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TWO-PHASE SWELLING AND ENTRAINMENT DURING PRESSURE RELIEF VALVE DISCHARGES

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SUMMARY

The influence of liquid space expansion, caused by thermal effects and boiling, on pressure relief valve (PRV) behavior is examined. Small scale (40 litres) and moderate scale (10 000 litres) experimental behavior is shown to behave similarly for a variety of ladings. There is clear evidence of interface entrainment and its resulting influence on pressure relief.

INTRODUCTION

The Fire Science Centre of the University of New Brunswick, Canada has been using a laboratory test facility to better understand the thermohydraulics of externally-heated vessels of pressure-liquefied gases and the causes of BLEVE behavior. Experimental programs have been conducted and evaluated to determine better protection strategies for transport and storage containers [ref. 1] and to prevent disasters such as occurred in San Juan Ixhuatepec, Mexico [ref.2]. Other laboratories [refs. 3-5] have conducted medium and large scale field trials on the fire engulfment of LP Gas tanks. The present paper examines the liquid space expansion caused by vapour bubble development during a PRV opening and its effect on entrainment. The purpose of this work is to ultimately develop generalized relationships for the prediction of discharge through the PRV.

EXPERIMENTAL FACILITY

University of New Brunswick small scale facility (UNB Tank)

The test vessel physically models the internal fluid behavior of a horizontal cylindrical pressure-liquefied gas tank subjected to external heating. The 380-mm internal diameter tank has a capacity of 38 litres and is equipped with externally-fitted electric heaters. Heating may be total or on a portion of the circumference. The tank has a remote-controlled PRV which may be positioned at any angle around the tank circumference to simulate conditions such as during a transport or liquid line storage accidents. The valve orifice may be varied. The test facility measures, as a function of time, pressure, mass, void fraction and valve mass efflux thrust, as well as temperature, at a variety of locations within the fluid (both liquid and vapour) and at the tank wall. The tank ends are of sheet acrylic to permit visual observation as well as video and still photography records of thermohydraulic behavior. The fluid used is Refrigerant 11 (R11) (tri-chlorofluromethane).

The major independent variables of the tests to be discussed here are given in Table 1. Detailed information on the test facility and a complete listing of the experiments performed is available [ref. 1].

TABLE 1

Values of major independent variables - UNB tests

	Test RD6 (14/03/85)	Test KS6 (09/04/86)
Liquid fill (volume %)	90.2	85
Power input (kW_e/m^2)	80	80
PRV Position (degrees)	0*	120
PRV orifice area (mm^2)	31.7	31.7

* vertically upright

Tests RD6 and KS6 were conducted with a 6.35 mm diameter PRV orifice. For Test RD6, the PRV was located in the vertical upright position, as commonly used in storage or transportation tanks. To simulate a transport accident, tests were conducted with the PRV not vertical (Test KS6). The valve size chosen was determined using the appropriate Association of American Railroads and National Fire Protection Association codes based upon the anticipated accident conditions [refs. 6,7].

The PRV discharge to atmosphere is a 50-mm diameter pipe, approximately 210 mm long. A 240-mm diameter thrust plate is placed 140 mm downstream of the outlet piping exit normal to the discharge to measure the mass efflux thrust.

HSE five tonne LPG tank

The Health and Safety Executive (HSE) has carried out a series of six tests on a five tonne LP Gas tank to investigate fire engulfment behavior. The tank was 1.69 m in diameter, with a parallel barrel of 4.06 m, closed by dome ends, with 1.37 m radii. It had a capacity of 10 000 litres.

The major independent variables of the HSE test to be discussed are given in Table 2.

TABLE 2

Values of major independent variables - HSE tests [refs. 3,8]

	Test HSE5 (02/12/86)
Liquid fill (normal volume %)	80
Power input (kW/m^2)	77*
PRV position (degrees)	0 (vertical)
PRV orifice area (mm^2)	887**

* As determined by water calorimeters.
** Tank fitted with two identical PRVs. During fire engulfment only one PRV operated. The tabulated value is the effective area of one fully-open valve.

Experiments were conducted by engulfing the instrumented tank in a ferosene pool fire for periods ranging from 9 to 30 minutes. Detailed information of the test vessel and procedures are available in references [refs. 3,8].

THERMOHYDRAULIC BEHAVIOR

Based upon the visual observations of the UNB tank, comments on the thermohydraulic behavior at both test series can be made.

The experiments were initiated by the application of heat to the outside of the test vessel. Free convection is the initial mode of heat transfer to the liquid and vapour. In the liquid space, free convection is followed by saturated, and later, subcooled boiling, as pressure increases. In the vapour space this convection leads to significant vertical temperature stratification. In the liquid, stratification also occurs with the vapour/liquid interface temperature dictating tank pressure.

When the pressure reaches the PRV setpoint, the PRV opens and material is discharged. The resulting pressure response is dependent upon valve size, behavior (i.e., valve area versus pressure) and position. Large fills, orifice size and liquid stratification may cause significant flashing and swelling of the affected liquid regions dependent upon pressurization. The swelling, caused by two-phase development, can result in liquid carryover and entrainment [refs. 9-12], resulting in significant two-phase discharge. If the PRV is improperly sized or located, significant rates of pressure increase, over that permitted by the codes, may result due to the occurrence of two-phase choked flow occurring in the PRV assembly.

As material continues to exit through the PRV, the level of two-phase material in the tank decreases. Single-phase vapour flow results after the interface level drops below the liquid entrainment height [refs. 9-12] and the tank empties with the valve possibly reseating.

EXPERIMENTAL RESULTS AND ANALYSIS

UNB small scale tests

Test RD6. Fig. 1 shows the pressure-time response curve and the PRV efflux thrust record. The pressure rises steadily as the tank contents heat, until the PRV setpoint (241 kPag) is reached. The PRV then opens; it is programmed to close at a pressure of 229 kPag under operation of a two-position pneumetically-operated and computer-controlled valve. The PRV cycles a few times and then remains continuously open, with pressure increasing. This experiment was concluded after 10 min of heating when the pressure reached 300 kPA or 125% of set pressure.

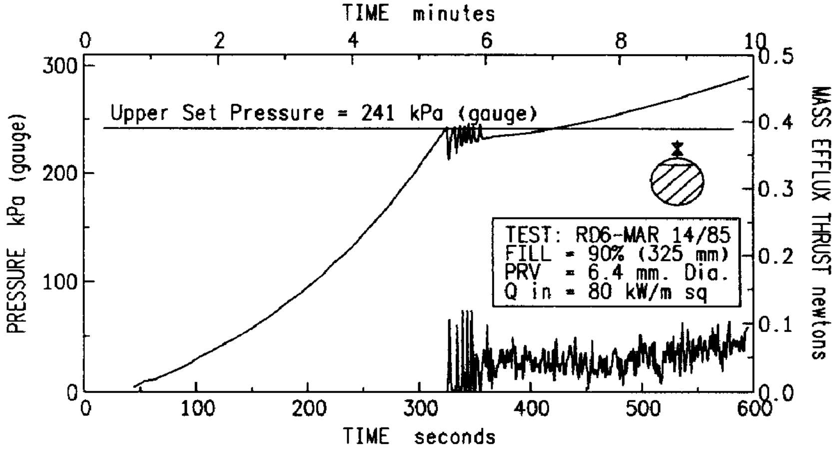

Fig. 1. Variation of tank pressure and valve efflux thrust - UNB Tank.

The change of fluid mass with time is given in Fig. 2. To estimate the PRV discharge, this mass data was fitted by piecewise polynomials in time. In order to eliminate noise, the standard deviation(s) of the data from the polynomials were computed, and any data beyond three times the standard deviations were eliminated and the remaining data refitted. This process was continued until all data were within 3 σ. Usually a third order polynomials fit the data best as determined by standard deviation and mean error consideration. The chosen polynomials were then differentiated with respect to time to obtain the instantaneous mass flow rate through the PRV.

In Fig. 3 the measured lading mass, the fitted polynomial and its derivative (i.e., the mass efflux rate) is indicated for the period 300 to 500 s. Also shown is the calculated choked single-phase vapour flow rate curve based upon a valve discharge coefficient of 1, a fully-opened valve and vapour exiting at a temperature as measured by the top-most thermocouple (closest to the PRV entry). During the first two PRV openings at 325 and 332 s, the calculations yield values higher than the experimental values (Fig. 3). This may be due to the presence of low boiling impurities and/or air trapped

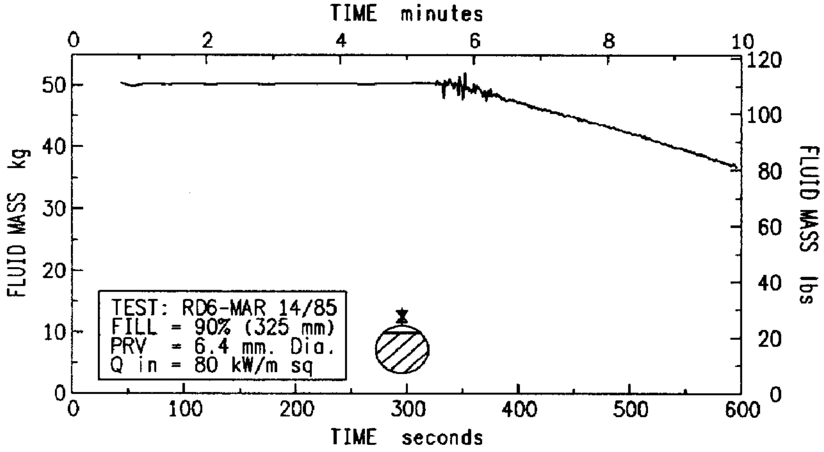

Fig. 2. Variation of lading mass with time - UNB Tank.

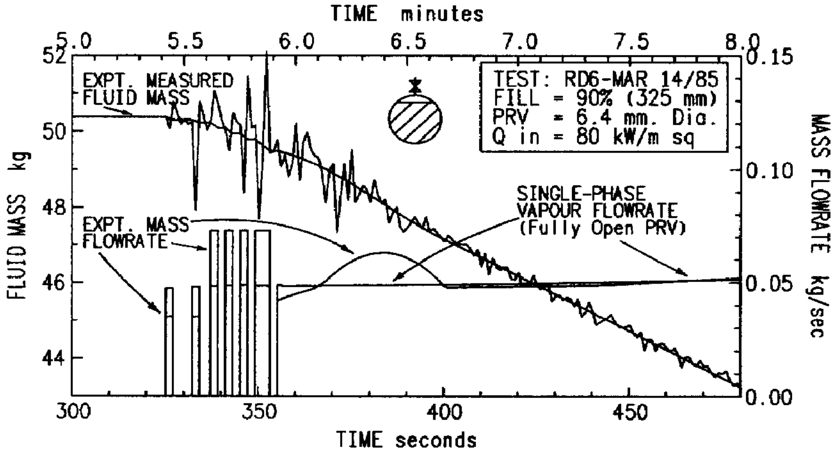

Fig. 3. Variation of lading mass and mass flowrate with time - UNB Tank.

in the test section during filling. Subsequent PRV openings, however, indicate higher flow rates. This is due to liquid entrainment [refs. 9-12] and was confirmed visually. In the continuous venting period commencing at 355 s, the experimental mass flowrate between 365 and 400 s deviates from single-phase choked vapour flow. This difference is due to the liquid entrainment of vapour discharge. A close examination of the pressure time response (Fig. 1) and the lading mass flowrate (Fig. 3) shows an inflection point at 384 s.

The change of liquid/vapour interface level with time is given in Fig. 4. The unswelled level is calculated using the instantaneous lading mass and average liquid temperature data. This volume-averaged temperature is computed from all the liquid measurements. The instantaneous lading mass is divided by the liquid density at the averaged temperature to obtain an unswelled lading volume. A curve accounting for the swell due to vapour bubble formation is also shown in Fig. 4 and was determined from the video recording. The difference between these two curves allow an "average" void fraction to be determined as shown. The actual void fraction, however, depends on location. The video and still photography indicates a high density of vapour bubbles along the tank walls and adjacent to the liquid/vapour interface, compared to the bulk liquid, during initial depressurization. The average void fraction values reported here, therefore, represent a lower limit for the interface and thus the entrained fluid (with PRV discharge).

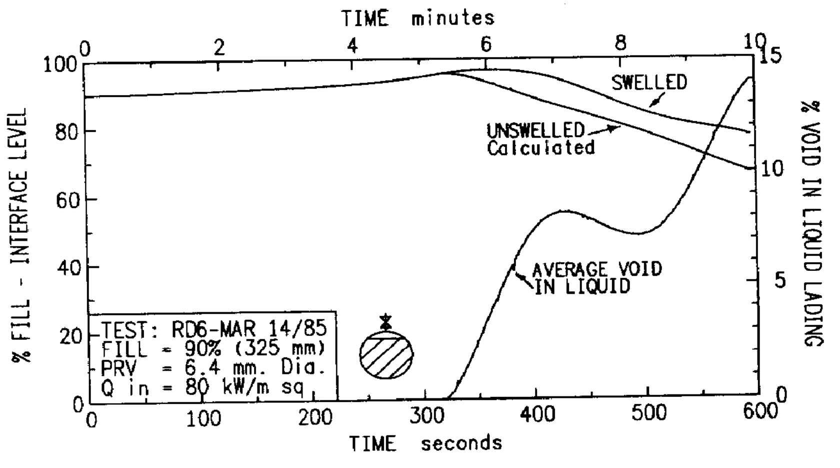

Fig. 4. Variation of interface level and average void with time.

Models to predict the beginning and end of liquid entrainment as a function of the vertical height difference between the discharge orifice and the interface are available [refs. 9-12]. Schrock et al. [ref. 11] presented a comprehensive summary of experimental data on liquid and vapour entrainment including their own for air-water and steam-water data. In their experiments the test sections did not, however, undergo large depressurization and therefore the degree of interface two-phase formation was small. The depressurization of any pressure-liquefied fluid subjected to external heating produces a significantly frothed interface, when the PRV opens or pressure is reducing. Under these circumstances, the entrained material is not single-phase liquid but a mixture of vapour and liquid. Estimation of the quality of this is essential to accurately model the pressure response.

During Test RD6, liquid entrainment of the PRV discharge was observed from the video records during the last four of the first six PRV openings and during the initial portion of the continuous PRV opening. If interface height and single-phase liquid properties are used in the "beginning of liquid entrainment" (ble) models, they do not predict entrainment. The model by Anderson et al. [ref. 12] is used as an example in Appendix 1. Since there was clear evidence of entrainment and a significantly frothed interface, the model can be used to "back calculate" a maximum interface density and therefore minimum interface void. Fig. 5 shows this result. The beginning and end of entrainment, as evidenced by video records and mass data, is also indicated in the figure. The average void fraction within the liquid is 6% (Fig. 4) whereas the minimum calculated interface void necessary for entrainment is 97.5%.

Test KS6. Fig. 6 gives the change of pressure and valve efflux thrust with time for an 85% fill test with the PRV rotated by 120° from vertically upright. As shown, the PRV cycles a few times before remaining open continuously for 65 s (416 s to 481 s). During this period of continuous venting the pressure-time gradient changes from positive to negative at 459 s. The valve efflux thrust records an instantaneous drop at the same time.

Fig. 7 shows the variation of tank mass. The PRV entry position is initially below the liquid/vapour interface and therefore initial PRV openings result in single-phase liquid discharges. This mass data, too, was fitted

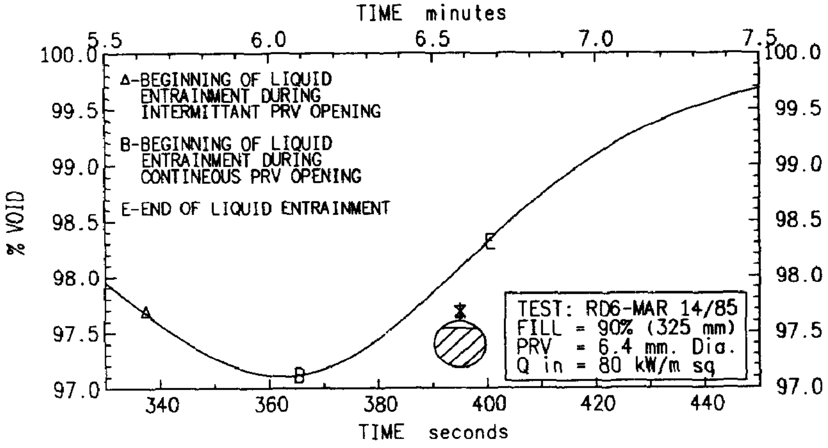

Fig. 5. Change of minimum void at interface for liquid entrainment - UNB Tank.

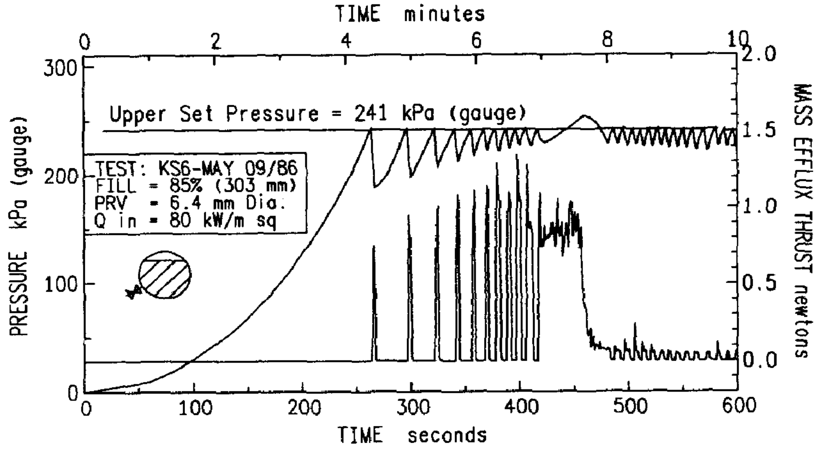

Fig. 6. Variation of tank pressure and valve efflux thrust with time - UNB Tank.

with piecewise polynomials in a manner similar to that for Test RD6, and the derived mass flowrate is also shown. In both curves, a discontinuity is noted at 459 s. The mass versus time data shows a sudden change in gradient which results in an abrupt change of the mass flowrate through the PRV.

Fig. 8 shows the PRV mass flowrate as a function of the liquid/vapour interface level. The figure shows the discharge to be single-phase liquid at (A), liquid flow with vapour pull-through at (B), vapour flow with liquid

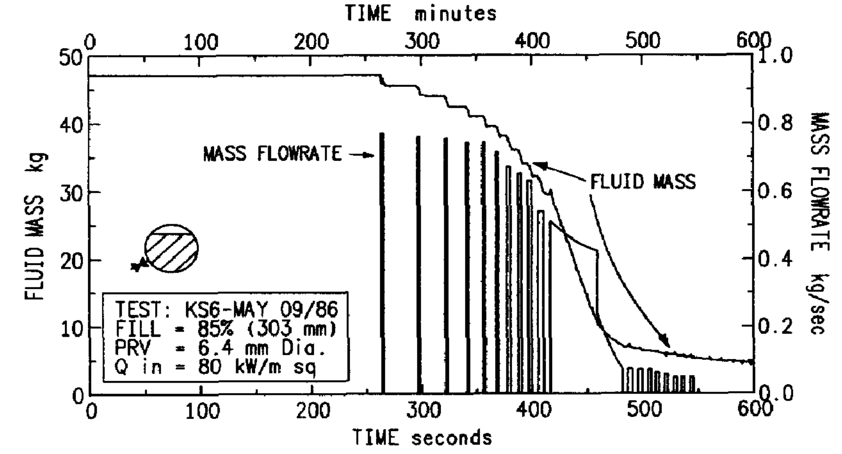

Fig. 7. Variation of lading mass and mass flowrate with time - UNB Tank.

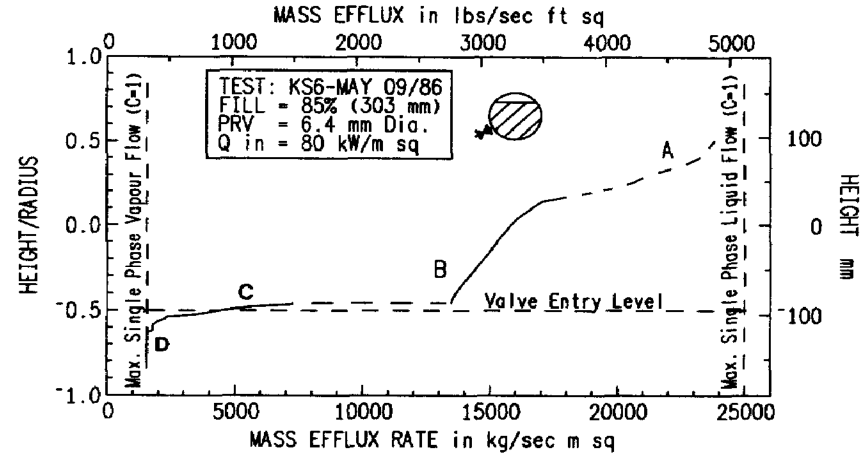

Fig. 8. Variation of mass flowrate with interface height - UNB Tank.

entrainment at (C) and single-phase vapour flow at (D). The transition from B to C is abrupt as denoted by the discontinuous line in the figure. This transition occurred at 459 s and is further reflected by the changes in pressure and thrust data (Fig. 6), mass data (Fig. 7), and by the audio recording (taken with the video) which indicates a change in pitch at the same instant. Fig. 8 also shows the theoretically-computed choked saturated vapour and saturated liquid (at 241 kPag) flows for discharge coefficients of unity.

At 459 s the PRV flow changes abruptly, from a mostly liquid to a mostly vapour. The liquid flow flashes at exit. This two-phase flow out of the PRV can be considered either as homogeneous or separated flow, depending on the difference in velocities between the vapour and liquid components. Which model is appropriate can be investigated using the valve thrust (or momentum flux) measurements shown in Fig. 6, and the procedure described by Whalley [ref. 13] (see Appendix 2). The thrust measurements during single-phase vapour flow (from Test RD6 thrust data in Fig. 1 and Test KS6, thrust data after 550 s in Fig. 6) can be used to determine the area over which the mass discharge would spread on the thrust plate, using equation (1) of Appendix 2. The average thrust determined during single-phase liquid and single-phase vapour discharge was 0.836 and 0.054 Newtons, respectively (Fig. 6). Evaluation indicates that the PRV mass discharge would spread over a circular area of 100 mm diameter, on the thrust measurement plate. This means that the mass discharge expands to four times its flow area while travelling the 140 mm distance between the PRV outlet piping (50-mm diameter) and the thrust plate. The two flow models were applied to the flashing single-phase liquid data and the two-phase quality results are given in Table 3. It is also possible to compute the equilibrium quality of a single-phase liquid undergoing an expansion from 241 kPa gauge to atmospheric pressure. These results are also given in the table. It is clear that a homogeneous flow model is most appropriate to satisfy the data.

TABLE 3

Quality of single-phase liquid R11 entering the PRV as measured at 350 mm downstream of the PRV

Model	Two-Phase Quality (x)	
Homogeneous flow	0.18	[from momentum
Separated flow	0.38	[measurements
Isentropic expansion	0.19	[from equilibrium
Isenthalpic expansion	0.20	[calculations

Fig. 9 indicates the changes in swelled and unswelled interface level for Test RD 6. The average void fraction obtained from interface level data is also presented in the figure. It is clear that when the PRV discharges single-phase liquid or mostly liquid, the degree of frothing in the tank lading was small. With the onset of vapour pull-through a small amount of vapour appears. It is only after the discharge changes to vapour flow (with liquid entrainment at 459 s) that frothing becomes measurable.

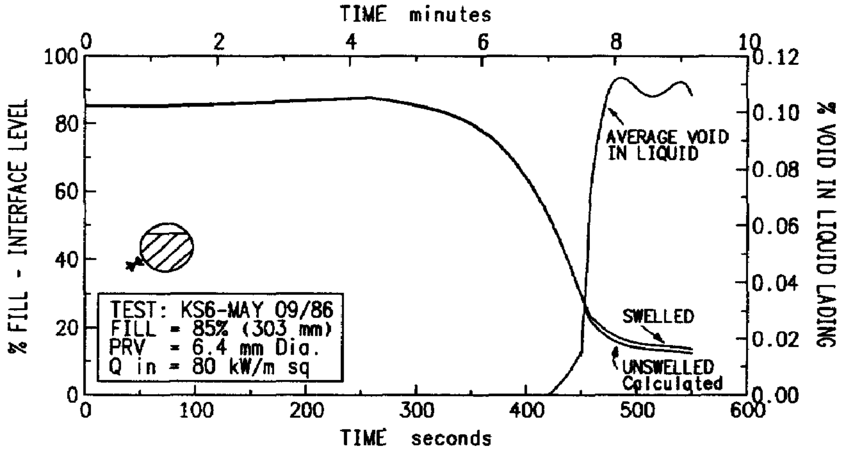

Fig. 9. Variation of interface level and average void with time - UNB Tank.

<u>HSE five tonne LP gas tank tests</u>

The variation of tank pressure with time for the fifth HSE test (80% volume fill) is given in Fig. 10. The spring-loaded PRV cycles once before going into a vent which continues until the tank is almost empty and the valve reseats. During the continuous venting period after the second PRV opening, the pressure trace reaches a maximum at 700 s.

Fig. 11 shows the variation of tank mass with time. This data was fitted in a manner similar to that for the UNB tests discussed earlier. The corresponding derived instantaneous mass flowrate is also shown in the figure. A single-phase vapour mass flowrate through the PRV was computed at the measured tank pressure using temperatures given by the uppermost vapour space

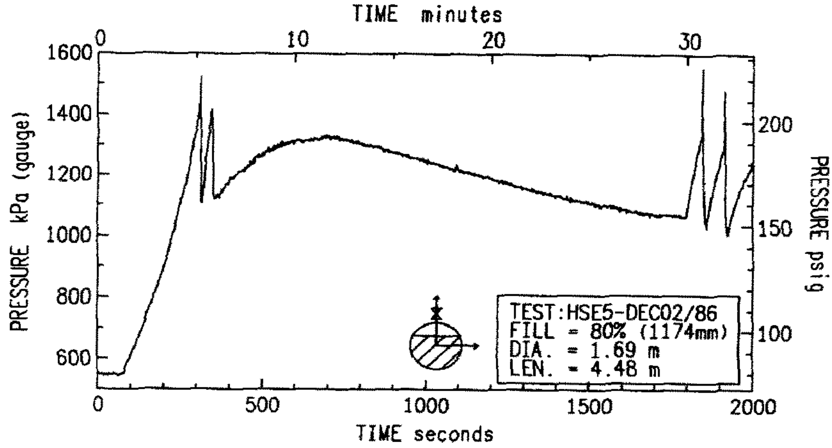

Fig. 10. Variation of tank pressure with time - HSE Tank.

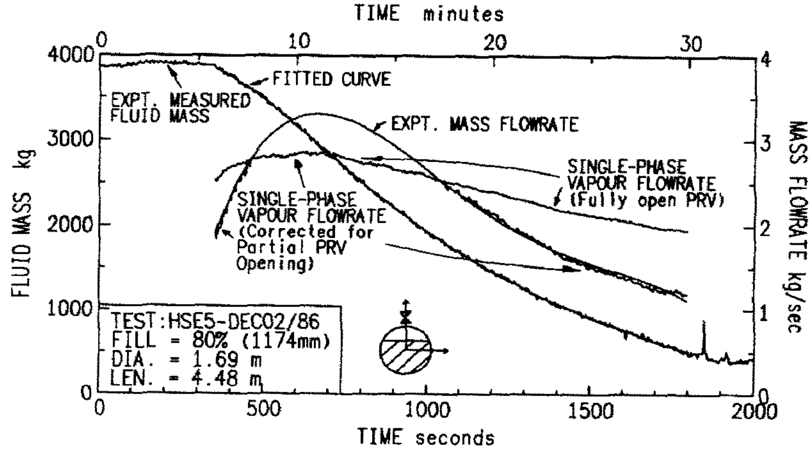

Fig. 11. Variation of lading mass and mass flowrate with time - HSE Tank.

thermocouple (# 9 which is 5 mm below the top wall). This computation (curve A) assumes the PRV to be wide open from 349 s to 1800 s. Both curve A and the experimental curves intersect at 465 s and 1040 s, implying significant liquid entrainment in the discharge during this interval. The theoretical vapour mass flowrate curve (curve A) for earlier and later times, however, shows larger values than the experimentally-obtained curve, indicating that the PRV was not fully open before 465 s and after 1040 s. A simple linear valve model can be used to account for the reduction in flow area due to partial PRV closing. At 1799 s, just before PRV closure, the essential mass flowrate is 57.5% of the single-phase vapour flow for a fully open valve. It is, therefore, assumed that the available flow area is also 57.5% of fully open. Between these times, the valve opening is taken to be a linear function of tank pressure.

The single-phase vapour flowrate, corrected for partial opening, is also shown in Fig. 11, as curve B. This curve conforms to the data not only between 1040 and 1799 s but also from 363 to 465 s, thus providing support to the assumed valve area behavior and the conclusion that entrainment of interface material occurs between 465 and 1040 s.

Estimates of the liquid/vapour interface level are given in Fig. 12. Two-phase swelling would not be expected from the start of the test up to the first PRV opening because the tank is pressurizing and only subcooled boiling occurs. The change in interface level is, therefore, only due to thermal expansion of the liquid lading up to this point with some slight void caused by heterogeneous boiling at the walls. The unswelled height is theoretically computed using the instantaneous tank fluid mass and liquid temperature data, in a manner similar to Test RD6.

The swelled height is obtained directly from internal experimental temperature data. A sudden temperature rise in a previously "wetted" thermocouple is taken as an indication of thermoelement uncovering. The height of the thermocouple at the time when such a discontinuity occurs is taken as a swelled interface level at that time.

The swelled and unswelled levels allow for the calculation of an average void fraction within the liquid lading as also given in Fig. 12. The model provided by Anderson et al. [ref. 12] can be used as before to compute the minimum void required for liquid entrainment. These results are shown in Fig. 13 along with the period during which entrainment was likely to have occurred (i.e., from 465 s to 1040 s.).

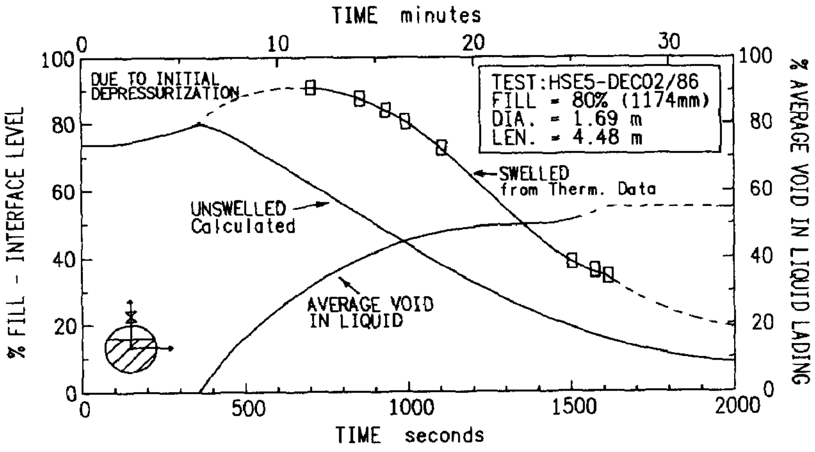

Fig. 12. Variation of interface level and average void with time - HSE Tank.

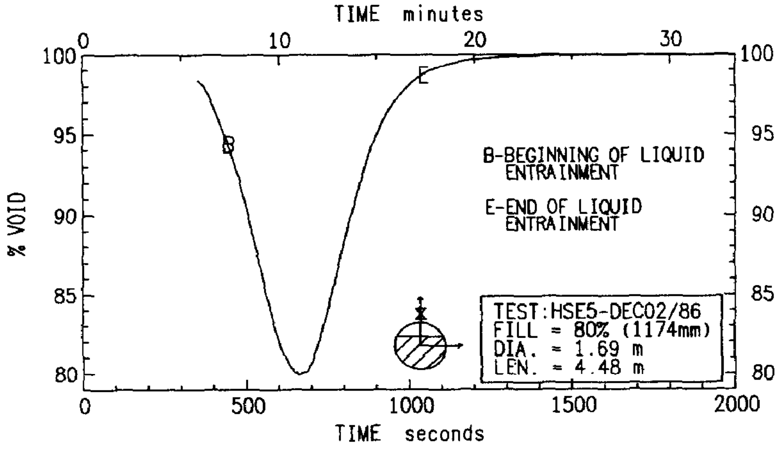

Fig. 13. Variation of minimum void at interface for liquid entrainment with time - HSE Tank.

CONCLUSIONS

From the experiments discussed, the following can be concluded:

1. During depressurization of a pressure-liquefied gas, the developed void fraction has a wide distribution. The average value is <u>not</u> representative of that at the interface.

2. The beginning and end of liquid entrainment is dependent upon interface height and also the interface quality. Single-phase theory is not appropriate to determine entrainment.

3. Two-phase flashing flow resulting from a single-phase liquid entering a PRV is better represented by a homogeneous flow model than by a separated flow model.

4. Comparison of these data with previous work by Zuber [ref. 9], Smoglie [ref. 10], Schrock et al. [ref. 11] and Anderson & Benedetti [ref. 12] is satisfactory when the quality of entrainment material is incorporated.

5. The discontinuous nature of the change over from vapour-pull-through to liquid entrainment has not been previously noted and indicates that during a two-phase flashing discharge, a certain range of the quality may not be achievable.

ACKNOWLEDGEMENTS

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APPENDIX 1

Minimum Void at Interphase for Liquid Entrainment (Figs. 6 and 14)

Using the relationship given in the EPRI report by Anderson and Benedetti [ref. 12, pp. 2-3],

$$[V_g^2 \rho_g / g(\rho_f - \rho_g)(D - h_{ve})]^{1/2} = 5.7(D - h_{ve}/d)^{3/2}$$

ρf - is taken as the average density of the two-phase froth layer, and is computed.
h_{ve} - same as swelled height
D - diameter of the tank. (No correction is made for the valve exit being at a level higher than the top of the tank.
ρg - saturated vapour density.
Vg - sonic velocity accounting for superheated vapour.
d - valve discharge area diameter (6.35 mm for UNB test. From 8.87×10^{-4} m^2 area for the HSE test [ref. 3,8].

APPENDIX 2
Two-Phase Flow Momentum
from Whalley [ref. 13, pp. 51-52]

1. single-phase gas flow:
   $M\rho g/G^2 = 1$

2. homogeneous two-phase flow:
   $M\rho g/G^2 = x + \iota (1-x)\rho g/\rho_\ell$

3. separated two-phase flow:
   $M\rho g/G^2 = x^2 + x(1-x)/s + \ (\rho/\rho\ell [1+x(s-2)+x^2(1-s)]$

where M - momentum flow per unit area (kg/m^2 s)
G - total mass flux (kg/m^2 s)
ρg - density of gas (kg/m^3)
x - mass fraction or quality
s - slip ratio (ug/u_ℓ)
ug - actual velocity of gas phase (m/s)
u_ℓ - actual velocity of liquid phase (m/s)

4. for separated flow the void fraction is:
   $\alpha = 1 / [1+(ug/u_\ell+(1/x)/x)\rho g/\rho_\ell)]$