Journal of Hazardous Materials, 25 (1990) 193–203
Elsevier Science Publishers B.V., Amsterdam

SIMPLE TRANSIENT RELEASE RATE MODELS FOR RELEASES OF PRESSURISED LIQUID PETROLEUM GAS FROM PIPELINES

V.H.Y. Tam and R.B. Higgins

BP Research, Sunbury Research Centre, Chertsey Road, Sunbury-on-Thames,
Middlesex TW16 7LN, United Kingdom

SUMMARY

Large scale experimental data have been used to compare and derive simple mathematical models to describe the time varying release rate of pressurised liquid petroleum gas (LPG) from a ruptured pipeline. The models studied consisted of a single box, a single-node slip-flow and an empirical model. The empirical model is based on data obtained using 100 metre long pipelines of internal diameters of 50 mm and 150 mm, from an experiment carried out jointly by BP Research and Shell Research Ltd. The empirical model was developed to describe the observed characteristics of the mass history of commercial liquid propane inside the pipe, namely the mass reduced approximately exponentially with time. While the single box model did not compare well with observed data, the single-node slip-flow model was found to produce exponentially time varying release rates.

INTRODUCTION

The consequences of loss of containment of pressurised liquefied gas, such as liquefied petroleum gas (LPG), depend upon the hazard of the gas and the rate at which the gas is released. Therefore it is important to determine the rate of release and its variation with time so that the consequences can be assessed accurately. To address the consequences following the breakage of a LPG carrying pipeline, BP Research has carried out the large scale Isle of Grain Experiment in collaboration with Shell Research Ltd on Pressurised LPG Release using commercial propane (Ref. 1). One aspect of this experiment was to study the transient release rate.

Transient releases in hazard analysis are releases which cannot be assumed to be constant. This could be because the rate at which mass is being removed is significant compared with the total mass inventory inside the vessel so that the release rate varies significantly with time. An example could be when an LPG carrying pipeline is ruptured and the supply of fluid upstream of the location of rupture is stopped, say by an excess flow valve or a blocked valve.

Steady-state and instantaneous discharges are the two release scenarios frequently used in hazard assessment. In the intermediate regime of discharge, the transient regime, releases are often assumed to be

0304-3894/90/$03.50

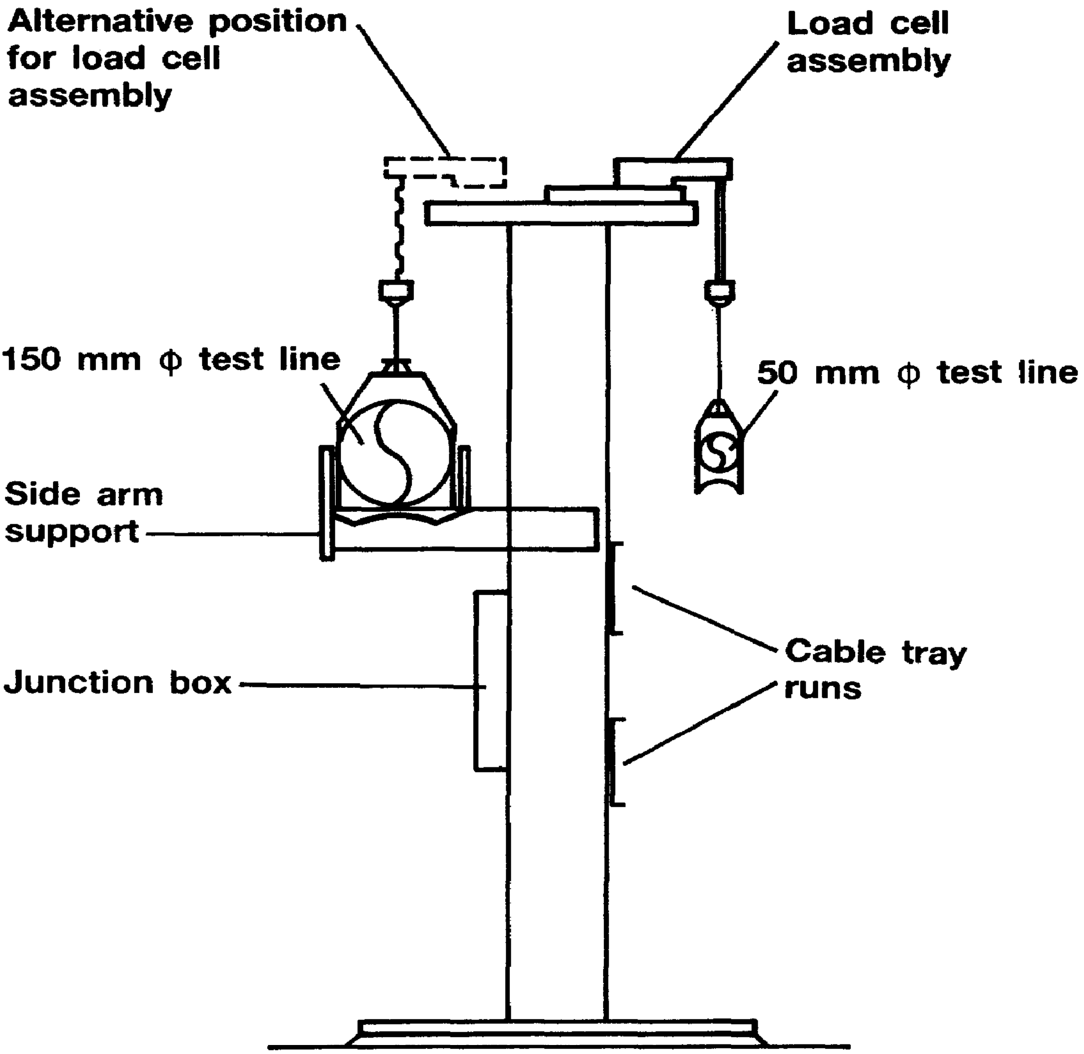

Figure 1. A schematic diagram showing the arrangement of the load cells and test lines.

instantaneous. Use of the instantaneous assumption can mean that the hazard of the release is overestimated. An appropriate, and validated, transient release rate model, therefore, would contribute towards a more accurate assessment of the actual hazard.

Because the flow inside the pipe during a transient release changes rapidly, as in the case of a pipe rupture, the approach has been to solve the rapidly changing flow conditions using either equilibrium choke flow conditions such as Sharma et al (Ref. 2) and Morrow et al (Ref. 3) or the non-equilibrium assumptions eg Trapp et al (Ref. 4). This resulted in relatively complex computer code which can often be expensive to run and inconvenient to use.

In this paper, a simple empirical model which describes the time varying release rate during a transient blow-down of a pipeline containing LPG is presented. The model is based on data from the BP/Shell Isle of Grain Experiment on Pressurised LPG (liquid propane) Release (Ref. 1). In addition, a single-box and a single-node transient release rate model were also considered and compared with the experimental data.

THE DATA

Both steady state and transient releases were simulated in the Isle of Grain Experiments on pressurised LPG releases using two 100 metre long pipelines of internal diameters 50 mm and 150 mm. This experiment was carried out in the former BP Oil Refinery in Kent, England. Further details of this experiment can be found in (Ref. 1). In transient tests, the 100 metre long test lines were filled with LPG, pressurised, and then isolated from the rest of the facilities. The rupturing of the test line was simulated by the breaking of a pair of bursting discs or the fracturing of glass or graphite discs at the spill end of the test line. Orifice plates were used to investigate the effect of different hole sizes and shapes on the releases. In total, 90 tests were carried out using LPG with 33 of these tests being transient releases and the rest steady state.

Line pressure, line temperature and mass of fluid inside the test line were measured. The mass inventory in the test line was measured by two independent methods, load cells and neutron backscatter. 20 load cells were used, at regular intervals along the line, to suspend the entire 100 metre length. Figure 1 is a schematic diagram showing this arrangement. For the nucleonic measuring technique, eight neutron source and detector pairs were used. They were located at different positions along the test line. It was found that the release rates measured from the load cell instruments agreed with those using neutron backscatter to about 10%. In this study, the data obtained from the load cells were used.

instantaneous. Use of the instantaneous assumption can mean that the hazard of the release is overestimated. An appropriate, and validated, transient release rate model, therefore, would contribute towards a more accurate assessment of the actual hazard.

Because the flow inside the pipe during a transient release changes rapidly, as in the case of a pipe rupture, the approach has been to solve the rapidly changing flow conditions using either equilibrium choke flow conditions such as Sharma et al (Ref. 2) and Morrow et al (Ref. 3) or the non-equilibrium assumptions eg Trapp et al (Ref. 4). This resulted in relatively complex computer code which can often be expensive to run and inconvenient to use.

In this paper, a simple empirical model which describes the time varying release rate during a transient blow-down of a pipeline containing LPG is presented. The model is based on data from the BP/Shell Isle of Grain Experiment on Pressurised LPG (liquid propane) Release (Ref. 1). In addition, a single-box and a single-node transient release rate model were also considered and compared with the experimental data.

THE DATA

Both steady state and transient releases were simulated in the Isle of Grain Experiments on pressurised LPG releases using two 100 metre long pipelines of internal diameters 50 mm and 150 mm. This experiment was carried out in the former BP Oil Refinery in Kent, England. Further details of this experiment can be found in (Ref. 1). In transient tests, the 100 metre long test lines were filled with LPG, pressurised, and then isolated from the rest of the facilities. The rupturing of the test line was simulated by the breaking of a pair of bursting discs or the fracturing of glass or graphite discs at the spill end of the test line. Orifice plates were used to investigate the effect of different hole sizes and shapes on the releases. In total, 90 tests were carried out using LPG with 33 of these tests being transient releases and the rest steady state.

Line pressure, line temperature and mass of fluid inside the test line were measured. The mass inventory in the test line was measured by two independent methods, load cells and neutron backscatter. 20 load cells were used, at regular intervals along the line, to suspend the entire 100 metre length. Figure 1 is a schematic diagram showing this arrangement. For the nucleonic measuring technique, eight neutron source and detector pairs were used. They were located at different positions along the test line. It was found that the release rates measured from the load cell instruments agreed with those using neutron backscatter to about 10%. In this study, the data obtained from the load cells were used.

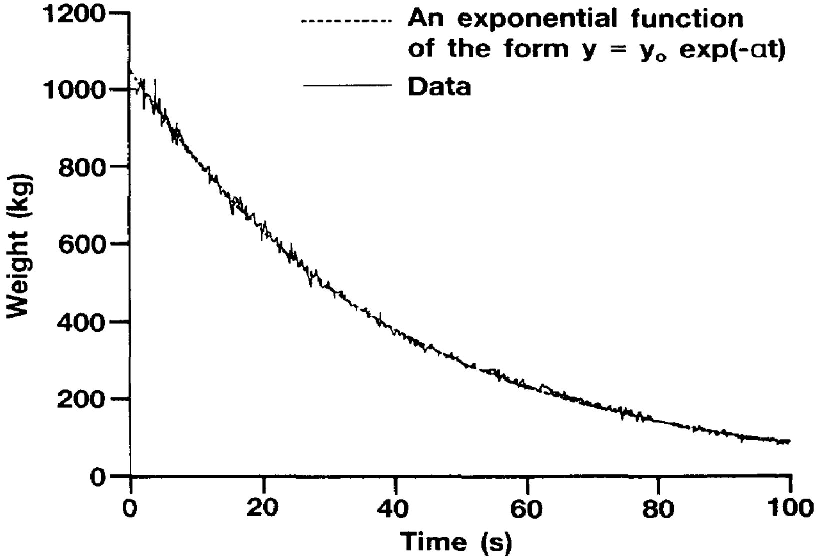

Figure 2. Variation of mass of LPG inside the test line with time during a transient release. The data are taken from a test in which a 50 mm diameter orifice plate was used in a 150 mm diameter test line.

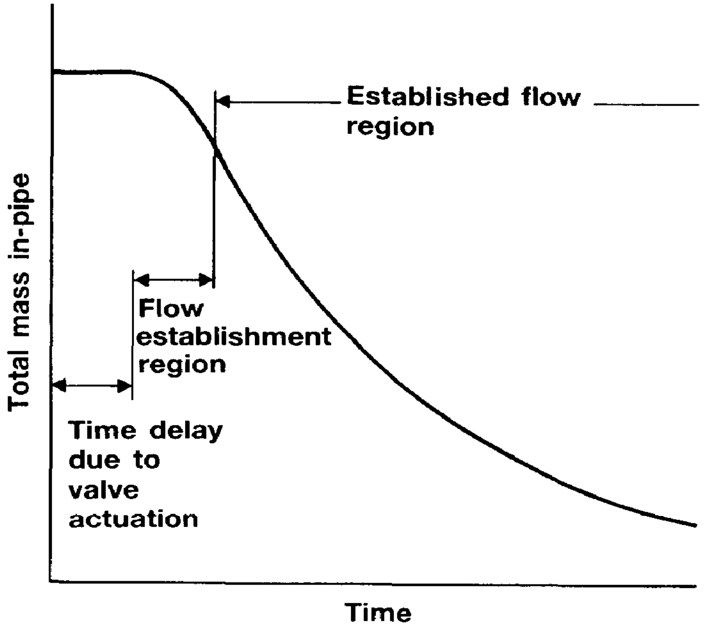

Figure 3. An idealised mass decay curve.

ratio of the square root of their densities. The pressure profile along the length of the pipe is defined using the Lockhart-Martinelli correlation (Ref 11).

Other assumptions used include: (i) the fluid throughout the pipeline and upstream of the orifice is in thermodynamic equilibrium, (ii) the effect of pipe friction is calculated from the pipe surface roughness for a fully turbulent flow and (iii) the process is adiabatic.

SIMPLE CORRELATION APPROACH

Although the flow conditions inside the test line varied rapidly in transient releases, the history of the fluid conditions is predetermined by the initial conditions of the fluid and the configuration of the test line. It follows that, if the transient release rate can be characterised, the characteristics are defined by these conditions.

Characteristics of the Observed Transient Releases: Exponential Decay

An important characteristic of transient releases in the test data was found to be that the total mass of LPG inside the test line decreases exponentially with time. It follows that transient release rates also decreased exponentially during the same period.

$$\frac{dM(t)}{dt} = -\alpha M(t) \qquad (1)$$

where $M(t)$ = total mass of LPG in the test line at time t

and α = mass decay constant.

Figure 2 shows the variation of total mass inventory inside the test line with time for one of transient tests (100 m long pipeline of diameter 150 mm using a 50 mm diameter orifice plate). It can be seen that the mass decay curve matches very well with the exponential curve which is superimposed.

The general characteristics of the mass decay curve are more complicated and can be divided into two parts: flow establishment and established flow regions. An idealised mass decay curve is illustrated in Figure 3. The flow establishment region lasted from less than 1 to about 5 seconds in duration depending upon the size of the orifice. The release rate does not decay exponentially in this region. The duration of established flow was 20 seconds or more, again depending upon the orifice size. The release rates were found to decay exponentially during established flow. It is this characteristic exponential decay which will be modelled empirically.

Exponentially varying release rates have been reported for transient releases in pipelines carrying gas. Models were developed by Bell (Ref. 12) and later refined by Wilson (Ref. 13) for the isothermal release of gases.

Exponentially varying transient release rates for pipelines carrying pressurised liquid have not previously been reported previous to the BP/Shell Isle of Grain LPG Release Experiment (Ref. 14).

Factors Governing the Constants of Exponential Decay of Transient Release Rate

The main factors which affect the value of the exponential decay constant, α, were assessed using statistical analysis. These factors were the initial fluid conditions, such as fluid temperature, and the test line configurations, such as pipe length, pipe diameter and orifice area.

DATA ANALYSIS

Data from the LPG release experiment were analysed and reduced to produce the following:

(1) decay constants of mass inventory in the pipe, α,

(2) conditions of the fluid before the start of the transient releases such as pressure and temperature

(3) the configuration of the test line - orifice sizes and diameter of the test line used.

The mass decay constants were measured from the data collected by the load cells. The data from each load cell were checked and the results from the 20 load cells were then summed. The mass decay constant was then found by a least squares fit of an exponential curve to the data.

RESULTS

Empirical Model

The following regression was obtained from the data set:

$$\begin{array}{llllll} \alpha = & D^{0.25} & (0.22A - & 0.13A^{1.5} & + 0.00068(T - 15)) & \qquad (2) \\ & [\pm.02] & [\pm.02] & [\pm.01] & [\pm.0003] & \end{array}$$

$$R = 0.973$$

Where

α = constant of decay (s^{-1})

D = radius ratio = (Pipe diameter in mm)/50

A = Area ratio (Area of orifice/internal area of pipe)

T = temperature of fluid in °C.

R = coefficient of multiple correlation

The numbers in square brackets are the asymptotic standard errors associated with the coefficients which are directly above them.

This regression accounted for 95% of the variance in the data. Each of the terms included are statistically highly significant (>95%). A comparison of the results predicted by this regression and those measured is shown in Figure 4. It can be seen that the differences between them are generally within ±20%.

Single-Box Models

The two single-box models did not predict the exponential variation in the release rate. This is illustrated in Figure 5, it can be seen that neither of the single-box models produced results which agree well with data.

Single-Node Slip Flow Model

This model produced a near exponentially varying release rate during the period where critical flow conditions were calculated at the orifice. An example of the comparison between the model prediction and observed data is shown in Figure 6. It was found that the mass decay constant calculated by the single-node slip-flow model agreed with those measured to within 20%. However, in about three quarter of the cases studied, the mass decay rate was overpredicted.

DISCUSSION

Pipe Geometry

The most important factor which determines the rate at which the pipe empties is the ratio of the exit area to the internal pipe area. It was found that a 25 fold increase in the area ratio produces a 13 fold increases in the value of α.

The next most important factor is the diameter of the pipe. For a given area ratio, the effect of increasing the diameter of the pipe is an increase in the value of the decay constant (α).

Initial Line Pressure

There was no statistically significant correlation between the initial pressure and the value of the decay constant (α). The fluid was kept at pressures ranging from its saturated vapour pressure to 22 bar before the start of the transient release. A change of over 10 bar did not produce any significant variation in the value of the decay constant, α.

Fluid Temperature

The rate at which the pipe empties increases with the initial fluid temperature. The effect of this on α is relatively small within the temperature range 14 to 24°C. A change of 10 deg. C, for example, produced a change of less than 10% in the decay constant, α, in the experiment.

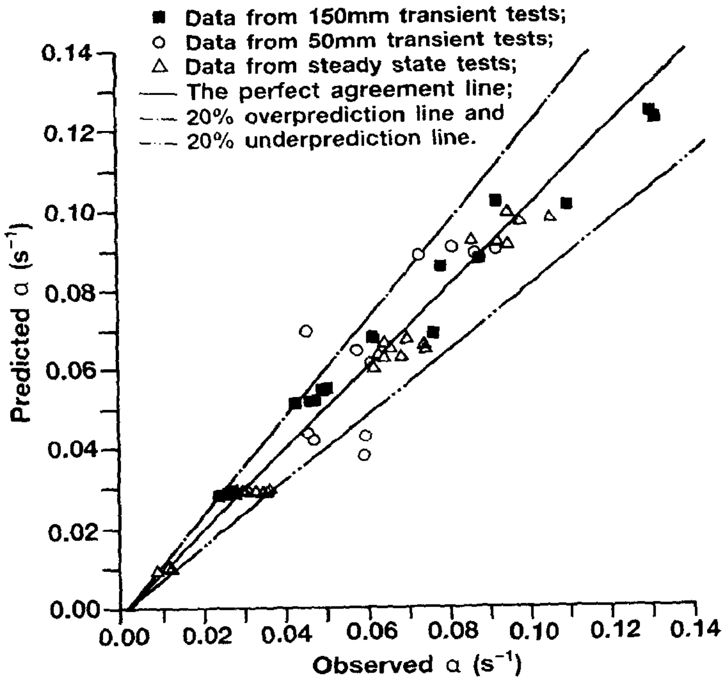

Figure 4. Comparison of predicted and observed mass decay constants (α).

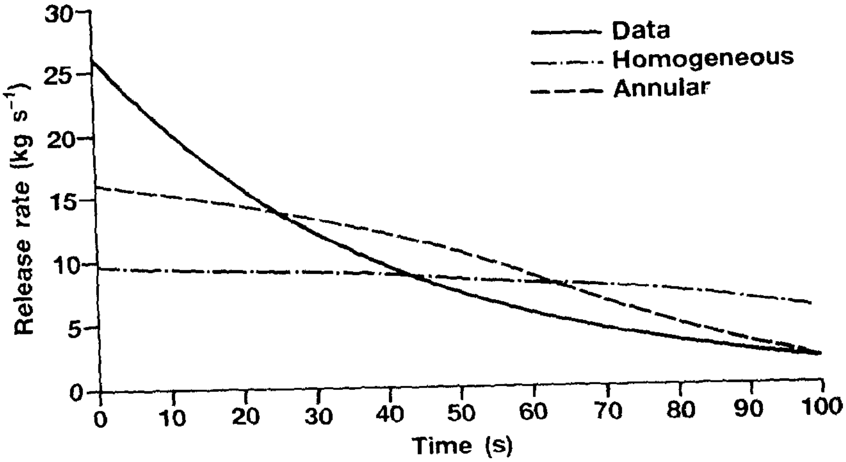

Figure 5. Comparison of data with two single-box models: (i) homogeneous and (ii) annular flow.

TABLE 1: Range of experimental parameters

Parameters	Minimum Values	Maximum Values
Initial pressure (bar)	7.5	22
Initial temperature (°C)	14	24
Pipe diameter (mm)	50	150
Area ratio of orifice to pipe.	0.04	1.0

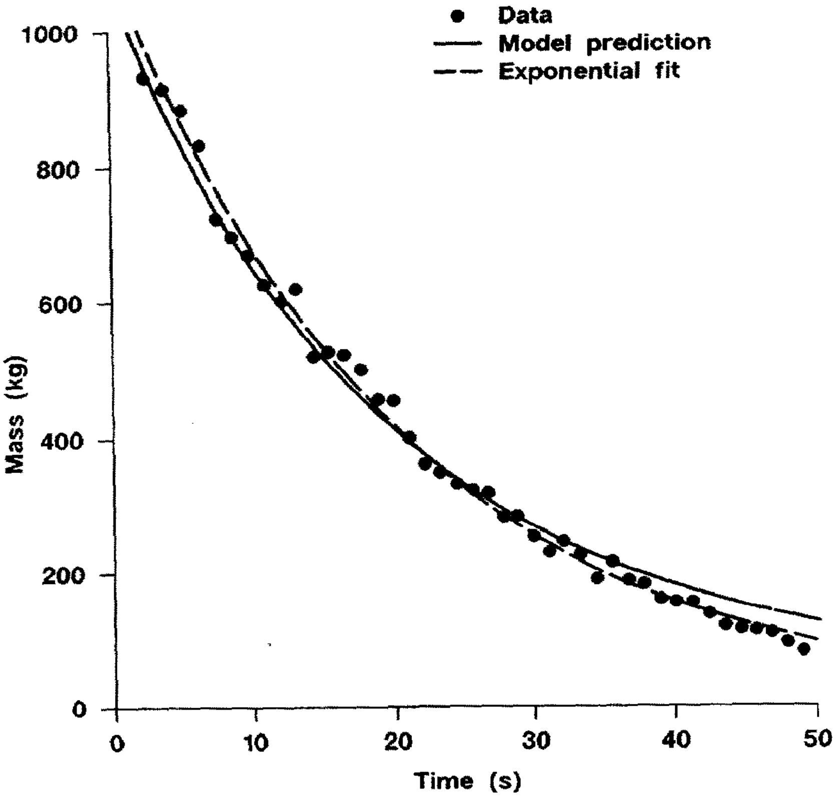

Figure 6. Comparison of observed mass inventory with that predicted by the single-node slip flow model. The data is taken from a test in which a 75mm diameter orifice plate was used in a 150mm diameter test line.

However, this comment cannot be generalised for temperatures outside the 14 to 24°C range and further validation will be required.

CONCLUSIONS

An empirical simple transient release rate model has been developed using data collected from the large scale BP/Shell Isle of Grain Experiments on pressurised LPG releases. It is based on the finding that transient release rates decay exponentially. The constant of exponential decay increases with an increase in (i) the ratios of the orifice area to the internal pipe area, (ii) the diameter of the pipe and (iii) an increase in the fluid temperature. The initial storage pressure of the fluid in the test line has no effect on the transient release rate once the flow has been established. While the single-box model is not suitable to describe the transient release rate of pipelines, the single-node slip flow model predicts well the main feature of the observed transient release rates.

REFERENCES

1. Tam V.H.Y. and Cowley L.T., Consequences of Pressurised LPG Releases: The Isle of Grain Full Scale Experiments. Proceeding of the GASTECH88 Conference, Kuala Lumpur, 1988.
2. Sharma Y, Scoggins, M W, Shoham O and Brill, J P, Simulation of Transient Two-Phase Flow in Pipelines, 2nd International Conference on Multi-Phase Flow, London, England, 19-21 June 1985.
3. Morrow, T.B., Bass, R.L. and Lock, J.A. An LPG Pipeline Break Flow Model, Journal of Energy Resources Technology, September 1983, Vol 105.
4. Trapp, J.A. and Ransom, V.H., A Choked-flow Calculation Criterion for Nonhomogeneous, Nonequilibrium, Two-phase Flows, Int. J. Multiphase Flow, 1982, Vol 8, No.6, pp669-681.
5. Fauske, H.K., The Discharge of Saturated Water Through Tubes. Chem. Engng Prog. Symp. Ser. 59 (New York: Am Inst. Chem. Engrs), 1965, p210.
6. Jones, M.R.O. and Underwood, M.C., An Appraisal of Expressions Used to Calculate the Release Rate of Pressurised Liquefied Gases, The Chemical Engineering Journal, 1983, 26, pp 251-254.
7. Grolmes, M.A., Leung, J.C. and Fauske, H.K., Transient Two-phase Discharge of Flashing Liquids Following a Break in a Long Transmission Line, Multiphase Flow and Heat Transfer III, Part A, Fundamentals (Edited by Vezirogln, T.N. and Bergles, A.E.), Elsevier Science Pub., BV, Amsterdam 1984.
8. Morrow, T.B., Development of An Improved Pipeline Breakflow Model, API Report SWRI-6917/3, December 1982.
9. Daniel, L.C. and Morris, S.D., Two-phase Flow Through Wellhead Choke Valves, A State of Art Review, AERE Report AERE-G 3710, October 1985.
10. Morris, S.D., A Simple Method for Estimating Critical Two-phase Flow Parameters in Nozzles, HTFS Fluid Flow Working Party Report HTFS/119/1985, 28th March 1985.
11. Lockhart, R.W. and Martinelli, R.C., Chem Eng Prog, 45,39, 1949.
12. Bell, R.P., Isopleth Calculations for Ruptures in Sour Gas Pipelines, Energy Processing/Canada, 1978, July-August, pp. 36-39.
13. Wilson, D.J., The release and Dispersion of Gas from Pipeline ruptures, Alberta Environment Research Report, 1979, Edminton, 91pp.
14. Tam, V.H.Y., A Simple Transient Release Rate Model for Releases of LPG from Pipelines, 6th International Symposium "Loss Prevention and Safety Promotion in the Process Industries", Oslo, Norway, 19-22 June 1989.