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Substituting

$$P_1 - P_c = P_c - (1 - C) P_v$$

Solving for P_c

$$2 P_c = P_1 + (1 - C) P_v$$

or

$$P_c = \frac{P_1 + (1 - C) P_v}{2}$$

This relationship only applies to the flow regions where stable liquid enters the second orifice. If flashing occurs in the intermediate chamber, two-phase flow will take place initially through the downstream orifice which represents a departure from the assumptions.

Table 1 gives surface-tension values as supplied by Zemansky and the corresponding calculated values of c, the surface-tension coefficient for pressures up to 1500 psia. The calculated intermediate pressures between two rounded-entrance orifices in series for metastable flow and critical pressures developed within the second orifice also are given with respect to various vapor pressures and initial pressures up to 1500 psia.

Discussion

W. T. Bottomley.[4] The values of C for pressures below 200 psi abs given in Table 1 of the paper, based on Zemansky's surface-tension values, are considerably higher than the values of C given by Burnell[5] based on Hall's surface-tension values. Fig. 2 of Burnell's paper shows that his values of C are in agreement with experimental results and since the authors' Fig. 7 agrees with Burnell's Fig. 2, it is clear that the authors' values of C do not agree with their Fig. 7. If Zemansky's surface-tension values are correct then Burnell's suggestion that $P_v r$ is constant does not agree with experimental results, in which case the authors' determinations of C by extrapolation for pressures above 200 psi will not be correct as they are based on the assumption that $P_v r$ is constant.

Have the authors direct or visual evidence that cavitation occurs before the outlet of the parallel-throated orifice as shown in Fig. 4(b)? This could be established by observing the flow through a two-dimensional orifice having glass sides as described in the writer's 1948 paper.[6] Fig. 2 of that paper shows a two-dimensional converging-diverging nozzle, but the same idea can be applied to a two-dimensional orifice discharging into a two-dimensional pipe. The results of the tests on the flow of hot water at 212 F and 17 psi abs initial pressure through the converging-diverging nozzle is shown in Fig. 10. Visual observation of the flow under metastable condition does not support Bailey's suggestion indicated in Fig. 14 of his paper.[7] There is no sign of cavitation before the throat of the nozzle. The authors suggest that a vapor envelope will tend to form at the surface of the converging stream. This implies that a condition of stable thermal equilibrium exists at the boundary, but the evidence is against this.

Fig. 10 also shows that a considerable free fall of pressure beyond the throat is necessary to obtain metastable flow which is a condition which does not exist in the parallel section in Fig. 4(b). The free fall also rules out the authors' suggestion that the flow through the sharp-edged orifice is metastable essentially to the final pressure in Fig. 2, because P_c is the mean between P_1 and P_2.

Benjamin and Miller (1941) show in Fig. 11[8] no vena contracta beyond the throat of a sharp-edged orifice when discharging from high pressures to atmosphere indicating that the orifice-discharge coefficient is nearly unity with metastable flow. They also show the same values of M/A for sharp-edged orifices when discharging to atmosphere as those given in Fig. 7 of the authors' paper for orifices with radiused entry. These two facts indicate that the critical pressure at the throat of the sharp-edged orifice is the same as that for the radiused-entry orifice.

The discharge coefficient for a sharp-edged orifice passing cold water is 0.62 and since $P_c = 57^1/_2$ in Fig. 2, the flow through the first orifice is

$$\frac{M}{X} = 0.62 \times 96 \sqrt{p(P_1 - P_c)}$$

$$= 0.62 \times 96 \sqrt{57^1/_2(100 - 57^1/_2)} = 2940$$

For the second orifice Burnell's coefficient of cavitation $C = 0.298$ when $P_c = P_v = 57^1/_2$

$$\frac{M}{X} = 96 \sqrt{pP_c \times 0.298} = 2980$$

These flows are practically the same which confirms that $P_c = 57^1/_2$, but there is nothing in the two flow equations to indicate that P_c is necessarily the mean between P_1 and atmospheric pressure. It appears to be a coincidence.

Rateau has shown that when passing dry steam through a sharp-edged orifice the discharge coefficient is 0.63 for small pressure drops and rises to 0.83 when the pressure ratio is 0·4 (see "Flow of Steam").

There is no indication of the value of M/X when P_c is less than P_v. For example, what was the measured value of M/X when $P_v = P_1$? It does not appear that two orifices in series are suitable for draining interstage feed heaters in power stations. A single orifice with radiused entry as recommended by the writer in 1936, has been proved perfectly satisfactory, and is universally adopted in this country.

Authors' Closure

The discussion submitted by W. T. Bottomley is very much appreciated from the standpoint of the pertinent questions raised and the opportunity afforded for further comment on these issues.

Zemansky's surface-tension values were used in preference to the values calculated by Hall's formula to satisfy the approach to zero limitation at the critical pressure which Hall's values do not satisfy. While it is quite true that the calculated flow values based on Zemansky's surface-tension data do not check the measured flow values as closely as those of Burnell based on Hall's formula, the difference is a square-root function and is therefore less than the direct difference of the values. It is interesting to note that the formula $\alpha = 75.64 - 0.1391T - 0.0003\, t^2$ as given in "Thermodynamics," by J. H. Keenan, yields values which are closer to those of Hall at the lower pressures and temperatures and approach somewhat closer to the zero limit at temperatures approaching the critical. The rather wide differences in surface-tension values quoted by the different authors clearly indicate a need for further work to establish the true relations for universal adoption.

Although no specific evidence of cavitation was observed in the parallel-throated orifice of Fig. 4(b) of the paper, this could be the subject of further investigation along the lines suggested.

The formation of a vapor envelope about the liquid core does not appear to conform to a cavitation phenomenon since only

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[4] Springfield, Colvend, Dalbeattie, Kirkcudbrightshire, Scotland.

[5] Reference (5) of the paper.

[6] "Erosion Due to Incipient Cavitation," by W. T. Bottomley, *Journal of The Institution of Mechanical Engineers*, vol. 158, 1948.

[7] Reference (6) of the paper.

[8] Reference (4) of the paper.

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dry vapor is emitted without turbulence at the liquid surface. This is well illustrated by Fig. 9 of the Stuart-Yarnall paper (2). These photographs show that initially subcooled liquid can pass through an orifice to subsaturation pressures in a metastable condition and literally explode to stable conditions at a point below the orifice when the vapor pressure exceeds the surface-tension forces. Between the orifice and the point of transformation to stable conditions the jet remains clear but dry vapor blows outward from the surface of the liquid jet. Under these conditions thermal equilibrium at the surface cannot become established unless the emitted vapor is confined about the jet.

The reference to necessary "free fall" of pressure beyond the parallel section of the orifice throat to obtain metastable flow is not clear. Curve 5 of Fig. 2 shows that if water flows through two identical sharp-edged orifices in series from an initial pressure of 100 psia to atmosphere, the intermediate pressure will remain constant with increase in temperature and vapor pressure of the water up to the intermediate pressure of $57^1/_2$ psia. Under these conditions the water is saturated as it enters the second orifice but subsaturated with respect to the first orifice. Since the pressure drop and the flow rate through both orifices remains the same, it is concluded that the flow through the second orifice must be metastable.

It will be noted with reference to Benjamin and Miller's paper (4) that the authors applied an orifice coefficient in accordance with the values given in Fig. 13 of their paper. These values are in close accord with the normal hydraulic coefficient.

Flow relations for conditions where P_c is less than P_v are outside of the scope of the present paper. Two orifices in series are particularly useful for further investigation in this area, however, since the pressure drop and flow through the first orifice will serve as a meter for the flow through the second orifice.

While it is true that two orifices in series have little or no advantage over a single orifice as applied to direct drainage, the utilization of the intermediate pressure between two control orifices in series to actuate a valve member greatly increases the capacity range and efficiency of condensate drainage. Fig. 6 shows such a steam trap.

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