Figure 2. Flow through a vortex diode: (a) forward flow—low resistance; (b) reverse flow—high resistance.



1. Boiler
2. Valve
3. Superheater
4. Manifold
5. Pressure gauge
6. Orifice plate
7. Cooling pots
8. Differential pressure transducer
9. Drain
10. Vortex diode
11. Digital thermometer
12. Sub-atmospheric condenser
13. Pump
14. Pressure relief valve
15. Surge vessel
16. Rotameter
17. Water spray

Figure 3. Vortex diode steam characterization rig.

that the measured temperatures were stagnation values. Pressures at various positions in the rig were measured using calibrated pressure gauges. The outputs from the pressure transducers and thermocouples were connected to a multi-pen chart recorder so that not only could the steady-state flow characteristics be recorded but so too could any flow instabilities which might occur. The pressures before and after the diode were controlled by two throttle valves. The steam was exhausted into a sub-atmospheric condenser which enabled high pressure ratios to be obtained, especially in the reverse flow direction. The diode has a 19 mm dia exit throat and was identical to that used by Syred & Roberts (1979).

Superheated steam

The initial tests were carried out using superheated steam so that the effects of compressibility could be first established before considering the more complex case of compressible wet steam flow. During these tests the upstream pressure, P_u, was kept constant whilst the downstream pressure, P_d, was decreased gradually. The characteristics for forward and reverse flow were obtained for inlet pressure from 3 to 12 bar abs at 1 bar intervals. This procedure is a standard method for investigating the pressure-flow characteristics of components (nozzles, valves etc.) in compressible flow. For each inlet pressure the flow rate through the diode was seen to increase with increased pressure drop until the diode choked. Beyond this point, lowering the downstream pressure had no effect on the mass flow through the diode.

In figure 4 the mass flow rate through the diode is expressed as a fraction of the mass flow through a choked isentropic nozzle of the same minimum area, i.e.

$$\mathrm{Cf} = \frac{\dot{m}}{\dfrac{A_e P_u}{\sqrt{T_u}}\left[\dfrac{\gamma}{R}\left(\dfrac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{\frac{1}{2}}}.$$

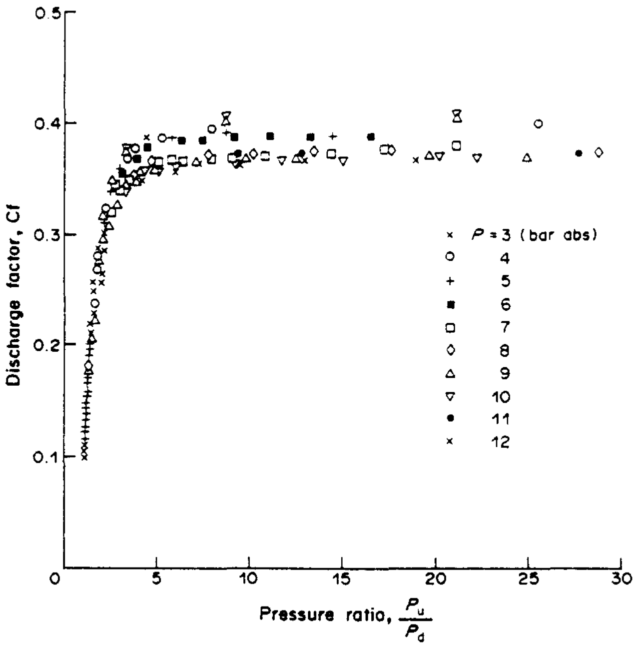


Figure 4

Cf, the discharge factor is not a true discharge coefficient except in the choked region. The isentropic expansion index, γ, for superheated steam was taken to be 1.35. The isentropic critical pressure ratio for superheated steam is 1.85. It can be seen from figure 4 that in the reverse flow direction the diode choked at a pressure ratio of about 4, considerably higher than the ideal one-dimensional value. It can also be seen in figure 4 that Cf in the choked region is about 0.38, i.e. the diode passes 38% of the flow of an ideal nozzle. This compares with a value of 0.4 obtained by George *et al.* (1975) whoe used a number of different gases and a different design of vortex diode.

The corresponding characteristics for the forward flow direction are shown in figure 5. In this case Cf asymptotes to a value of about 0.95 which shows that, despite the relatively complex geometry of the diode, the forward flow resistance is close to that of an ideal nozzle. In this case the diode chokes at a pressure ratio close to the ideal value of 1.86. The degree of superheat of

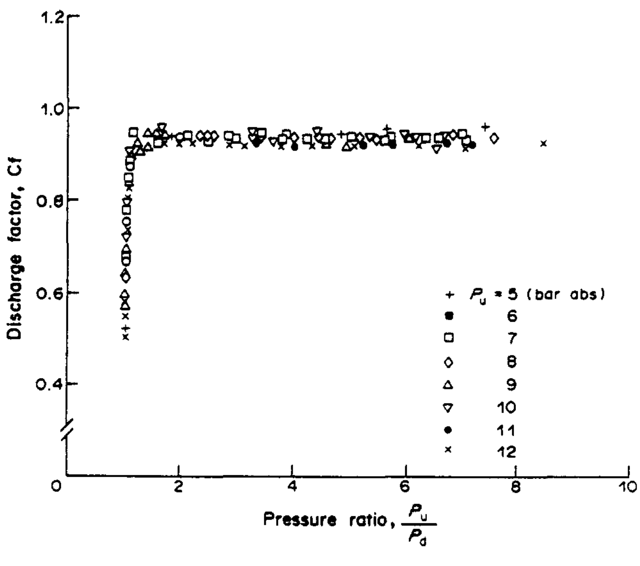


Figure 5

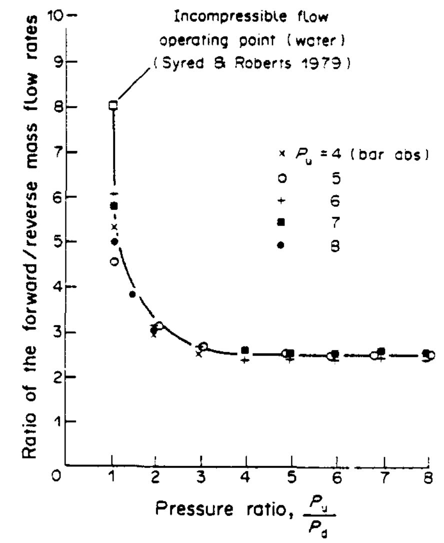


Figure 6. Effect of compressibility on diode performance.

the steam entering the diode varied throughout the experiments as the demand on the boiler and superheater changed. The fact that the data collapses towards a single characteristic suggests that the steam was behaving, as expected, like an ideal gas.

A measure of the effectiveness of a vortex diode is its "diodicity". That is, the ratio of forward to reverse flow at a given pressure ratio and inlet pressure. In figure 6 it can be seen that the diodicity quickly reduces as the flow becomes compressible; falling from a value of 8, obtained using water as an incompressible fluid, to the constant value of 2.5 in the choked condition. This represents a serious deterioration in the diode performance and merited further investigation.

Although it is often assumed that the high resistance produced by a vortex diode is due to the radial pressure gradient through a vortex flow, in fact much of the resistance occurs in the exit throat of the diode. The swirl generated in the exit of the diode causes vortex breakdown and a reverse flow zone forms extending to the back wall of the diode (King & Syred 1980). In other words there is a fluid-dynamic "plug" located in the exit throat and the flow has to leave the diode through the annular passage which is thus formed. The size and strength of this reverse flow zone is governed by the strength of the main vortex generated in the vortex chamber. The minimum area of the diode is at the throat and when the flow chokes it will do so at this section. If the flow is choked at the throat then clearly there cannot be reverse flow. Therefore, it can easily be reasoned that as the flow becomes transonic so the reverse flow zone is pushed downstream and out of the throat, thereby removing the blockage. Lewellen *et al.* (1969) showed that in confined transonic swirling flow it is possible for the reverse flow zone to divide such that the area with vortex breakdown moves downstream, as described above, and a separate recirculation forms in the centre of the main vortex, before the throat. Owen & Motamed-Amini (1986) measured the static pressure profile across a vortex chamber and along the axis of the exit port and showed that in the unchoked condition an adverse pressure gradient was present in the throat region whilst in the choked condition it was not. Since an adverse pressure gradient is associated with reverse flow, this observation was in keeping with the present discussion.

Wet steam

Wet steam was produced by injecting water, in the form of a fine spray, into the superheated steam flow. The quality of the steam was calculated from the measured enthalpies and flow rates of the incoming superheated steam and injected water, and by measuring the temperature and pressure of the resultant two-phase flow. During the course of the experiment it was not practicable to pre-select a particular dryness fraction since it was influenced by the steam flow rate, pressure and temperature; all of which changed when the water was injected. Therefore the controlled

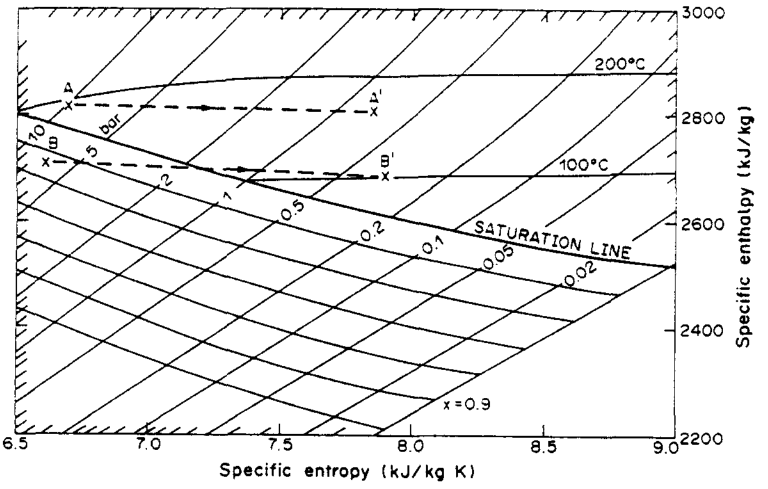


Figure 7. Steam conditions at the inlet and outlet of the vortex diode.

parameters during this part of the experiment were the inlet and outlet pressures of the diode and the mass flow rate of the injected water.

For this procedure to be accurate it is vital that the resultant two-phase mixture is in thermal equilibrium. Calculation of the evaporation of water sprays and drops in a steam environment shows that this can happen extremely quickly (Ryley & Lee 1968; Lee & Tankin 1984). Nevertheless it is always advisable to allow the flow additional time to regain equilibrium. The overall thermodynamic process from the inlet to downstream of the diode is a throttling one. In the superheated condition it is possible to uniquely identify the state point of the steam. In the wet condition the specific enthalpy was calculated using the energy balance described above. When the steam quality at inlet was not too low (>95%) and there was a sufficiently large pressure drop across the diode, the steam changed from being wet at the diode inlet to being superheated downstream of the diode. The end-points of such an expansion are shown in figure 7 together with similar end-points measured for superheated steam, both are for the reverse flow direction. It can be seen that this confirms the process is a throttling one and serves to give confidence in the calculation of the dryness fraction. It should be emphasized that although the end-points of the expansion show a constant enthalpy process, when the steam is expanding through the vortex the flow velocities (tangential and radial components) will be very high and the static temperature will fall accordingly. One of the original concerns about using vortex diodes in steam was that such a fall in temperature might cause condensation to occur and the vortex to collapse.

The pressure-flow characteristics of the diode in wet steam were obtained by maintaining a constant inlet pressure and varying either the downstream pressure or the flow rate of the injected water independently. Inlet pressures from 5 to 8 bar abs were used in the reverse flow direction and from 3 to 6 bar abs in the forward flow direction. This range of inlet pressures was less than that used with superheated steam but was considered sufficient to demonstrate the characteristics of the diode in wet steam.

As with superheated steam, the wet steam flow through the diode was measured and expressed as a fraction of the ideal wet steam flow through a choked isentropic nozzle. A number of theoretical and semi-empirical formulations have been developed to describe critical two-phase flow. In the present work we are dealing with a relatively high quality two-phase flow with the steam having dryness fractions >0.88. It is important that a simple and yet reasonable representative model for the critical flow of wet steam be adopted; otherwise the purpose and reporting of the present study might become confused in the wider complex issue of critical two-phase flow.

The simplest two-phase model is the frozen homogeneous model which assumes:

(1) the average velocities of the phases are equal;
(2) no heat or mass transfer occurs between the phases;

(3) the vapour expands isentropically as a perfect gas, i.e. pv^{γ} is constant;
(4) the kinetic energy is due solely to the vapour expansion;
(5) the critical flow is defined by gas-dynamic principals.

In other words the flow is considered to be that of a perfect gas through an ideal nozzle and the water content is simply suspended in the flow as fine droplets with no slip and no evaporation.

The frozen homogeneous model used in the present work has been described by, amongst others, Henry & Fauske (1971) [N.B. equation (43) in this reference is misprinted].

Thus the critical mass flow rate, $\dot{m}_{cm}$, of wet steam is given by

$$\dot{m}_{cm} = \frac{A_e}{v}\left[2x_u P_u v_{gu}\left(\frac{\gamma}{\gamma - 1}\right)(1 - \epsilon^{\frac{\gamma-1}{\gamma}})\right]^{\frac{1}{2}},$$

where

$$\epsilon = \left[\frac{2}{\gamma + 1}\right]^{\frac{\gamma}{\gamma - 1}},$$

the specific volume of the mixture at the throat of nozzle, is given by

$$v = (1 - x_u)v_{fu} + x_u v_{gu}\epsilon^{\left(\frac{-1}{\gamma}\right)}.$$

The critical flow equation for $\dot{m}_{cm}$ reduces to the one-dimensional critical gas flow equation when $x = 1$. Cf, the discharge factor of the diode, is therefore given by

$$\mathrm{Cf} = \frac{\dot{m}_m}{\dot{m}_{cm}}.$$

There is some controversy regarding what value should be taken for the isentropic index of expansion γ in wet steam flow. Mayhew and Rogers (1973), for example, suggest a value of 1.35 for superheated steam and 1.135 for wet steam. Others argue (e.g. Ryley 1970) that γ has no physical meaning in two-phase flow and that to consider the homogeneous mixture as a single medium is misleading. In the present model it is assumed that the gas phase follows the laws of gas dynamics, i.e. of the dry saturated steam. The value of γ which has been used is therefore 1.35.

Although this model will not be accurate over the entire range of dryness fraction, it will be more representative at the higher dryness fractions where the water will be more dispersed and will suffer less thermal and mechanical disequilibrium. Furthermore, due to the fact that phase change is metastable and takes a finite time to occur there will be little or no phase change before the nozzle throat, thus satisfying some of the assumptions of the model.

As was suggested earlier, it was difficult and time-consuming to maintain a constant value of dryness fraction over the entire range of pressures used. However, in figure 8 the reverse flow discharge factor of the diode is shown for wet steam at a constant inlet pressure of 7 bar abs and a dryness fraction of 0.93, together with corresponding curve for superheated steam. From this limited wet steam data it can be seen that the diode chokes at much the same pressure ratio as for superheated steam but with a higher discharge factor.

It was recognized that, in practice, steam supplies normally have pressures in excess of about 6 bar abs and that a diode would normally be operated in the choked condition. Therefore, the following data was collected when the diode was operating well into the choked region.

In figure 9 the reverse flow discharge factor (in the choked region) is shown for dryness fractions ranging from 0.91 to 0.98 and for inlet pressures from 5 to 8 bar abs. Also included is the corresponding data for superheated steam which has been assumed to be the same as that for dry saturated steam. This latter data fits in with the observed trend for wet steam. It can be seen that as the steam becomes wetter, so the discharge factor rises from 0.38 for dry steam to 0.48 for steam at 0.93 dry. This reduction in the diode resistance is not due to extra mass being carried out in the water content since this is allowed for in the model. In trying to explain this observed trend two other possibilities come to the fore. Firstly, it is possible that the water content causes an increase in the apparent viscosity of the fluid and leads to an increase in viscous dissipation within the flow, this is known to occur in cyclone dust separators as the dust loading is increased (Sproll 1966). Another possibility arose from observation of the flow in the vortex chamber. This was made

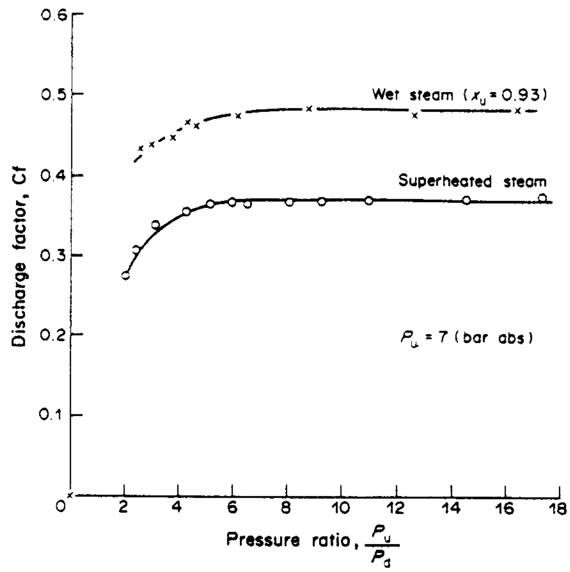


Figure 8. Comparison of reverse flow discharge factor of wet steam and superheated steam.

through a glass wall which had been specially manufactured for this purpose. It will be seen later in this section that an annular condensation fog was observed in the exit region at the centre of the diode. It was argued earlier that it is the flow in the exit throat of the vortex diode that governs its resistance properties. Condensation in this area (caused by the high velocities and hence low static temperatures) will enable more mass to pass through the throat. It is not clear why this effect might increase with an increased water content but it is known that drops already existent in the flow can act as condensation sites. Neither of these explanations are wholly satisfactory but certainly their combination will lead to a deterioration in the diode resistance.

Flow oscillations

It was found that in the high-resistance direction, as the water content was increased so a point was reached where the resistance of the diode decreased suddenly and at the same time the flow of steam through the rig increased rapidly. This phenomenon did not occur at a particular value

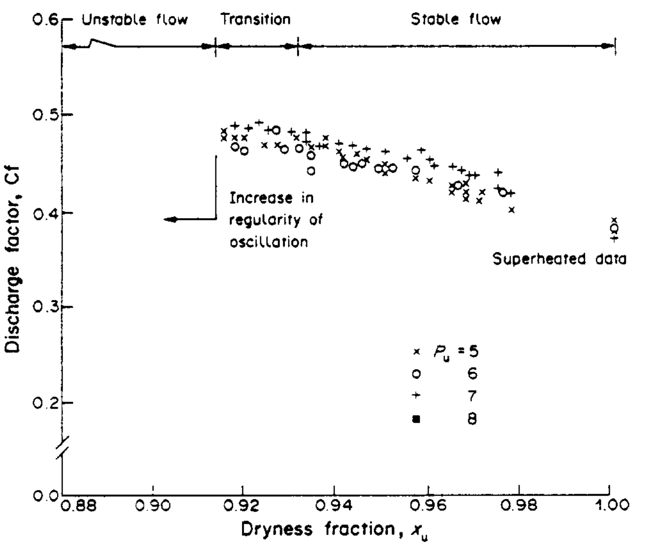


Figure 9

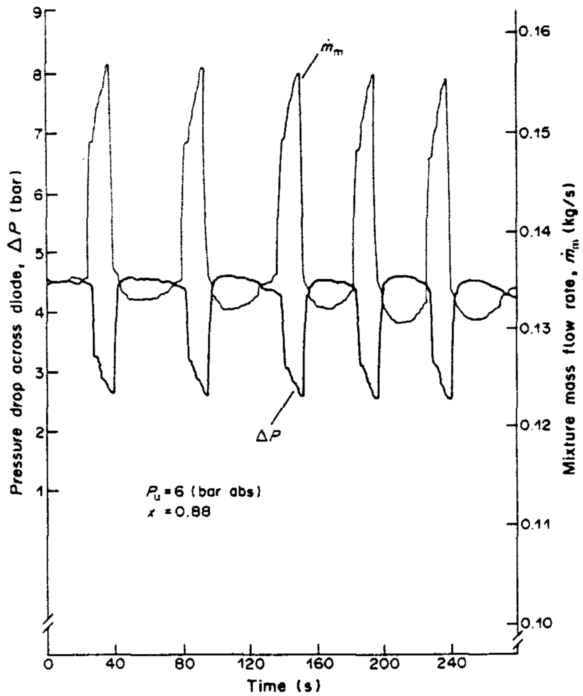


Figure 10. Vortex diode oscillation in wet steam.

of dryness fraction and its onset could not be predicted with any accuracy. It occurred within an approximate range of dryness fraction between 0.93 and 0.91. This is shown in figure 9 as the transition region. For dryness fractions $\lesssim 0.91$ the oscillations became regular and it was impossible to take reliable measurements. Figure 10 shows the regular nature of these oscillations which had a period of approx. 45 s.

To assist in the understanding of this behaviour the half of the diode body which formed the plane back wall was machined to accommodate a 125 mm dia glass plate of 25 mm thickness. This enabled the flow in the vortex chamber to be seen. Figure 11 shows dramatically the reason for the oscillations in Figure 10. Figure 11 shows four different stages during a single oscillation, with the flow being relatively dry in (a) to it becoming severely flooded in (c). On investigation, it became clear that for dryness fractions $\lesssim 0.93$ the water content is not all carried with the steam but flows down to the "U" bend in the rig, figure 3. Although the water is introduced as a fine spray, it is inevitable that much of it deposits on the pipe wall and is swept, either as a rivulet or as a film, through the pipework. This is the case with all wet steam flows. When the steam becomes too wet, reversal of the water flow can take place in upward vertical pipes, this is a well-known feature in vertical two-phase flow (O'Brien *et al.* 1986). The water accumulates in the "U" bend until there is sufficient such that some of it will be swept by the steam flow into the diode and the internal flow changes from (a) to (b) (figure 11). The tangential inlet is towards the lower left-hand corner of the photographs. In figure 11(a) the water which has been deposited onto the glass wall can be seen tracing out the flow in the boundary layer. The flow (a spiral vortex) is symmetrical around the axis of the chamber and the annular condensation fog discussed earlier can be seen clearly. This annular region coincides with the area of maximum velocity and hence minimum static temperature. In figure 11(b) the effect of the water on the flow structure is to reduce the size of the vortex and to move it over to the right-hand side. The centre of the "dry vortex" is shown in each photograph. Much of the resistance of the diode has now been lost and, as was shown in figure 10, the flow through the diode increases rapidly. The increased steam flow will now sweep the water from the "U" bend and through the rig, figures 11(c) and 11(d). After the trapped water has been purged the steam becomes drier again and the vortex structure recovers. The cycle can then start again.

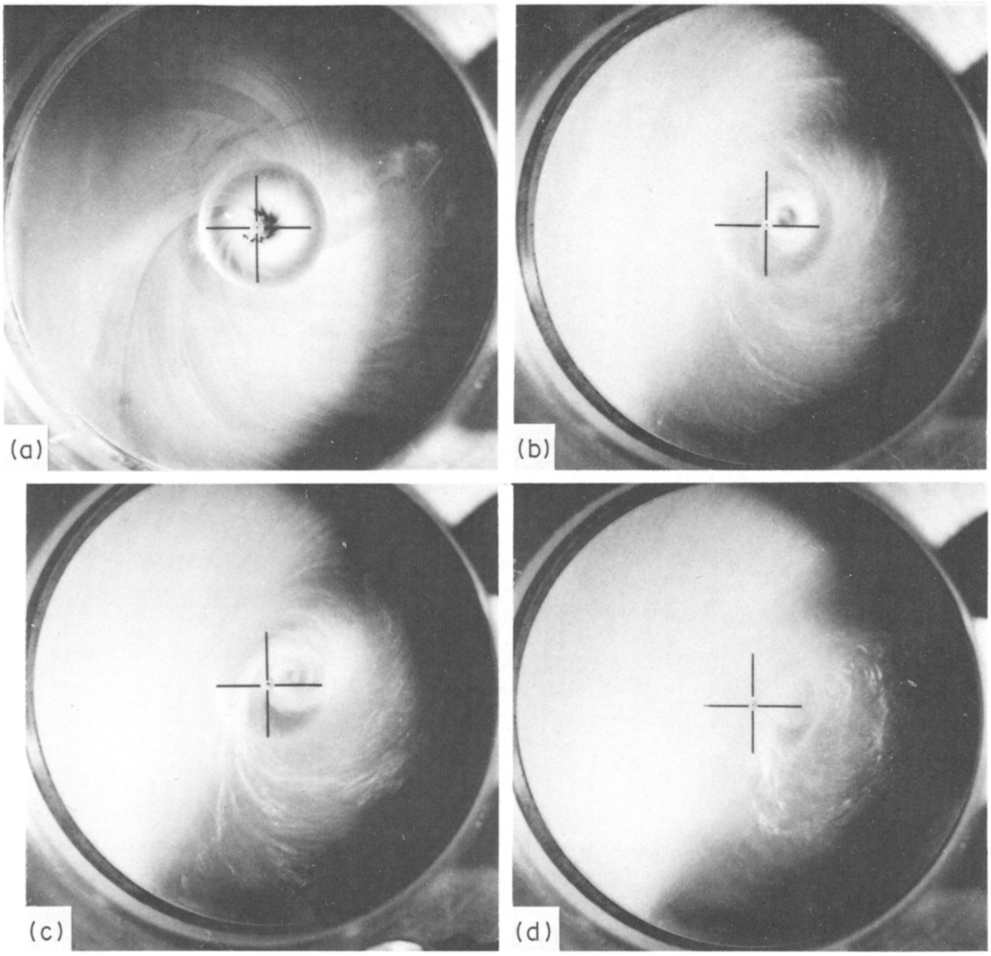


Figure 11. Visualization of wet steam flow in the vortex chamber during an oscillation.

Therefore, the oscillations are as a result of the rig configuration and the effects of the excessive water on the diode internal flow structure. The purpose of the diode is to produce a high resistance and hence low velocity in the pipework. If the steam is too wet, water flow reversal can occur in any upward vertical run of pipe.

In the forward flow direction the diode presents a low resistance to the flow and hence the steam velocity was always high enough to sweep the water along with it. The forward flow discharge factor is shown in figure 12, where it can be seen that, as with superheated steam, the value approaches unity. This shows that the diode presents very nearly the minimum resistance to flow. There is a suggestion in the data that higher values of inlet pressure give higher values of Cf.

DISCUSSION AND CONCLUDING REMARKS

This paper provides, in some detail, additional information regarding the pressure-flow characteristics of a vortex diode. Firstly, the effects of compressibility are seen to reduce significantly the high-resistance performance of a vortex diode. Secondly, the use of wet steam will reduce further the resistance; and thirdly, if the steam is sufficiently wet for flow reversal to occur the diode and associated flow network will suffer from significant oscillations in pressure and flow. It is interesting to note that if slugs of water are swept into a conventional valve that, due to the increased density of the throttled fluid, the valve resistance goes up, unlike the vortex valve where, due to the destruction of the vortex, the resistance goes down. The nature of the oscillations are therefore completely different in each case. For the present rig configuration a practical lower limit of 0.93 has been found below which the diode will not operate in the reverse flow direction without

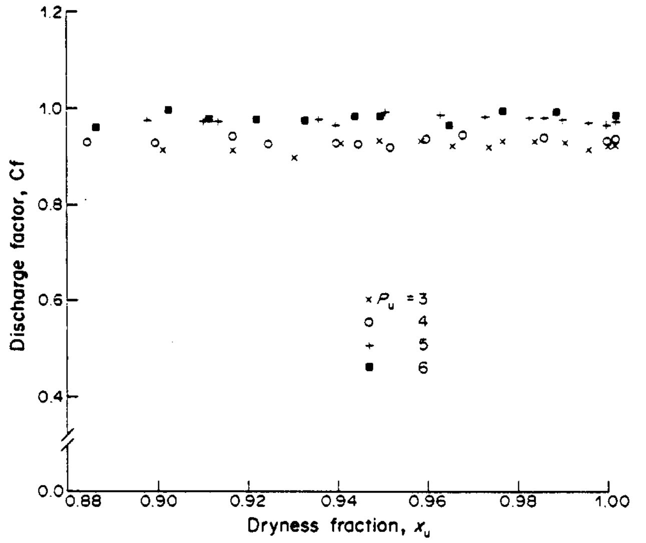


Figure 12. Forward flow discharge factor for wet steam (choked condition).

experiencing the oscillations which have been described. This limit is not universal, however, and relates solely to the present experimental rig. If, for example, the pipework consisted only of horizontal or downward vertical runs the build-up of water would not occur. Also, the pipework used in the present rig has an internal diameter of 77 mm and is oversized in relation to the diode. A smaller bore pipe will have higher steam velocities and could therefore accommodate higher wetness fractions before experiencing flow reversal.

In general, however, the pipework will have upward vertical runs, valves and other fittings, all of which can lead to a build-up of water. It would be prudent to install a water separator in the pipework before a diode if it is to operate in wet steam. Baffle-type separators, for example, have a separator efficiency >70% and would stop the diode being flooded. Steam traps, located at suitable positions in the pipework, would also prevent a build-up of water. Precautions such as these will enable the diode to operate in wet steam with a performance comparable to that which might be expected in a dry compressible flow.

Finally, although it has been shown that the high resistance of the diode reduces significantly in a compressible wet steam flow, it should be pointed out that the device is also designed to offer minimum resistance in the forward direction. By designing for this, the reverse flow resistance is always compromised. If a diode is to be installed into a system simply as a restrictor, as described by Priestman & Tippetts (1982b), then the design will change. The discharge factor of a vortex throttle is about 25% lower than that of the comparable vortex diode. The high-resistance performance can also be partly recovered by installing a number of vortex diodes in series. Although this can obviously be done for any type of throttle, it was shown in figure 5 that the diode performance reduces rapidly as the pressure ratio across it increases and the flow chokes. By sharing the pressure drop between a number of diodes arranged in series, the pressure ratio across the first diode in particular can be located in the unchoked region where the resistance has been shown to be much higher.

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