NBS TECHNICAL NOTE 608

Steam-Water, Critical Flow in a Venturi

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R. V. Smith

This paper is the second part of an analytical and experimental investigation,in which the primary object was to test the hypothesis that the flow of the gas phase controls critical and near critical two-phase flow for cases where the gas and liquid flow essentially in separate streams. In the first part of the investigation, a two-component system (air-water) was used. The results presented here substantiate the hypothesis. The analytical results also indicate the use of one dimensional flow equations with reasonably accurate estimates for droplet size and for the drag and heat transfer coefficients (without consideration of mass transfer--vaporization or condensation) describe critical and near-critical flow reasonably well. This indicates that mass transfer may be a secondary effect for these flow conditions.

Key words: Critical flow; pressure profile; steam; venturi; water.

1. Introduction

This study was the second part of a two-phase critical flow program. In the first part, (Smith 1968, 1971) a two-component, two-phase system (water and air) was employed, and the experimental program was quite extensive. This second part was an extension of that work, and was conducted primarily to compare two and one component behavior. The analytical program was essentially the same as that used for the two component system. The hypothesis to be tested for both studies was that the gas behavior primarily controls the critical (choking) two-phase flow for higher qualities where essentially all the gas flows in separated and continuous streams. A more detailed description of previous work and objectives of this program may be found in Smith (1968, 1971).

This study differs from many of the previous works in that it follows the flow from an upstream point and it defines critical flow as a state that occurs when the gas, rather than the mixture, reaches critical conditions. In the largest number of studies the primary interest has been in critical flow at the geometric point where critical flow occurs. This restriction of the study is useful, but it imposes several disadvantages. One is that the fluid conditions at the critical point are difficult to determine. The pressure gradient in that region is very steep and experimental measurements from conventional wall taps in a converging or straight section must be extrapolated to the point of critical flow. Also, in one component flow the quality or gas-liquid distribution cannot be directly measured and must be calculated by various equilibrium or phase-rate-of-change assumptions. In almost all works at the critical point, thermal equilibrium has been assumed. The first phase of this study and other works, such as Fauske (1965) and Carofano and McManus (1968), indicate that this is not a valid assumption.

Further, the velocity of each phase cannot be determined accurately because experimental void (gas-volume fraction) measurements are so difficult to obtain that such velocity data must be evaluated with the use of uncertain quality data. These disadvantages make data for the point of critical flow of limited use, for example, for designers of flow systems.

Nevertheless, work at the point of critical flow has resulted in fairly reliable expressions for the critical flow rate, for example, Fauske (1961), Moody (1965), Zivi (1964) and Cruver and Moulton (1966).

These works, although they have the same general range of reliability of prediction, vary widely in assumptions regarding equilibrium and the gas and liquid velocities. The assumptions made for the gas-liquid velocity ratio are, in almost all cases, substantially higher than experimental measurements reported by Fauske (1965) and Klingbiel (1964).

In the program described here, an attempt was made to minimize and resolve some of these difficulties by studying the flow from points upstream where fluid conditions are known more reliably. Thus, estimates regarding mass, momentum and energy transport can be made throughout the region of rapid acceleration to critical flow. These estimates can then be checked by comparison of analytical and experimental pressure profiles. This procedure of analysis from an upstream point is also followed in a more recent work by Henry and Fauske (1971) and that approach together with the interface analysis procedure reported here is very similar to that reported by Carofano and McManus (1969). This work and that of Carofano and McManus were developed independently at about the same time.

The second difference between this study and most previous works lies in the analytical conditions prescribed for critical flow. For the most part, in previous work the fluid has been treated as a mixture and critical flow has been related to mixture properties. In this treatment, dealing with cases where the flow is essentially separated it has been assumed that critical flow occurs when the gas reaches critical flow. This assumption for critical condition is the same as earlier works using the "vapor choking" model at the point of critical flow, for example, Ryley (1961).

2. Experimental Procedure

The experimental apparatus was similar to, but smaller than, that used in the first part and is shown in figure 1. The two-phase mixture comes from the heater and flows through the annulus of the venturi. The rack and pinion permitted the venturi core to be moved axially, which allowed axial pressure measurements to be closely spaced near the throat where the gradient was very steep. The support for the venturi core was rigid with concentricity thoroughly checked before installation. Any possible variations could be observed visually and by examination of motion pictures and still photographs taken during the runs. The quantity of liquid film flow at the tube wall was measured by extracting the film. The ratio of liquid at the wall to total liquid flow (m_{ff}/m_f) is shown in figures 3 and 4. The mixture quality at the venturi entrance was determined by calculations which took into consideration the energy input and in which thermal equilibrium was assumed. Critical flow at the throat was verified by the presence of a shock wave in the divergent portion of the venturi. If the shock were very near the throat, the readings in that region could have been disturbed, so only data from runs where the shock was greater than 0.05 inches downstream of the throat are reported. Liquid flow was measured by calibrated rotameters between the condenser and the heaters. Pressure was measured at the entrance and near the throat by transducers. Estimated 3 σ error in the flowmeter reading was 3% and in the pressure readings was 4%.

3. Qualitative Observations

As in the case for air-water flow (Smith, 1968, 1971), there were some qualitative observations which support the hypothesis of gas-controlled flow. As shown in figure 2, after critical flow was estab-

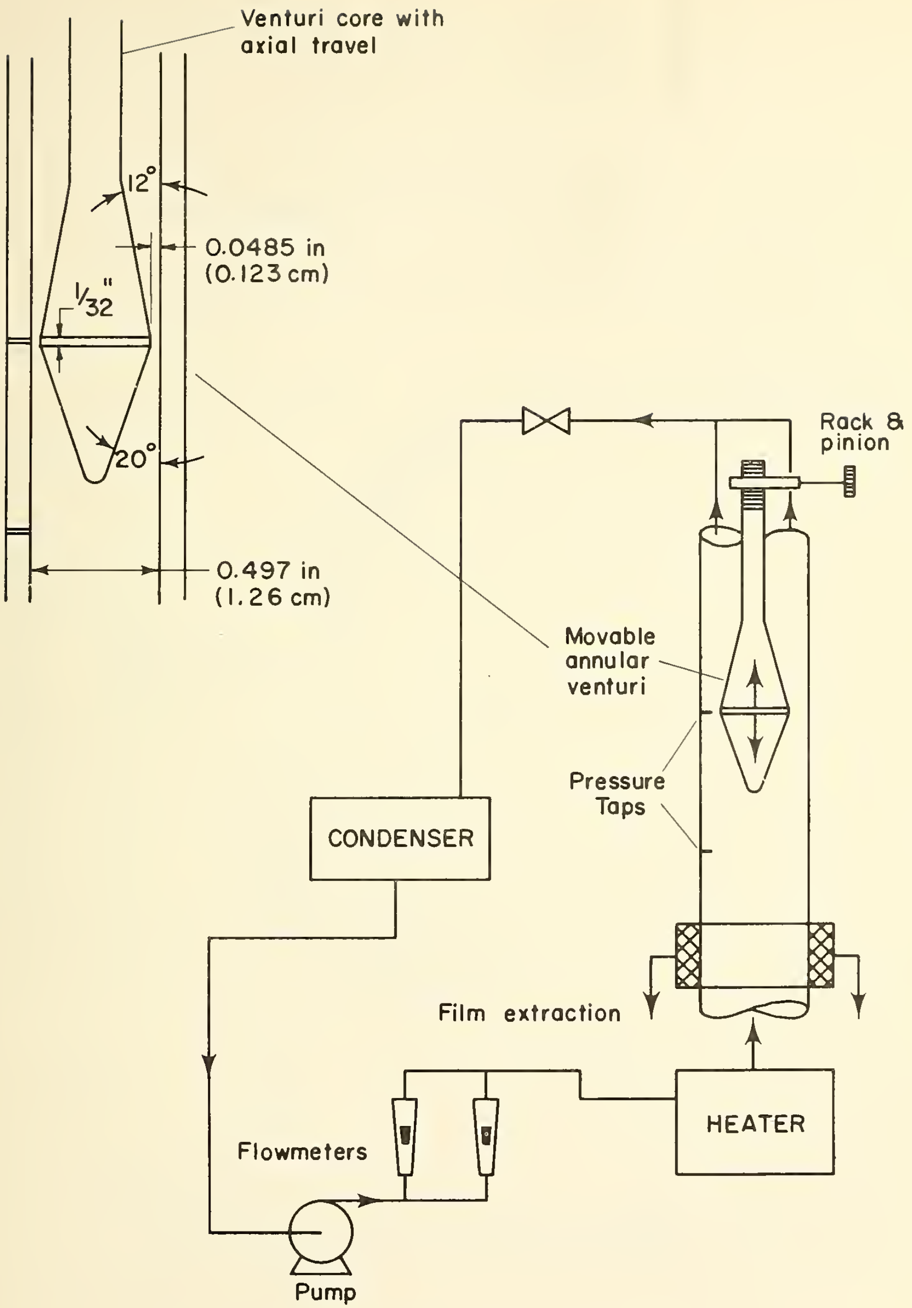

Figure 1. Flow circuit of the steam-water loop

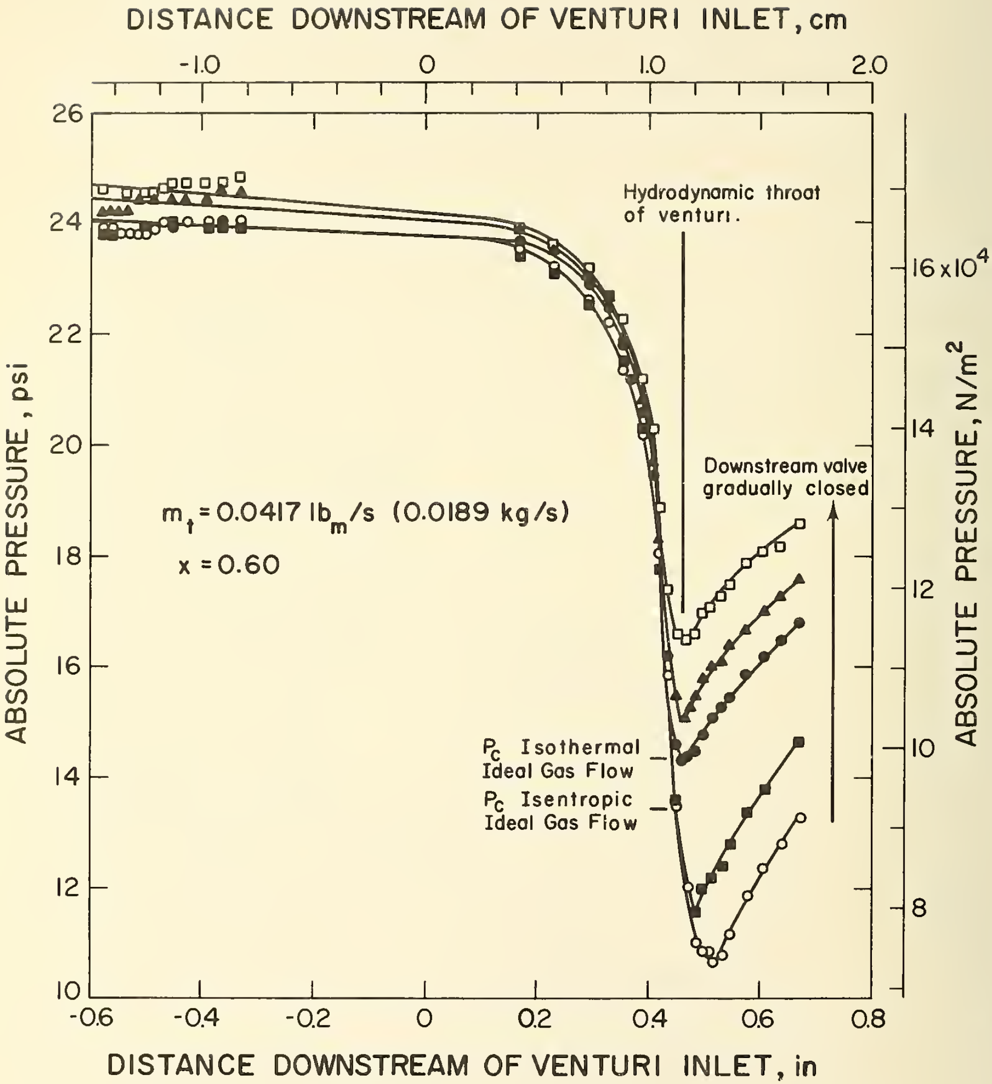

Figure 2. Pressure versus distance along the venturi showing the effect of raising the downstream pressure

lished, the downstream pressure was raised from its minimal value and this moved the shock wave toward the throat. When the shock reached the throat, the pressure was approximately that which would be expected for ideal steam flow alone.

Also, when the standing shock wave reached the throat, the changes in the downstream pressure were transmitted upstream. If the gas were not controlling the critical flow behavior, one might expect pressure signals to be transmitted upstream at different velocities. For example, some pressure signals might be transmitted through a continuous liquid phase at a high velocity and have some influence on the upstream pressure throughout the range of downstream pressure changes. Since the upstream pressure was not noticeably changed until the shock reached the throat, it would appear that the vapor flow characteristics were controlling.

The accuracy of the experimental critical pressure ratios (p_c/p_o) was estimated to be within ± 0.03. This was primarily a result of the uncertainty in the location of the hydrodynamic venturi throat. The location was fixed by studying runs where the back pressure was raised to produce subcritical flow, as shown in figure 2. The hydrodynamic throat was identified as the minimum pressure point for the sub-critical runs, where downstream pressure changes changed the upstream pressure. Smith (1968) showed that with a similar venturi the geometric throat, the hydrodynamic throat as defined here and the throat indicated by pressure measurements with critical, all gas flow all fell within an axial range of 0.020 inches. It was concluded that the relationship would be approximately the same for the case reported here. As studies following this general procedure are continued, further detailed examination of the critical flow at the throat is indicated. These critical pressure ratios varied from 0.5 to 0.6, considering the experimental uncertainty, in the general range indicated for isentropic to isothermal flow of the vapor alone, which is 0.55 to 0.61. Of course, vaporization or condensation and momentum transport would change the value of p_c/p_o from that for ideal gas alone. It would appear, however, that the general agreement, between the experimental data and the expected behavior for the ideal gas flow indicates that the characteristics of the gas flow was the primary factor in controlling the critical flow behavior for the conditions reported. Critical pressure ratios in this range were also reported by Carofano and McManus (1969) for a steam-water system with similar flow conditions.

4. Analytical Procedure

The analytical model was the same as that used for the air-water portion of the program. Thus, the rates of vaporization or condensation were considered zero or negligible. It was recognized that the vaporization and condensation effects could be significant. However,it seemed useful to compare data processed using this "frozen flow" model with the experimental data.

Briefly, the analytical model consisted of a liquid film flowing at the tube wall and a gas core containing entrained liquid droplets. As mentioned previously, the distribution of liquid between film and droplets was experimentally determined by extracting and measuring the rate of the liquid film flow. Assuming one dimensional flow, working expressions were derived from the conservation equations. Frictional pressure drop, due to forces at the tube wall, was considered negligible compared to the momentum pressure drop in equations (1, 2). Potential energy terms such as changes in elevation, and pressure changes were neglected in the energy expression (6).

The momentum equation for the mixture was written as:

$$- dp/d\ell = \frac{m_g (du_g/d\ell) + m_{fe} (du_{fe}/d\ell) + m_{ff} (du_{ff}/d\ell)}{A_t} \quad . \tag{1}$$

Fluid velocities from momentum and continuity equations were:

for gas velocity $$du_g/d\ell = \frac{- (d A_g/d\ell) u_g}{A_g [1 - u_g^2/(dp/d\rho_g)]} \quad , \tag{2}$$

for liquid velocity

$$du_{ff}/d\ell = \frac{- A_{ff}(dp/d\ell) - \rho_f A_{ff} g + 2\pi r_{fg} f_{fg} \rho_g [(u_g - u_{ff})^2/2]}{m_{ff}} \quad , \tag{3}$$

and for liquid droplet velocity

$$du_{fe}/d\ell = \frac{\rho_g \left[\frac{(u_g - u_{fe})^2}{2} \right] A_d C_{dr}}{\frac{4}{3} \pi R_d^3 \rho_f u_{fe}} \quad . \tag{4}$$

Energy transport and fluid temperatures from energy and heat transfer equations were:

for interface energy transport

$$q = h_c A_{fg} (T_g - T_f) \quad , \tag{5}$$

for gas temperature

$$dT_g/d\ell = \frac{u_g(du_g/d\ell) + (m_{fe}/m_g)\, u_{fe}(du_{fe}/d\ell)}{c_{pg}} + \frac{(m_{ff}/m_g)\, u_{ff}(du_{ff}/d\ell) + 1/m_g(dq/d\ell)}{c_{pg}} , \quad (6)$$

and for liquid temperature

$$dT_f/d\ell = \frac{dq/d\ell}{m_f c_f} . \quad (7)$$

Gas density from the ideal gas equation of state was

$$d\rho_g/d\ell = \frac{dp/d\ell - R\rho_g\,(dT_g/d\ell)}{RT_g} . \quad (8)$$

Effective gas flow area, empirically adjusted to account for waves and droplet distribution, was:

$$A_{gE} = A_t - A_{f\ str} - C_1 A_{f\ str\ 1} . \quad (9)$$

After considerable study, the droplet diameter, the values or expressions for drag coefficients, and the interface heat transfer coefficients were determined. These were selected from data reported in the literature for similar cases and, from among that group, were primarily the values or expressions which best fitted the experimental, critical pressure-ratio data for air-water flow. It was found that variations in the assigned values of these terms by factors of two to four produced computed critical pressure ratio changes no greater than five percent, except in the case of droplet radii, where the variations were as high as ten percent. Therefore, the final results were not particularly sensitive to the assigned values for these terms. Droplet radii, R_d, data were from Wicks et al. (1966) and Ryley (1961). Droplet drag coefficients, C_{dr}, involved three studies, Ingebo (1956), Lappel (1950), and Rabin et al. (1960), with the last of these chosen as best describing the data. The liquid-gas interface drag coefficient, f_{fg}, was set at the equivalent fluid-solid interface value for complete turbulence with rough tubes, using conventional friction factor curves. The convective heat transfer coefficient, h_{ce}, for the droplets was of the Ranz and Marshall (1952) type for laminar flow. The interface heat transfer coefficient for the liquid film, h_{cf}, was the value for a fluid-solid system in turbulent flow, Dittus and Boelter (1930), and this value was partially confirmed by temperature measurements of the liquid film.

The effective gas flow area in (9) was determined by first subtracting a computed liquid flow area, which would occur for the liquid flowing in a smooth stream, and then subtracting the final term in the equation, which is a blockage factor, to account for the reduced gas flow area caused by waves and by droplet distributions. The value of C_1, which is a multiplier for the venturi-inlet, stream liquid flow areas, was empirically determined so that the analytical program would achieve critical flow at the venturi throat. Although the value of this coefficient did empirically fix the location of critical flow for the analytical program by adjusting the effective gas flow area, it did not influence the relationship in equations (1-8), which determined the pressure distribution that was used to compare analytical and experimental results. The value of C_1 varied between 1.5 and 3.0 for the range of experimental data reported. Although the higher values of C_1 may seem large, one must remember that this is an adjustment

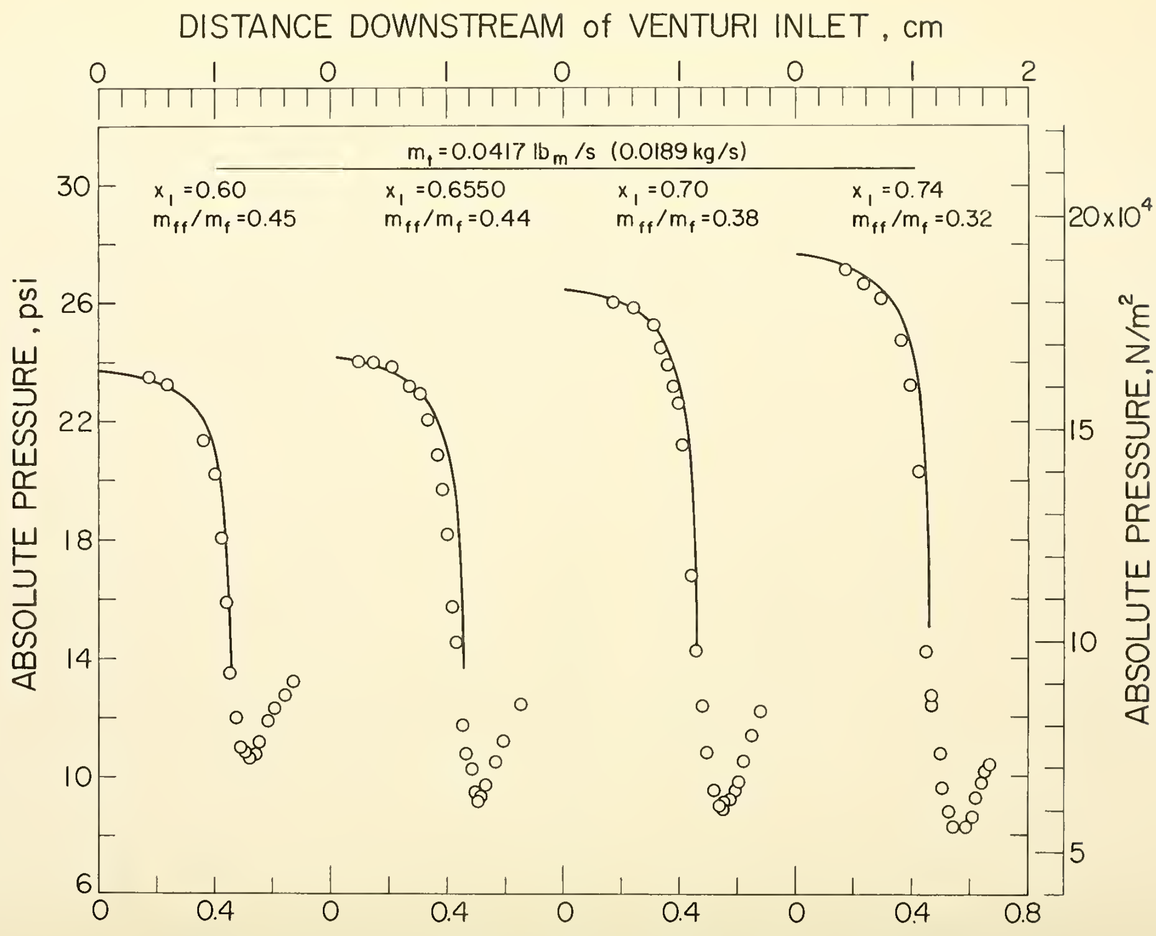

Figure 3. Pressure versus distance along the venturi. Curves are from the analytical program and points from the experimental program.

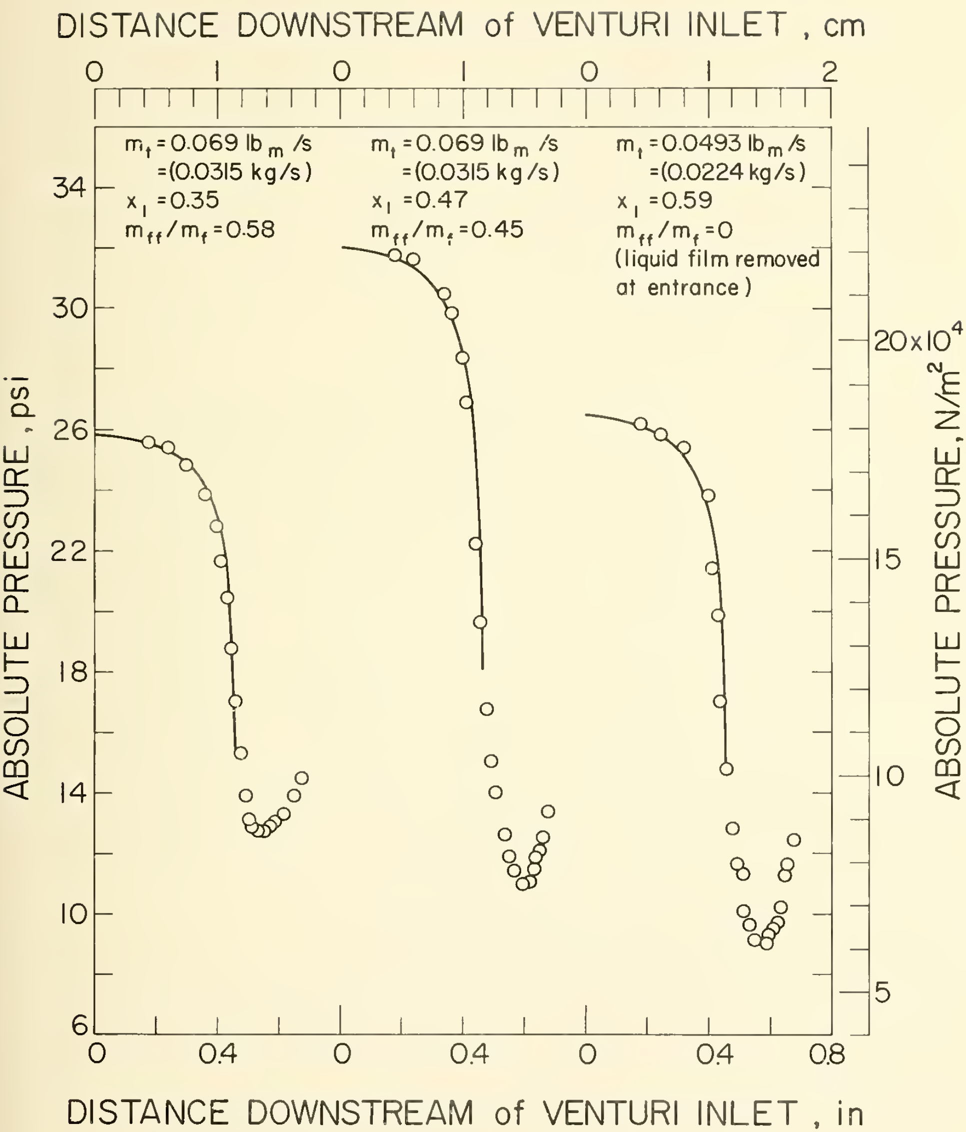

Figure 4. Pressure versus distance along the venturi. Curves are from the analytical program and points from the experimental program.

from a liquid-flow model which is far from realistic. The multiplier C_1 is applied to the stream flow area, which at these high qualities, is very small compared to the total area. Also, estimates of wave behavior and droplet distribution indicate that these blockage values are in a reasonable range, (Smith, 1968).

The computational procedure was to numerically integrate the flow equations from the entrance point of the venturi to the point of critical flow, using the Runge-Kutta (1962) method. The axial length of step between computation points was determined by,

$$\Delta \ell_{step} = C_2 \left[1 - \sqrt{\ell} / C_3\right]. \tag{10}$$

The constants C_2 and C_3 were adjusted to produce the required accuracy in the final numerical results. This demanded that C_3 be approximately the value of the length of the converging section in the venturi, to insure a very short step length near the throat where the pressure gradient is very steep. The point of critical flow was detected in the numerical system by examining the behavior of (2). If the gas flow is primarily controlling, the mixture flow will be critical when the gas flow reaches the critical condition. For that case, the denominator of (2) becomes zero. The maximum uncertainty for this computational procedure was estimated at plus or minus 0.01, for example, for the critical pressure ratio.

5. Results and Discussion

The analytical and experimental results are shown in figures 3 and 4. These data are for different total mass flow rates, all at relatively high quality.

Both experimental and analytical data show a typical, gas-flow profile. The agreement between the analytical and experimental data is quite good, especially considering the "frozen" flow (no vaporization or condensation) model used. The agreement appears to be somewhat poorer than that for the air-water data. The steeper slope (tendency for the experimental pressures to be lower) which appears to prevail for the experimental data may indicate the influence of the vaporization or condensation omitted in the analytical procedure. One should note, however, that in these figures the slope of the pressure curve is very steep and this tends to make the agreement between the experimental and analytical data appear somewhat better than it actually is.

In comparing these data with air-water data from Smith (1968, 1971), the difference in the agreement between the experimental and analytical profiles appears significant but not great. This rather strongly indicates that the gas behavior exerts primary control. It may also indicate that the influence of condensation and vaporization, while noticeable, is of a secondary nature for these flow conditions.

Carofano and McManus (1969), using very similar analytical and experimental procedures, found what appears to be about the same level of agreement with the pressure profiles. In their analytical model, they took into consideration condensation and vaporization rates while employing a fog flow (liquid totally entrained) model. Rough comparison of critical mass flow rates on runs with similar entrance fluid conditions showed agreement at least within $\pm$ 5% between the experimental critical flow rate data reported here and that of Carofano and McManus (1969).

Calculation of the critical mass flow rate, G, using the equation of Cruver and Moulton (1966),

$$\frac{m_t}{A} = \left[\frac{-(u_g/u_f)}{C_{A1}\,(dv_g/dp)_s + C_{A}1\,(dx/dp)_s + C_{A}3\,(dv_f/dp)_s}\right]^{1/2}, \tag{11}$$

where
$$C_{A1} = x\left[1 + \frac{\left[(u_g/u_f)-1\right]}{3\,u_g/u_f}\left[x(3u_g/u_f + 1) - 1\right]\right],$$

and
$$C_{A2} = u_g\left[1 + 2_x\,(u_g/u_f - 1)\right] + u_f\,(u_g/u_f)\left[(1-2_x)\,(u_g/u_f - 1)\right],$$

and
$$C_{A3} = (u_g/u_f)\,(1-x)\left[1 + x\,(u_g/u_f - 1)\,(1 + u_g/3u_f)\right],$$

with $(u_g/u_f) = (\rho_f/\rho_g)^{1/3}$, predicted mass flow rates about double of those reported here. This is not unexpected , as in that type of equation, thermal equilibrium to the throat is assumed. For most of the runs reported here, this assumption would predict superheated steam at the throat. Therefore, it can only be concluded that the Cruver and Moulton type of equation will substantially overpredict the flow rate if the entrance quality is used; since liquid was always observed at the throat, the equilibrium assumption is known to be incorrect. Cruver and Moulton (1966) and Fauske (1965) have suggested that this type of equation may use a slip ratio higher than the actual ratio to compensate for the error in the equilibrium assumption. These data would tend to support that suggestion.

6. Conclusions

This work, following a more comprehensive air-water study, further substantiates the concept that gas flow behavior is the primary factor in controlling critical, two-phase flow for higher void or quality flow conditions where the phases flow separately. The analytical model for one-dimensional flow, with estimates for interface phenomena of momentum and energy transport, but neglecting mass transport (vaporization or condensation), showed good agreement with the pressure profiles just upstream of and at the critical point. The critical pressure ratios were in general agreement with those expected for ideal gas flow.

7. Acknowledgments

The experimental work for this program was carried out during a period when the author was attached to UKARE, Harwell England. Mr. L. B. Cousins and Dr. G. F. Hewitt made substantial contributions to the program.

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9. Nomenclature

A	=	Area, cross-sectional, flow area when single subscripted. Interface surface area when double subscripted L^2
c	=	specific heat L^2/t^2T
C	=	coefficient
D	=	tube diameter, L
f_{fg}	=	interface drag coefficient, dimensionless
g	=	gravitational acceleration, L/t^2
h_c	=	convection heat transfer coefficient, M/t^3T
k	=	thermal conductivity, ML/t^3T
ℓ	=	length along venturi, L
m	=	mass flow rate per unit time, M/t
p	=	pressure, M/Lt^2
q	=	energy (heat) transport at interface ML^2/t^3
R	=	gas constant, ML^2/t^2T
R_d	=	droplet radius, L
t	=	time, t
T	=	temperature, T
u	=	velocity, L/t
V	=	volume, L^3
x	=	mixture quality, dimensionless

Greek Letters

ρ	=	density, M/L^3

Subscripts

c	=	convection (first subscript)
	=	critical when subscripted to p or T
ct	=	total convection
d	=	droplet
dr	=	drag
e	=	entrained
f	=	liquid
fe	=	entrained liquid
ff	=	liquid film
fg	=	liquid-gas
f str	=	equivalent liquid stream flow
g	=	gas
o	=	stagnation conditions (first subscript)
p	=	constant pressure
t	=	total
1	=	venturi entrance
	=	coefficient identification
2, 3	=	coefficient identification

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This paper is the second part of an analytical and experimental investigation in which the primary object was to test the hypothesis that the flow of the gas phase controls critical and near critical two-phase flow for cases where the gas and liquid flow essentially in separate streams. In the first part of the investigation, a two-component system (air-water) was used. The results presented here substantiate the hypothesis. The analytical results also indicate the use of one dimensional flow equations with reasonably accurate estimates for droplet size and for the drag and heat transfer coefficients (without consideration of mass transfer --vaporization or condensation) describe critical and near-critical flow reasonably well. This indicates that mass transfer may be a secondary effect for these flow conditions.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Critical flow; pressure profile; steam; venturi; water.

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