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A STUDY OF TWO PHASE CRITICAL PIPE FLOW MODELS FOR SUPERHEATED LIQUID RELEASES

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ABSTRACT

Measurements have been carried out on the pipe release of heated freon 11 which are compared with a separated phase numerical model. Predictions from two analytical approaches are also discussed.

INTRODUCTION

In most cases of release from chemical reactors at high temperature and pressure or from pressurized hydrocarbons, the flow at the exit point is critical, with the release parameters dependent only on the source conditions and geometry. In recent years the increasing safety analysis applied to chemical plant and bulk transport systems has widened the scope of critical flow treatments, and there is a desire that these be routinely available to safety authorities.

The models which are available to describe the problem, range from analytical types which embody a range of simplifying assumptions concerning equilibrium, relative phase motion, etc., to those which perform numerical analysis on the conservation equations for each phase and include inter-phase coupling terms.

A review of the literature confirms the general view that analytical models are best suited to release paths which are sufficiently long to enable some degree of interphase mass transfer and equilibration. It is recognized, however, that in many loss situations, the release path may be only a few centimeters and it may then be necessary to interpolate mass flow rates between liquid jet and two phase equilibrium regimes.

An alternative which has presented itself in recent years is that of the numerical approach referred to above although this has yet to be tested for short release paths. However, the more fundamental nature of such an approach is attractive both from the viewpoint of realism and the greater ease of access to flow variables along the release path during calculation.

The major part of this study, therefore, concentrates on the performance of such a numerical approach over a range of experimental release conditions while comparisons are also made with two of the alternative analytical type treatments.

DESCRIPTION OF THE RELEASE PROCESS

Much of the effort on studying critical releases has gone into the idealized pipe geometry. The effect of venting a heated liquid through a simple pipe can be described with reference to Fig. 1.

Liquid accelerates into the pipe entrance and experiences a pressure head loss. For initially saturated liquids, this head loss creates a superheated state and nucleation bubbles form. The driving force for liquid evaporation is therefore its excessive temperature above the saturation curve corresponding to

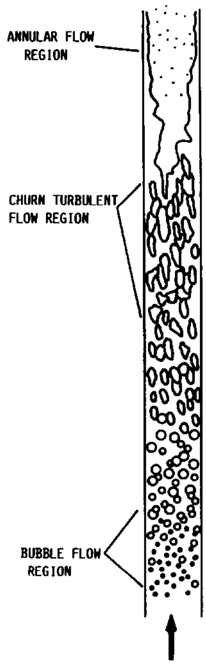
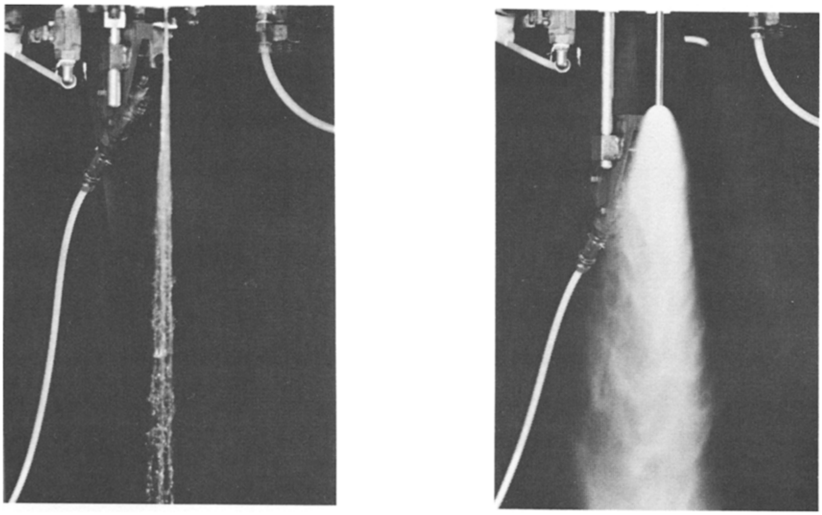


Fig. 1. Schematic of superheated liquid pipe flow.

the local pressure. Evaporation is usually taken to occur at the liquid bubble interface and bubbles may continue to form downstream.

Further continuous pressure losses arise due to liquid wall friction and more importantly due to the evaporation process. As a result, the degree of superheat tends to increase and consequently also the evaporation rate. In addition, the expanding bubbles begin to interact and coalesce and adopt different heat and mass transfer modes. In many flows the evaporation proceeds to a point where the liquid is forced to the pipe walls and the gas occupies a rapidly moving core. In critical flows, the acceleration has progressed to the point where the flow is choked, and this is characterized by very steep pressure gradients located at the pipe exit, where the pressure is above ambient.

Figs. 2a and 2b show the spray pattern at a pipe exit for different release pressures. In the higher pressure and higher superheat case, the exit behavior is markedly different due to the different degree of underexpansion.



(a) (b)

Fig.2. Examples of spray behavior for critical releases of freon 11 for 4 mm diameter pipe. (a) P_o = 2.5 bara (b) P_o = 6 bara

To complement the model analyses, a range of critical release experiments using freon 11 have also been carried out and model performance will be discussed with reference to these.

EXPERIMENTAL RELEASE GEOMETRY

The apparatus used for the freon 11 release experiments is shown in Fig. 3 and consisted of a 30-litre cylindrical vessel with a central piston which could seal an orifice on the lower face. Interchangeable pipe outlets could be fitted to the lower

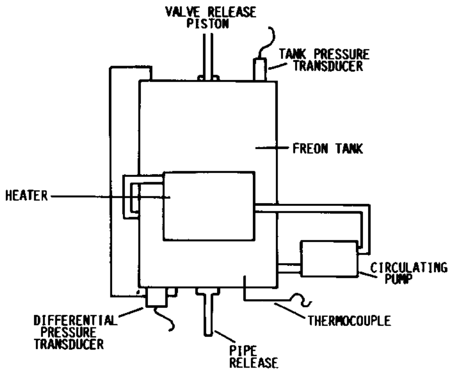


Fig. 3. Schematic of freon tank and pipe release geometry.

face of the tank. A high pressure pump circulated heating fluid around a short external loop which incorporated a 6 kW heating chamber.

The tank was instrumented to record the vapour pressure above the liquid and the liquid temperature by thermocouple. Mass flow rates were determined by following the head with a differential pressure transducer and calculating mass changes at the local temperature and density conditions.

Pipe diameters between 3.2 mm and 6 mm, and pipe lengths from 30 mm to 600 mm were used. For a selected set of 4 mm diameter pipes, the pressure along the pipe length at three points was also monitored. These points were situated at 10 cm downstream of the straight edged pipe entry, the mid-length position and 4 mm upstream of the exit.

The release conditions studied represent typical extremes of operation, these being on the one hand, saturated liquid and long pipes, and on the other, short pipes down to 30 mm with a level of nitrogen padding pressure to simulate strongly subcooled entry condition.

The definition of cases studied is incorporated with the model assessment results referred to below. However, the general behavior of mass flux with source pressure and pipe length is shown in the three-dimensional plots of Figs. 4a and 4b for two pipe diameters. These graphs demonstrate that regions of sensitivity and relative insensitivity of mass flux exist depending on pressure and length. This result is consistent with a recent report by Fauske (ref. 1) who suggested a limiting length of 100 mm for transition to homogeneous equilibrium.

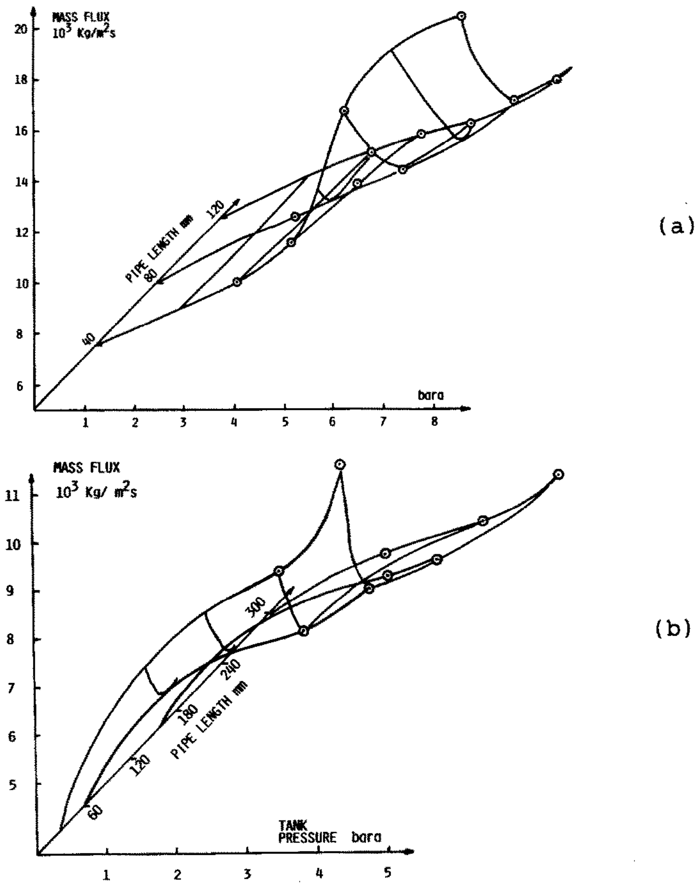


Fig. 4. Typical behavior of mass flux with pipe length and source pressure. (a) pipe diameter 4 mm
(b) pipe diameter 3.2 mm

DESCRIPTION OF MODEL APPROACHES

Analytical models

The chosen starting point for many analytical treatments of frictionless, critical two phase flow is the re-statement of momentum conservation in the form

$$-G^2 = \frac{dv_m}{dP}^{-1} \qquad (1)$$

where G is mass flux, v_m is the mixture specific volume and P, the pressure.

Various degrees of simplifying assumptions can be made to this equation depending on the region of the pipe considered and these are detailed further in (refs 3, 4). A frequent assumption is that thermodynamic equilibrium exists between phases as well as that of identical phase velocities. Two available analytical models which embody the phase equilibrium condition have been used in the present comparative work. Both employ a phase slip ratio suggested by Fauske (ref. 5). The first described by Carter (ref. 6) assumes a fixed pressure drop factor and a stepwise solution procedure down the pipe length, and incorporates two phase wall friction contributions.

The second is available through HTFS (ref. 7) and is known as PIPE2. In this case, a number of empirical correlations have been developed for mass fraction and pressure gradient, which in combination with the above equilibrium and slip conditions enable an iterative evaluation of the mass flux.

Description of numerical integration solution procedures

The calculation method which has been assessed in this study employs a stepwise numerical integration procedure using the differential equations of mass, momentum and energy conservation. This procedure was that implemented by Richter (ref. 8) and has a number of features which attempt to embody the main characteristics of the release process.

In addition a finite rate for evaporation is prescribed which shows the rate of change of mass fraction X in terms of a heat transfer coefficient H_T and phase temperature difference (T_L - T_G). In this way the important structure of the solution procedure is laid down and attention must be given to the choice of interfacial friction terms, heat transfer terms and starting conditions.

Richter has recognized that different regimes of the pipe flow should be associated with different values for those terms and has used the void fraction as an indicator of which regimes to apply. Three regimes have been defined, namely bubble flow for $\alpha < 0.3$, churn turbulent for $0.3 < \alpha < 0.8$ and annular for $\alpha > 0.8$. For the bubble and annular regimes, there are some literature correlations available which describe the interfacial friction and heat transfer, and between these extremes the values are estimated by linear interpolation based on void fraction. The wall-gas friction term is taken as zero and the liquid-wall term is taken from the Martinelli and Nelson correction (ref. 9) which incorporates void fraction dependence.

A remaining unknown is that of the entry bubble density and size. Some authors (e.g., Ardron (ref. 10)), choose to calculate this by means of nucleation theory and append this calculation to the starting procedure. In the present work the example of

Richter has been followed and the entry bubble density and size has been optimized for a single release case. Richter obtained a value of $10^{11}/m^3$ for the bubble density and a diameter of 25 μm based on pressurized water releases. In the present work with freon 11 valuesof $5 \times 10^{10}/m^3$ and 25 μm diameter have been chosen. The solution procedure involves solving the conservation equations for the gradients of the main flow and mass variables at each successive grid point along the release path. At some point the pressure gradient becomes large and negative, which characterizes the choked state. This value was taken as 50 bar/mm consistent with the choice of other authors. At this point the choking length is compared with the pipe length and the mass flow rate is sensibly varied until the choking distance corresponds with the pipe exit.

BEHAVIOR OF FLOW VARIABLES

It is interesting to examine the typical behavior of some of the flow variables between entry and exit, since all of these are calculated within the code. Fig. 5 shows the variation of liquid

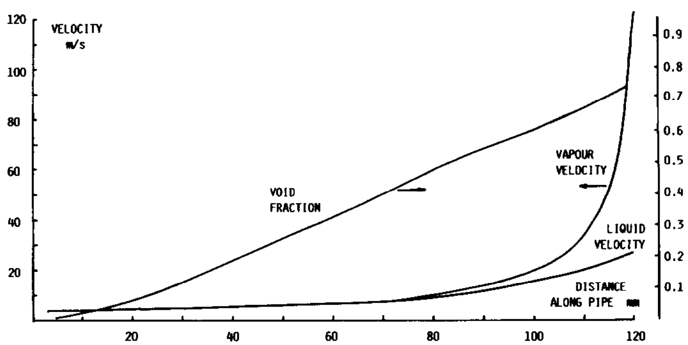


Fig. 5. Variation of vapour and liquid velocities and void fraction along pipe length for freon 11 release based on Richter model for typical case.

and gas velocities as well as void fraction. In the initial stage, where bubble flow applies, the strong interfacial friction prevents the bubbles from accelerating away from the liquid phase and the two curves are coincident. For $\alpha > 0.3$ this friction is progressively reduced, characteristic of the flow regime and the two phases develop a velocity difference. By the exit this difference is very marked with liquid velocities typically between 20 -30 m/s and gas velocities around 120 m/s. This is in contrast to similar studies carried out by Ardron (ref. 10) who only considered a bubble flow behavior and observed gas/liquid velocity ratios close to 1 up to the exit.

Fig. 6 shows predicted behavior of liquid and gas temperatures. Typically, liquid temperature drops by around 10C^{o}. Due to the common assumption of the vapour phase temperature being at the saturation value corresponding to local pressure, the predicted vapour temperature undergoes a substantial drop following the pressure, giving rise to temperature differences up to 30 C^{o} at the exit.

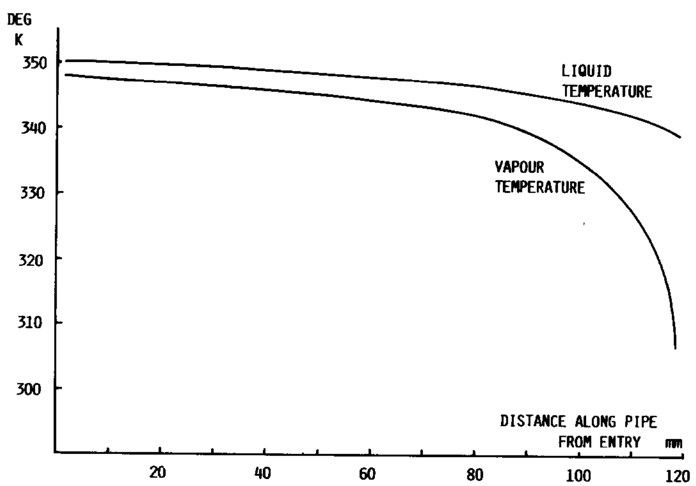


Fig 6. Typical variation of liquid and vapour temperatures along pipe length for freon release predicted by Richter model.

Fig. 7 shows the predicted pressure variations for three release cases. These are compared with values measured at three pipe sections. Discrepancies near the pipe exit indicate that the code is overpredicting the pressure drop; this aspect clearly requires further investigation.

The results of the code assessments applied to all the measured mass flow cases are presented in Figs. 8a and 8b. These are also include under each set of points the release geometry and source pressure. The results are presented as the percent difference between the code prediction and measured value. In both figures the results have been grouped according to pipe length. Fig. 8a relates to saturated release and Fig. 8b, to nitrogen padded cases simulating subcooled discharge.

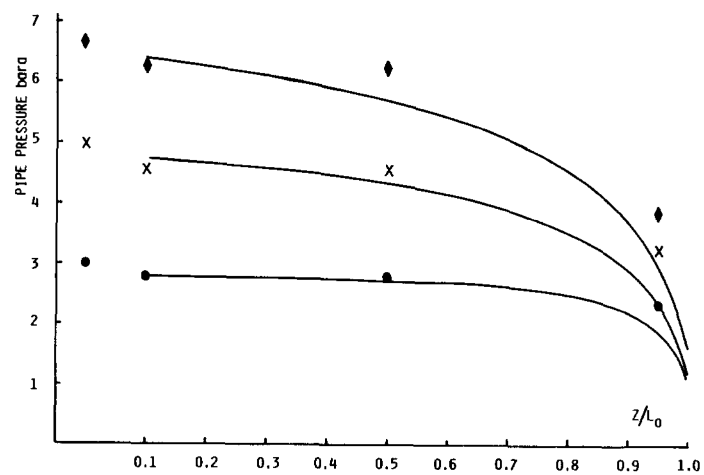
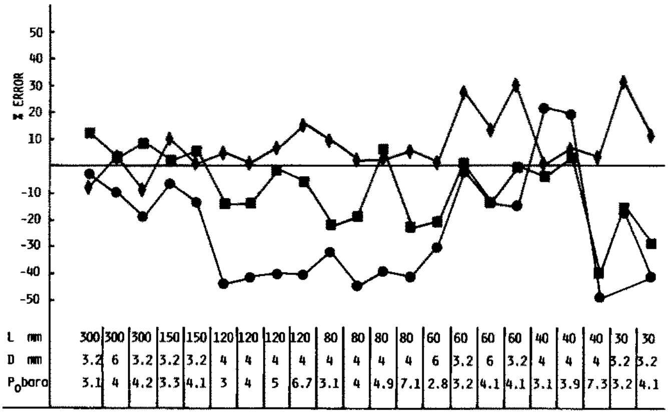


Fig. 7. Variation of measured and predicted pressure along release pipe length using Richter model. Pipe length = 120 mm, diameter - 4 mm.

= 6.7 bara, = 5 bara, = 3 bara.

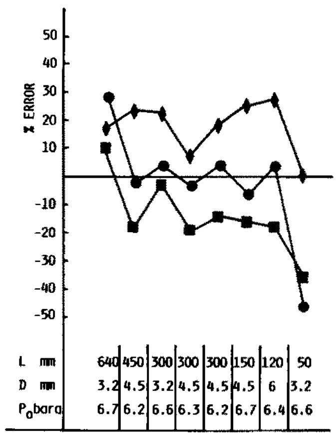
In Fig. 8a, it can be seen that the three models are comparable for lengths down to 150 mm. From 150 - 60 mm, the Richter model predicts within a 10% band, whilst the Carter and PIPE2 error bands increase to 25% and 45%, respectively. Below 60 mm the Richter model overpredicts with a mean error of 15% and



(a)

Fig. 8. Comparison of model predictions for measured mass flow cases. Performances are given as % error from measured values. L is pipe length, D, pipe diameter and P, the source pressure.

(b)



Richter model
Carter model
PIPE2 model

(a) represents saturated cases
(b) represents N_2 padded subcooled cases

exhibits a greater variability, whilst the Carter model tends to underpredict with a mean error of -15% and PIPE2 also underpredicts with a mean error of -23%.

For the padded cases, again the Richter code overpredicts with a mean of 17% and some variability. The PIPE2 code appears to perform better in these cases with a mean of 5% error in the length range of 120 - 450 mm but overpredicting by 30% for the 640 mm case and underpredicting by -46% for the 50 mm length. Similar behavior is found for the Carter model although errors overall are more negative.

The overall performance of the models average to 11% for Richter, 14% for Carter and 23% for PIPE2. With reference to the Richter code it seems that much of its error comes from 30 - 60 mm length cases and these suggest that the overprediction results from an underestimate of the evaporation rate in the bubble flow regime. Some improvement might therefore be expected from a re-assessment of the available heat transfer correlations for liquids, with the possible inclusion of turbulence contributions.

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