

Phase distribution in vessels during depressurisation

L. Friedel* and S. Purpst†

Systematic vessel depressurisation experiments have been performed in the laboratory and in a pilot plant using initially saturated refrigerant R12 as the model fluid. Transient (vertical) distribution of the void fraction across the vessel height and the two phase level swell are affected by the initial liquid level, relief cross-section, initial pressure and initial degassing of the liquid pool. The measurements also show that at different times a variety of vertical phase distributions are obtained; only after 1.5 s at the earliest is a linearly increasing void fraction over the vessel height obtained

Keywords: *thermodynamics, phase distribution, depressurisation, vertical pressure vessels*

Rarely have the complex transient thermodynamics and fluid dynamics of vertical pressure vessel top venting of an initially saturated gas/vapour-liquid mixture been thoroughly investigated, and then mostly on a laboratory scale¹⁻⁴. This situation is inadequate since each different system state during the transient acts as a datum for reliable modelling of the total depressurisation process, especially of pressure decay, single and two-phase flow discharge, and relieving time.

Systematic laboratory and pilot plant scale vessel depressurisation experiments with initially saturated refrigerant R12 as model fluid were performed to determine two phase level swell and the transient distribution of the mean void fraction across the vessel height.

Test facility

The test facility is based on a vertical pressure vessel (1.6 or 107 litre with a height to diameter ratio of about 2) which is part of a complete test rig designed for depressurisation experiments⁵ (Fig 1). Vessel instrumentation includes conventional shielded thermocouples, pressure transducers, and a capacitance liquid or mixture level swell and void gauge (Fig 2). The latter is vertically located at the same radial position as the thermocouples and consists of a rod and seven independent coaxial capacitance units which allow determination of both the vertical phase distribution profile and the two phase mixture level at discrete vertical intervals. Indeed, it is assumed that the gauge does not promote a substantial nucleation and that the locally measured mean void fraction is, to a first approximation, representative of that prevailing in the total vessel cross section.

Depressurisation is initiated by opening of a fast acting ball valve and controlled by orifices with different bores inserted in the discharge line. All primary measure-

ments (temperature, pressure, capacity etc.) are logged by a Kontron KAP 1000 computer system.

Experimental results

Opening of the fast acting valve in the relief line is followed⁶ by a characteristic sudden decrease in vessel system pressure due to vapour outflow, a subsequent more-or-less pronounced pressure recovery during the vapour generation stage which restores the initial thermodynamic equilibrium, leading to mixture level swell in the vessel and, in most experiments, to the development of a two-phase outflow, and then finally a moderate and uniform fall of pressure occurs while again only vapour is discharged⁷ (Fig 3).

During the experiments, the influential parameters such as initial liquid level, relief cross-section, starting pressure and initial degassing of the pool were varied systematically. As a result, the developing time-dependent phase distribution is presented as a series of void fraction profiles across the vessel height, continuously recorded on a 25 ms cycle but only extracted at different measuring times after initiation of depressurisation for seven (equidistant) vertical positions.

Typical phase or mixture distributions are shown in Fig 4. Initially, capacitance gauges C1 to C5 are in liquid while C6 and C7 indicate pure vapour. After 325 ms a substantial amount of vapour is present in the interphase and bottom region. At the same time, the mixture level has slightly increased and a two phase mixture of vapour and some first droplets rises through the vapour dome to the outlet. The lowest recorded pressure during the intermediate pressure undershoot process occurs at 325 ms. At the next control point considered (525 ms), the two still clearly separated two phase mixture zones have expanded downwards and upwards. Furthermore, the mixture level and the void fraction (in the mixture) as a whole increased. After 675 ms the two zones have grown together and, due to the intensive agitation in the swelling mixture caused by the

* Hoechst AG, D 6230 Frankfurt 80, FRG

† DECHEMA, D 6000 Frankfurt 97, FRG

Received 26 July 1983 and accepted for publication in final form on 7 September 1984

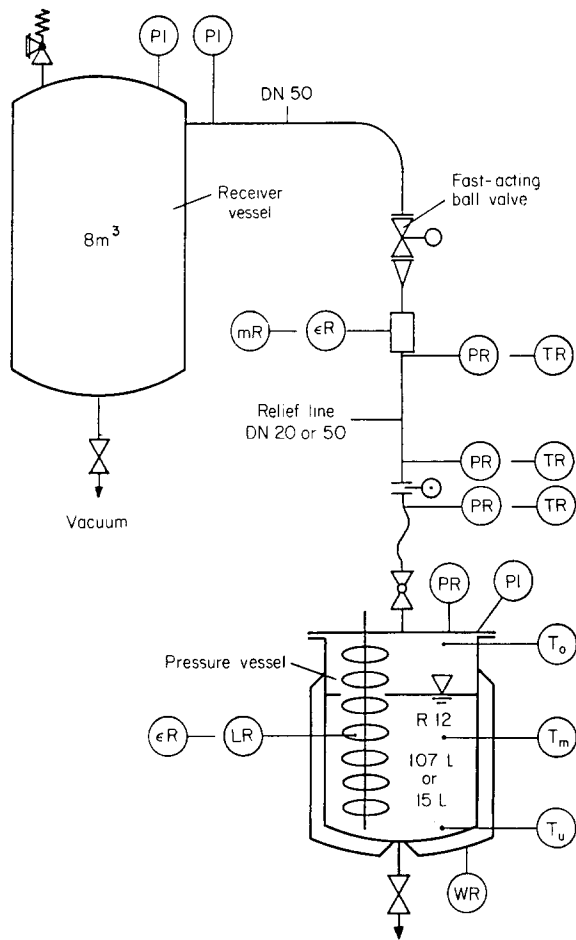


Fig 1 Test facility

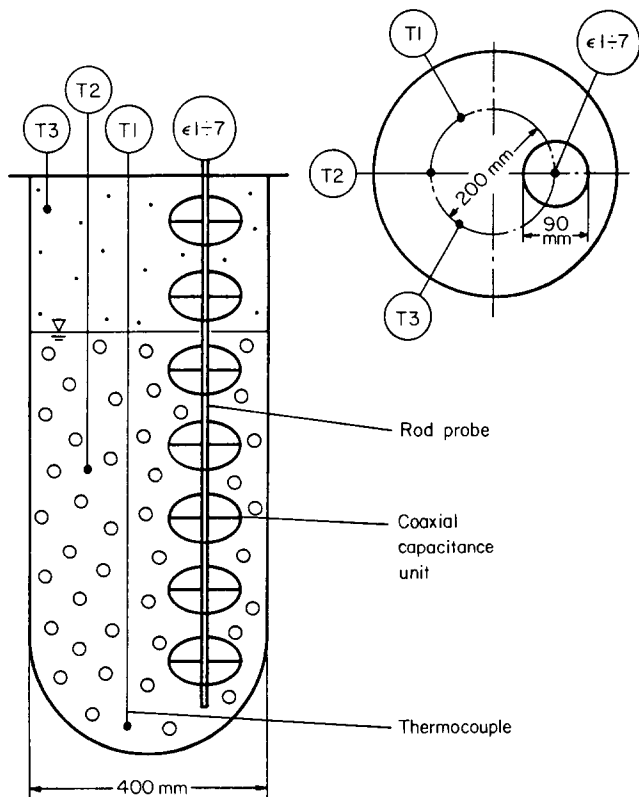


Fig 2 Capacitance level and void fraction gauge

vapour generation occurring throughout the superheated fluid volume, a practically uniform void distribution as a function of height is obtained. The next two sets of data show mixture extending to the top of the vessel and an almost linear increase of void fraction with height. At 1.875 s this is more pronounced due to the definite residence time of the ascending vapour phase in the mixture at simultaneously advanced phase separation, while at the vessel bottom the void fraction remains practically unchanged.

After this partial sequence, a characteristic phase distribution with three distinct zones follows for the next two sets of data. There is a linear increase of the void fraction in the near bottom region, followed by a relatively short intermediate zone with constant void fraction which changes into an area with exponentially increasing vapour content. In the lower and upper regions, unrestrained phase separation seems to occur while in the central zone the rising of the vapour phase is still somewhat restricted due to intensive momentum exchange, flow pattern, vortex circulation or horizontal homogenisation effects. It takes up to about the 9th second for the mixture level to start to drop. Later on (13, 20 and 25s), the constant void fraction zone in the mixture disappears, indicating complete separation of the vapour from the now only slightly superheated mixture. Simultaneously, the mixture level drops further; after 35 s pressure equalisation in the test and receiver vessel and full thermodynamic equilibrium are attained. Throughout all test phases with a mixture level well below the vessel top there is a constant void fraction below unity in the dome resulting from vapour flow with entrained liquid.

Initial liquid level ratio

Variation of the initial liquid level in the vessel before depressurisation results in similar, regularly spaced traces of the phase distribution across the vessel height. At the first measuring point, at 375 ms since the trivial basic phase distribution of pure liquid and vapour in the respective areas has been omitted, the highest initial liquid level gives the lowest void fraction (Fig 5). This is particularly surprising, since depressurisation was most rapid in this case and, therefore, the highest superheating or departure from thermodynamic equilibrium and the most intensive vapour generation should occur. With respect to the greater amount of liquid contained in the vessel, however, little vapour needs to be generated in

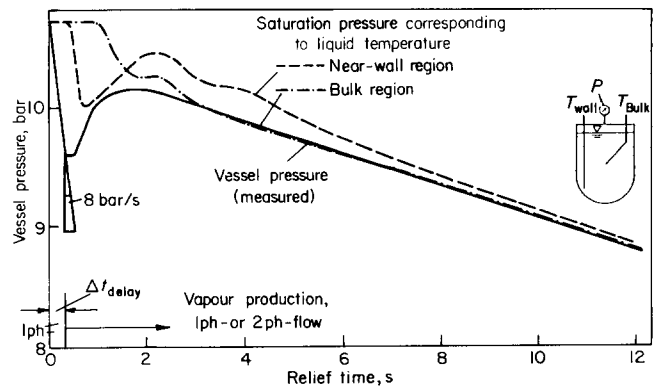


Fig 3 Characteristic pressure trace for the vessel

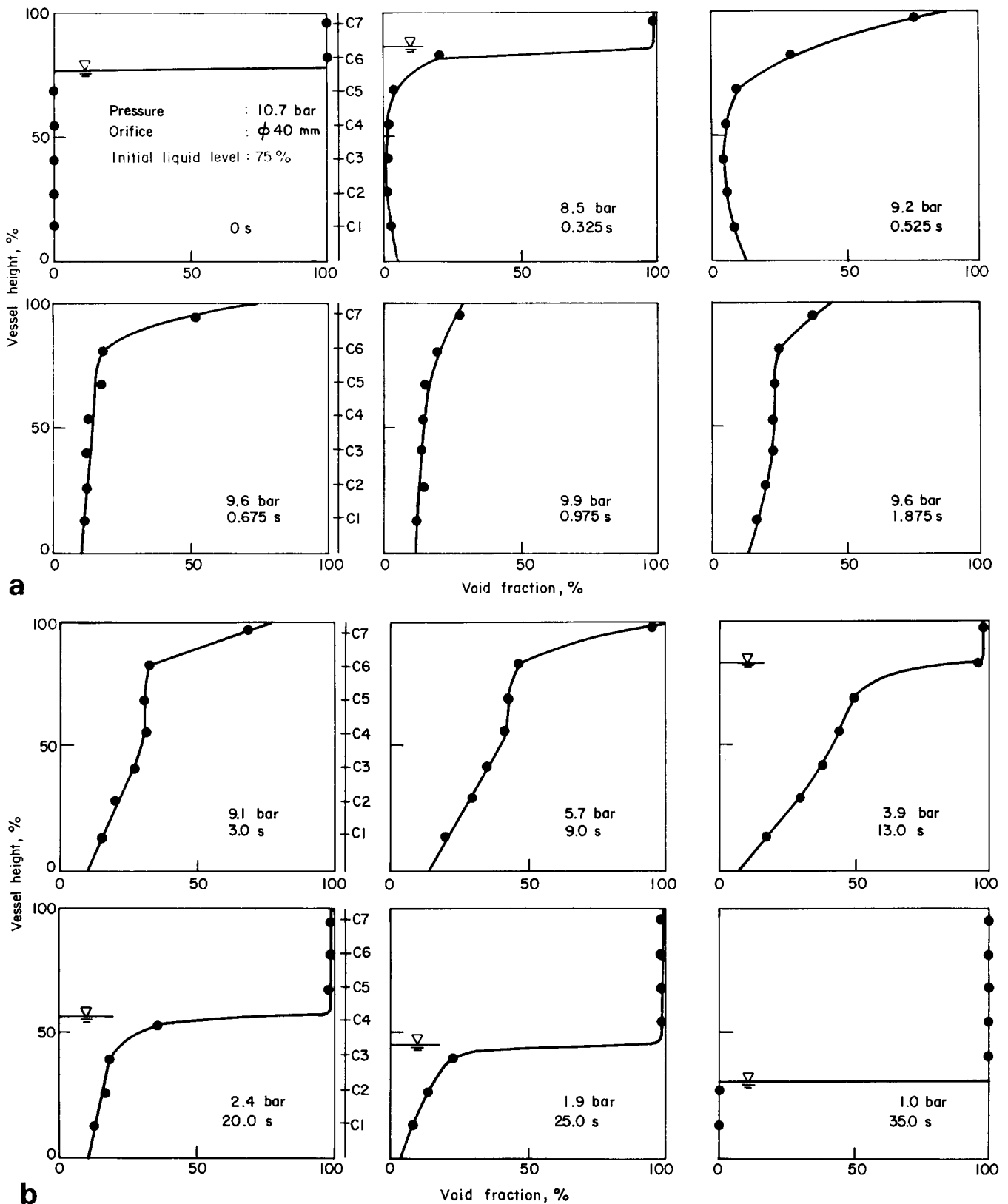


Fig 4 Characteristic void distributions

proportion to unit liquid volume to compensate for the vented vapour and produce a pressure rise.

After 850 ms the level of the mixture with the highest initial liquid level ratio (75%) has reached the top of the vessel and a fully developed two phase flow is discharged; the volume of the two other mixtures is still expanding, their level being well beneath the outlet flange.

Comparison of identical geometrical positions in the vessel shows that the void fraction is still greatest for the mixture with the lowest initial liquid level. In the next set of data (1.5 s), the 50% initial liquid level mixture has swelled to the top of the vessel; the remaining mixture will never reach the outlet flange because of the low initial liquid volume. At this point all three mixtures show a practically

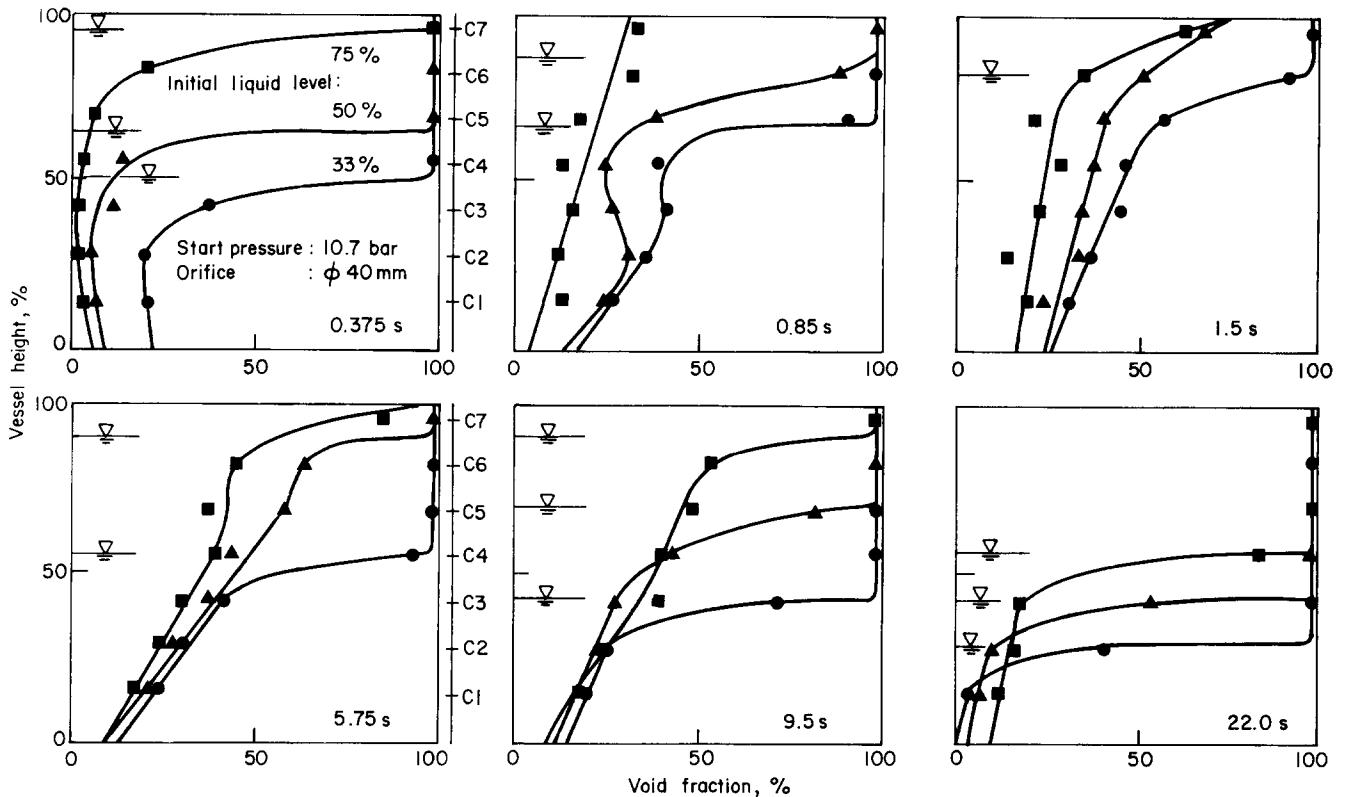


Fig 5 Void distributions for various initial liquid levels

linear increase of the void fraction. At the next two measurement points (5.75 and 9.5 s) the two phase mixtures are collapsing, equilibrium is being restored, and the different void fraction curves adopt similar shapes, although at different times. Again a mixture of vapour with some entrained droplets rises through the vapour dome in the vessel to the outlet flange.

In the final set of data, a further reduction of the vapour generation is seen. The still differing phase distributions can be attributed mainly to the varying pressures in the vessel, the highest void fraction now corresponds to the mixture with the highest initial liquid level where the vessel pressure is still greatest.

Relief cross section

Decreasing the relief cross-section gives slower depressurisation and a smaller deviation from thermodynamic equilibrium between the two phases, resulting in lower vapour generation and hence a lower void fraction distribution for identical initial liquid levels. This is reflected in the traces throughout Fig 6. At 2.25 s and 5 s the characteristic phase distribution with three distinct zones is obtained and the two mixtures have swelled to the top of the vessel causing a two phase flow discharge.

After 12 s, both mixtures have begun to collapse; their levels obviously differ because a higher mass flow is delivered through the larger orifice. At this point, again only vapour with some entrained droplets ascends through the vessel dome to the outlet. A change in the trace orientation occurs after roughly 20 s; in the system relieved via the larger orifice there is, overall, a lower void fraction across the mixture since the more intensive vapour production and mass outflow gave a lower departure from equilibrium and a lower system pressure.

This emerges more clearly at 30 s when the pressure in the test and receiver vessel have equalised.

Starting pressure

With a lower starting pressure, but keeping all other variables constant, there is less vapour mass above the almost unchanged liquid mass and a lower critical mass flux in the outlet. Although the expansion of the vapour volume proceeds in all tests practically with the same initial pressure gradient, in this case the period of boiling delay lasts longer and a greater departure from equilibrium builds up. Consequently, after 375 ms the highest void fraction is present in the system with the lowest initial pressure (Fig 7). Here vapour generation is predominantly at the interphase and, as at 1.625 s, there is only a negligible void concentration in the bottom region. Indeed, at this moment the mixture level in all three experiments seems to reach the top of the vessel and, in terms of the assumptions about the axial void distribution made in the codes, a practically linear increase may be accepted at this time.

At the later data points a systematic arrangement of the vertical void profiles, with the largest void fraction in the system with the highest initial pressure, is obtained. This results from the most intensive vapour generation due to the still highest energy level of this mixture. After 15 s the mixtures are collapsing and diverse levels apply mainly due to different discharge times with fully developed two phase flow within the relief time thus far. By the end of this series (35 s) the lowest mixture level coincides with the highest initial pressure as a result of the greater mass outflow.

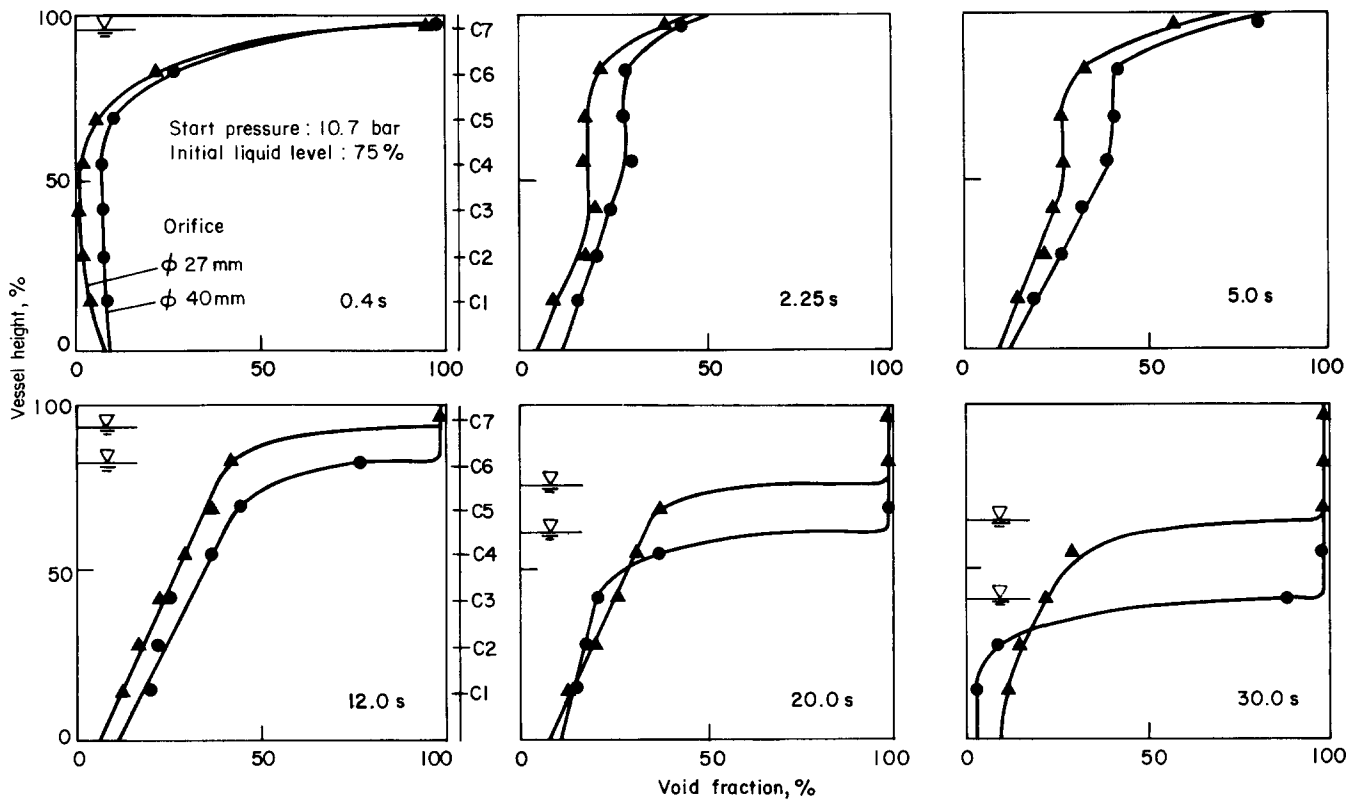


Fig 6 Void distributions for different relief cross sections

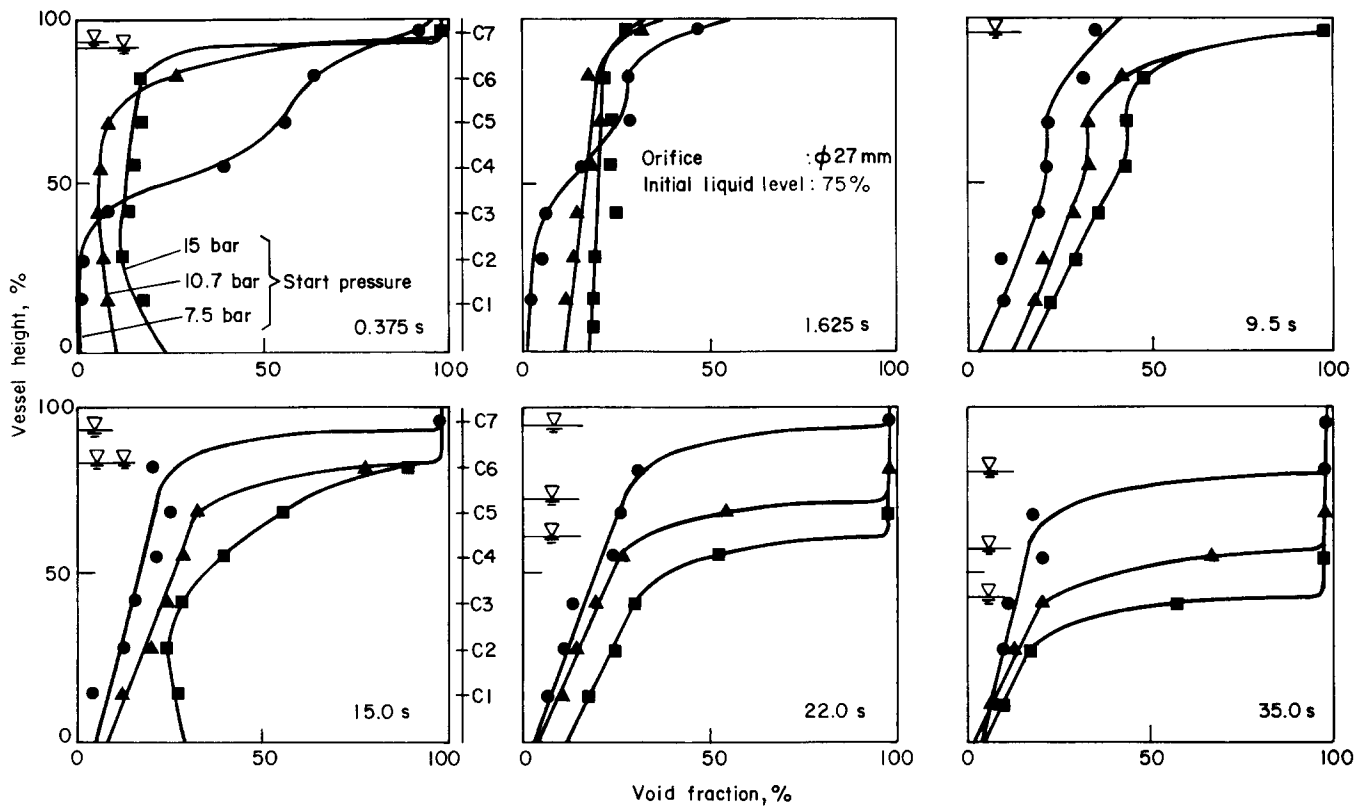


Fig 7 Void distributions for different initial pressures

Initial pool degassing

Sudden vapour generation in the tests only occurs after nucleation in microscopic cavities or crevices at the vessel walls, on gaseous or solid impurities in the liquid bulk or at the interphase in spots locally not at thermal equilib-

rium. Through degassing of the initially saturated two phase system by briefly relieving several times before starting the depressurisation experiments, the number of available nuclei is reduced and a lower vapour content in the mixture should therefore result. This is indeed confirmed by the traces of the void fraction in the first

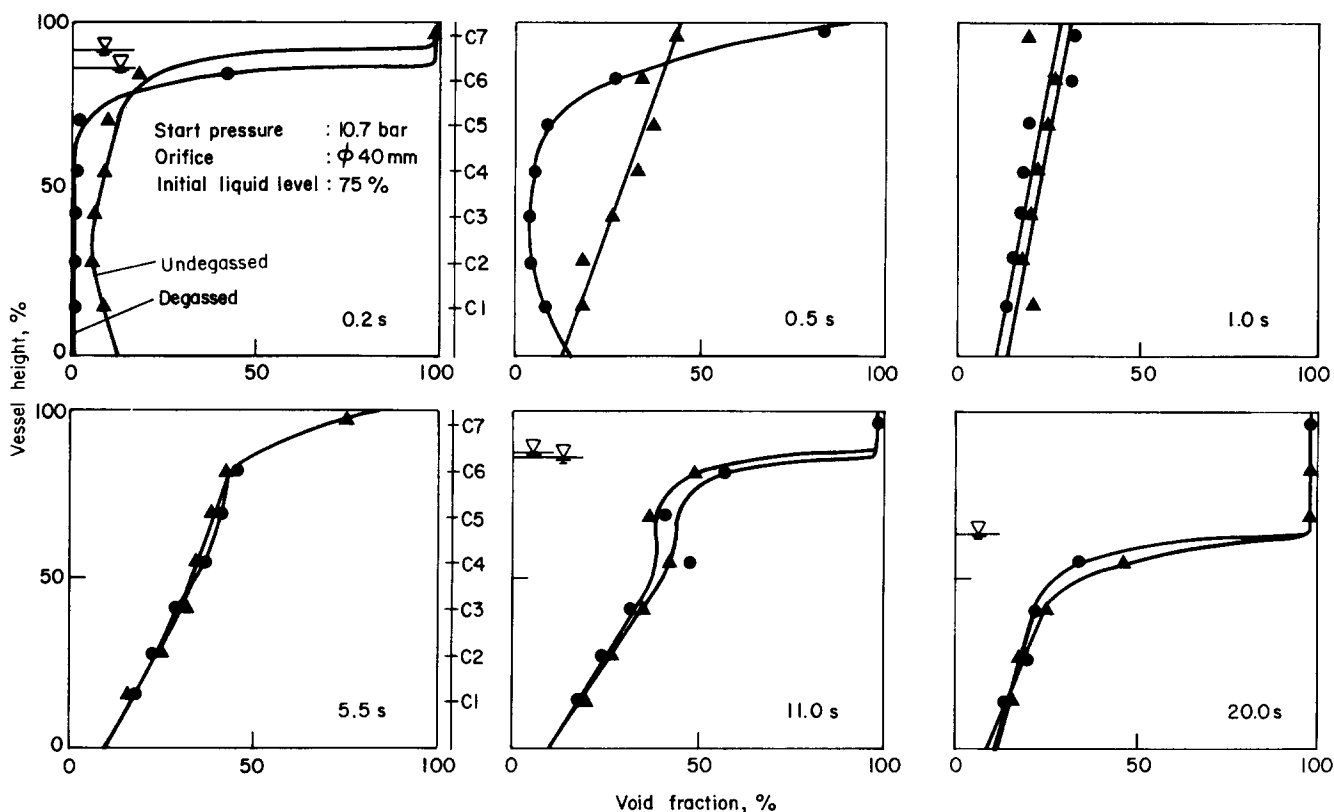


Fig 8 Effect of degassing on void distributions

measuring point (200 ms) in Fig 8. In the degassed system, low vapour generation occurred only in the interphase, while in the other system there is a substantial void fraction throughout the mixture. On comparing the states of the two mixtures, the degassed system remains in the boiling delay stage still undergoing a decrease of pressure due to outflow of pure vapour while, in the undegassed system, the pressure is about 0.5 bar lower, but is just starting to recover from the intermediate minimum pressure. After 500 ms there are obvious differences in the void fraction profiles although the difference between the two system pressures decreases. The non degassed mixture has swelled to the top of the vessel and shows an uniform void distribution.

From the next measuring point (1 s) there are only marginal differences in vertical void fraction distribution and in the system pressure present, and a practically linear increase of the void fraction with the height has been established. In the remaining data the two void traces, collapsing mixture levels, vessel pressures and temperatures always coincide and the negligible deviations can be attributed to the measuring and calibrating accuracy.

Differences between the behaviour of the degassed and undegassed system only occur during the initial depressurisation phase lasting roughly for 1 s and vanish in the latter process. The final state of both relieved systems seems to be identical.

From consideration of these measured test-variable-dependent, time-dependent, and more-or-less systematically changing phase distributions across the vessel height, it becomes clear that the simple assumptions of constant void fraction or linearly ascending vapour concentration in vessels^{8,9}, often applied in computer codes through necessity, are not valid and can only be justified by the presence of internal or structural heat. Indeed, no earlier than roughly 1.5 s after initiation of the

depressurisation process, by which time the initial thermodynamic disequilibrium has already been reduced significantly and the vessel pressure during the undershoot process has been recovered to the maximum possible extent, can a linearly increasing void fraction in the mixture be assumed, as a first approximation. In total these deviations from linearity do not seem to play the most important role in the prediction of the pressure transients when comparing the rather accurate predictions with the codes.

Conclusions

The transient vertical distribution of the void fraction across the vessel height depends critically on initial liquid level, relief cross-section, starting pressure and initial degassing of the liquid pool. Only after 1.5 s at the earliest does a linearly increasing void fraction over the height occur.

References

1. Gardner G. C. *Int. J. Multiphase Flow*, 1980, **6**, 399-410
2. Viecez H.-J. *Diss. Univ. Hannover*, 1980
3. Labunsov D. A. et al *Teploenergetika* 1969, **15** (4), 78-84
4. Ardron K. A. et al *Paper presented at OECD/NEA Specialists Meeting on Transient Two Phase Flow, Toronto, 1976*
5. Friedel L. and Purps S. *BMFT-FB01 VD 418*, 1983, or *Chem.-Ing.-Tech.* 1982, **54**, (3), 256-257
6. Scriven A. H. et al *Paper presented at the European Two Phase Flow Group Meeting, Glasgow, 1980*
7. Friedel L. and Purps S. *Paper presented at European Two Phase Flow Group Meeting, Paris — La Defense, 1982*
8. Moore K. V. et al *EPRI NP-408*, 1977
9. Rettig W. H. *ANCR-NUREG-1335*, **1**, 1976