pressure ratio at the throat (critical pressure ratio) and initial quality, it is seen that the data from each nozzle lie in separate bands and the correlation for a particular nozzle is approximately ±2 percent. However, the data from the two nozzles differ from each other by 10 percent, when IHS assumptions would predict them to be the same.

Since all pressures were measured with the same gauges, the separate data bands for the two nozzles suggest that perhaps the throat pressure taps had different relative locations on each nozzle. Calculation showed that changing the location of the throat tap 0.010 in. would result in approximately a 10 percent change in pressure. This is because of the severe pressure gradient existing at the throat.

In order to check the tap location with respect to the minimum area, cold water was run alternately in each direction through the two nozzles. The resulting pressure data showed that the throat tap was at the minimum area and, thus, it would seem that the throat taps were properly located. On the other hand, the taps were 0.051 in. dia, and during the two-phase experiments should have reflected an average pressure at the throat.

The question arises as to what sonic velocity and critical flow mean in a two-phase flow. Since one of the components is an incompressible fluid, the principles of compressible fluid mechanics cannot apply. One thing that can be concluded from the data is that dp/dA changes sign at the throat and so the flow in this regard definitely behaves like a compressible fluid.

Overexpansion

When the nozzles were run at conditions which caused them to overexpand, the pressure profiles exhibited an abrupt change in slope, but not nearly so abrupt as a completely gaseous flow exhibits. A normal shock wave in single-phase compressible flow is much more distinct and quite strong. The two-phase “shock” appears to be much weaker and less distinct.

Fig. 16 illustrates the difference between the appearance of the single-phase and two-phase overexpansion. As expected, this pseudo-shock phenomenon has a deleterious effect on nozzle performance as example for reaction propulsion, but beyond the recording of this observation, no further treatment of the subject will be included here.

Conclusions

1. The weight flow of a steam-water mixture flowing through a de Laval nozzle can be predicted to an accuracy of 90 percent at qualities greater than 10 percent, using an assumption of isentropic-homogeneous equilibrium. At lower qualities the flow predictions are much less dependable but can be approximated by other simple models.

2. With an initial state in the two-phase region the experimental weight flows can be fitted within the bounds of an isentropic-homogeneous equilibrium flow model and a frozen composition model, and also within the bounds of an isentropic-homogeneous equilibrium flow model and an isentropic flow model. To explain the weight flow increase at extremely low qualities the liquid velocity can be only one-half the gas velocity, that is, the slip ratio must be 0.5 or greater.

3. A phenomenon akin to a gas-phase shock occurs when a two-phase fluid is overexpanded in a nozzle. The pseudo-shock is, however, of much less abrupt nature than in gas-phase systems.

References


Discussion

Joseph H. Keenan

The authors have made a contribution to a subject which is in need of systematic investigation. In a Master’s thesis of 1941, John L. Danforth made some observations at M.I.T. of flow of liquid water through an orifice. The objective was to find how far into the metastable region water could be expanded in steady flow without the formation of bubbles. One of Danforth’s curves of flow versus exhaust pressure was used by the writer in 1941 to illustrate a chapter on metastable states.¹

Danforth found that the shape of the curve was not reproducible. This observation would seem to indicate that uncontrolled turbulence in the orifice entry or development of nucleation sources on the passage walls, or some other uncontrolled variable affected the results substantially.

In order to resolve some outstanding questions of this sort, a detailed experimental study of flow from an initial state of zero quality would be required. Do the authors intend to include such a study in their program?

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The authors have set forth a very nice experimental study of two-phase expansions, on the basis of which they have been able to evaluate three analytical models for such flows. In these models, and the experiments which they describe, the upstream fluid is either a two-phase mixture or at least saturated liquid. The three models are found to fail near zero quality—a fact that prompts the authors to note that an improved prediction would result if a Bernoulli flow component were accounted.

In this connection, the specification of upstream condition for which pure Bernoulli flow will result presents an important related problem. It is not obvious that this will occur for saturated upstream flow since the liquid becomes increasingly superheated as it moves through the nozzle, and it could flash anywhere. Some light is shed upon this question by recent experiments by Brown and York and current tests being made in this laboratory. These reveal that initially subcooled water can pass into the atmosphere through sharp-edged orifices and convergent nozzles at 200 deg F or more without flashing.

In view of these observations, the writers have made a set of simple tests which place an approximate limit on the upstream subcooling for which the Bernoulli flow model is valid. Fig. 17 shows data for hard tap water flowing through both a horizontal orifice and a horizontal convergent nozzle, and discharging into the atmosphere (about 13.4 psia, locally). Observations were made with a constant upstream pressure, by slowly increasing the upstream pressure until steady flashing began from within the aperture. In the case of a horizontal nozzle, the flow became unstable when flashing began, and took the form of a rhythmic alternation between flashing and pure liquid flow. flashing between 3 and 0 deg F subcooling in all cases.

The implication of these tests is that the Bernoulli flow model provides an accurate description for converging flows, initially subcooled 6 deg F or more, so long as the upstream pressure is not too high. Possibly this would be true of the Authors' converging-diverging nozzles as well, if separation does not occur in the diverging diffuser portion.

The authors are to be complimented on providing information which will be of great aid to those concerned with the design of nozzles for expanding very wet steams or other working fluids. This writer found especially interesting the observation of a shock phenomenon and the question raised as to the meaning of sonic velocity in two-phase mixtures.

A thermodynamic analysis performed by Heinrich considered the sonic velocity in a homogeneous foam. The same analysis would apply to a homogeneous mist. The behavior of the acoustic velocity in such a mixture was found to be dependent upon the pressure and quality as well as the temperature through the specific heats. More remarkable yet was the fact that the analysis predicted for a given pressure and temperature a variation of acoustic velocity with quality which would exhibit a minimum. The minimum value of velocity occurs when the volume of gas equals that of the liquid.

The authors data for the No. 2 nozzle at 16.8 lb/sec in have been analyzed to see if this effect is present. By using the experimentally determined critical pressure ratio, the flow rate and the chamber conditions, the assumption of thermal equilibrium between phases at the throat will allow calculation of quality, velocity and, of course, density. The results of these calculations appear in Table 1. The acoustic velocity calculated from the analysis of Heinrich is shown in the right-hand column of Table 1.

In view of the agreement between the authors data and the theoretical values, it would appear safe to conclude that the two-phase mixture does behave as a compressible fluid and that a meaningful (in the normal sense) sonic velocity does exist at the throat. Additionally, the assumption of thermal equilibrium in performing calculations for this type flow appears preferable to the frozen-flow model.

The dependence of sonic velocity, hence Mach number, upon quality would appear to offer an explanation for the nature of the observed shock. A nonuniform vapor distribution across the nozzle could cause a gradual progression of the shock across the section thus resulting in its softness.

This writer has observed substantial reduction of sonic velocities in air-water mist systems and shocks of a somewhat related type described by the authors. Again the authors are to be complimented on an important piece of work. Their thoughts on the above comments would be welcomed.
Authors' Closure

The authors are grateful for the comments and interest in the paper by Professor Keenan, McManus, and Lienhard and Mr. Stephenson. Professor Keenan has asked about the case where subcooled liquid enters the nozzle and we are sure he will find the data contributed in the discussion by Professor Lienhard and Mr. Stephenson of interest in this connection. We have obtained data with the nozzles described in the present paper for inlet subcooling of 0 to 145 deg F and inlet pressures from 160 to 1300 psia and are now preparing a paper on this aspect of the work. The flow rates in these experiments were found to be less than predicted by Bernoulli flow and considerably greater than predicted by equilibrium considerations. In practically all cases the liquid becomes superheated before reaching the nozzle throat. Departures from Bernoulli flow in the convergent section indicate vaporization begins there, however, pressure profiles do not display an abrupt change between the Bernoulli flow range and the two-phase flow range.

Professor McManus has added a very interesting discussion regarding the significance of sound speed in two-phase flow. His comparison values from four of our data runs and predictions by Heinrick make a homogeneous-equilibrium calculation procedure look very promising. Another analysis of the sound speed by Karplus gives rather poorer agreement for the four cases cited, however. For these throat conditions Karplus gives 220, 300, 340, and 470 fps in the order of Professor McManus' table. These values are only 50 to 65 percent of the calculated velocity at the throat. Other problems we see in applying the concept of sonic velocity at the throat are: (a) that sound speed apparently depends upon the size of bubbles and droplets in the mixture so there is not a unique sound speed for each saturation state and quality; and (b) that the strong dependence of sound speed on quality in the low quality region may lead to strong variations of sound speed at the throat plane due to the distribution of the liquid and gas phases. The liquid may be concentrated near the wall. More experiments are needed on sound speed and nozzle flow before we can firmly establish the significance of sound speed in two-phase (low quality) critical flow. Nozzle experiments with adjustable back pressure would also help to clarify this point.