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Paper:

Flashing, void fraction and pressure drop in pipes during rapid depressurisation

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Transient flow phenomena in pipes during depressurisation are not yet well understood. This is especially the case with hydrocarbons and binary mixtures as flashing and flowing substances. Dynamic phenomena in horizontal pipes of L/D ratios between 10 and 200 were studied by using Propane and Butane. Non-intrusive impedance probes were inserted in the wall of the pipe at several locations to measure void fraction instantaneously.
For longer pipes (L/D > 100) instabilities in the form of density-wave-oscillations were observed. These oscillations result from a highly complicated interaction between feeding from the pressure vessel and escaping flow through the orifice and are physically based on the fact that friction in the pipe is strong function of void fraction. So throttling in the orifice and two-phase-friction in the pipe are in competition. From the experimental data theoretical conclusions could be drawn for predicting the flashing, slip ratio and friction in highly transient two-phase-flow. Comparison of experimental results with some existing two-phase models are presented.

1. Introduction

Due to its importance in power and process industries the depressurisation at transient flow of two-phase mixtures is the subject of many investigations. Most of these research work was focused on boiling delay, critical flow through cracks or the flashing and phase separation in pressure vessels.

Jones /1/ was the first to suggest that boiling delay is a function of the static decompression and the turbulent fluctuations of the flowing liquid. Elias and Chambre /2/ presented a model for predicting the thermodynamic condition at the onset of flashing.

A review of several critical flow models, tested against a set of data from experiments with water as the test fluid, is given by Elias and Lellouche /3/. Giot /4/ shows a comparison of some flow models and criticizes the lack of data available for fluids other than water. Feburie *et al.*/5/ developed software to predict the mass flow rate through a crack and Dagan *et al.*/6/ presented a two-fluid model for critical flow in pipes, taking account the relative motion at the interface between liquid and vapor bubbles. Viecenz /7/, Thies and Mewes /8/ investigated the phase separation in a depressurized vessel.

On the contrary fluiddynamic phenomena in pipes with flow flashing and the interaction between the fluid in the pipe and a pressure vessel, which feeds the pipe during depressurisation are rarely studied.

To contribute to the understanding of the dynamic phenomena in horizontal pipes with flashing two-phase flow is the object of this study. Propane and butane were used as working fluids because there is only few information on hydrocarbons.

2. Experimental installation and measuring technique

The experimental facility in which the blowdown tests were performed consists of three main components:

- a pressure vessel containing the fluid - Propane or Butane - under saturated conditions

- a depressurisation pipe through which the flashing fluid flows, equipped with an orifice of various diameter at its down stream end and

- a low pressure containment system in which the depressurised two-phase mixture is captured and the vapour is condensed by a refrigerative cooling equipment

The experimental set-up is schematically shown in fig. 1.

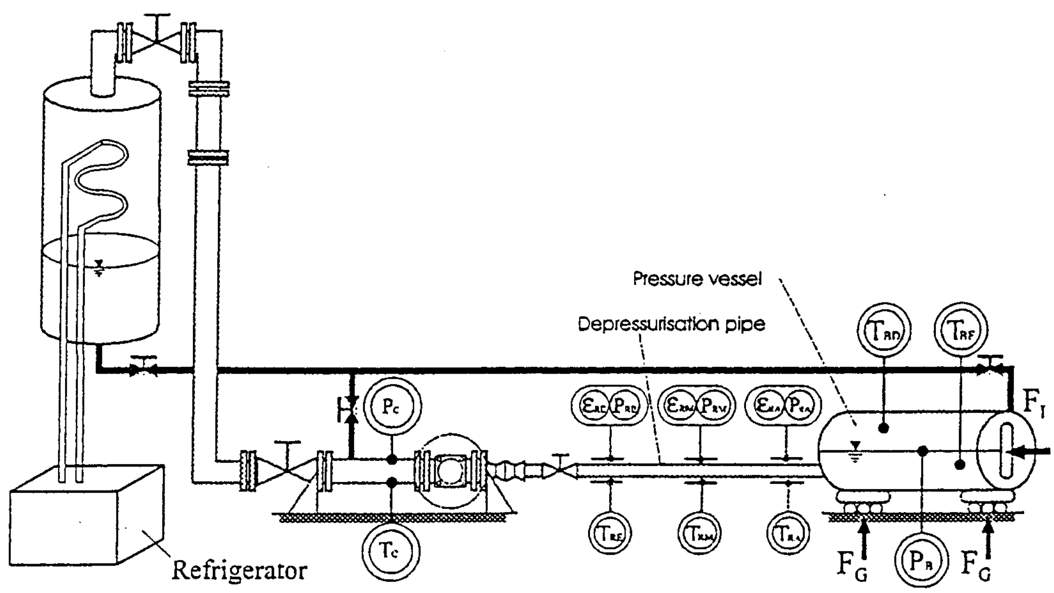


Fig. 1: Experimental set-up

Before initiating the depressurisation, the high pressure part and the low pressure system of the facility is separated by a burst disc, mounted behind the orifice at the end of the pipe. This burst disc is designed in such a way, that it can withstand a pressure difference which corresponds to approximately half the value of the initial pressure in the vessel. Therefore a small room behind the burst disc has to be pressurised to about half the initial pressure in the vessel. This is done by closing a large ball valve at the down stream end of this small room and by filling the room with vapour up to the desired pressure. After suddenly opening the large ball valve the pressure in the room is very rapidly decreasing. The disc finally cannot withstand the increasing pressure difference and bursts. The arrangement of the orifice and the rupture disc shows fig. 2.

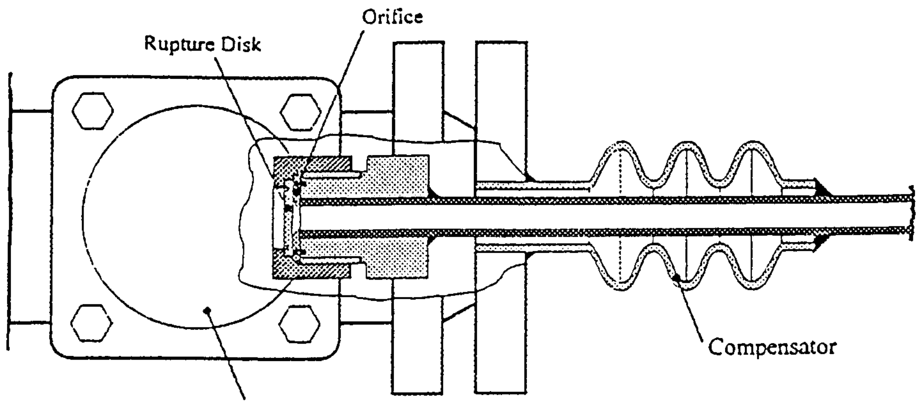


Fig. 2 : Rupture disc and observation window

The thermo- and fluiddynamic conditions in the pipe during the depressurisation are the main objects of interest for the investigations presented here. Three different pipe lengths were used having an L/D ratio of 10, 110 and 200. The pipe diameter was kept constant with 10mm. Two different sharp edged orifices were used having diameters of 3 or 5 mm respectively. Also experiments with open pipe (without orifice) were performed.

Vessel and depressurisation pipe were mounted on a movable carriage so that the momentum of the flashing flow leaving the pipe through the orifice could press the vessel against a pressure gauge acting as a dynamometer. Four other dynamometers support the pressure vessel from below instantaneously and continuously indicating the mass inventory of the fluid in the vessel.

The local and temporal value of the void fraction in the pipe during depressurisation is a key parameter of the experiments. Therefore a special impedance void fraction sensor acting on a capacitive basis and using the difference in the dielectric constant of vapour and liquid was developed. The design of this impedance sensor is shown in fig. 3.

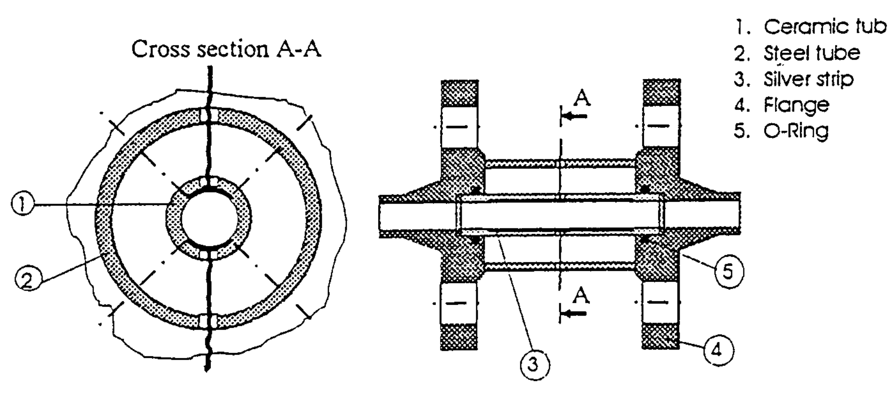


Fig. 3 Impedance void fraction sensor

The electrodes of this sensor were installed in the pipe wall in such a way, that they were not intrusive to the two-phase flow. Depending of the lengths of the pipe 1 (for L/D = 10), 2 (for L/D = 110) or 3 (for L/D = 200) were mounted into the pipe wall. The axial distribution of these impedance sensors is shown schematically in fig. 1. The capacity signal of the impedance sensor was measured by a highly accurate LCR-meter and evaluated into void data by using the well-known Maxwell equations.

At each position of an impedance sensor also the fluid temperature was measured by thermocouples integrated into the inner surface of the pipe wall and by pressure tabs. The small pressure sensors are of the strain gauge type. Further thermocouples and pressure sensors were arranged in the pressure vessel. Positioning the thermocouples on various levels inside the pressure vessel allowed to measure the instantaneous height of the swell level of the two-phase mixture. This is based on the experience that the pure vapour in the vessel has a different temperature from the two-phase mixture during depressurisation.

3. Experimental results and discussion

Experiments were performed with two different fluids, namely with Propane and with Butane. Before initiating the depressurisation the fluid in the pressure vessel was kept on saturation conditions by an electrical heating system attached to the outer wall of the pressure vessel.

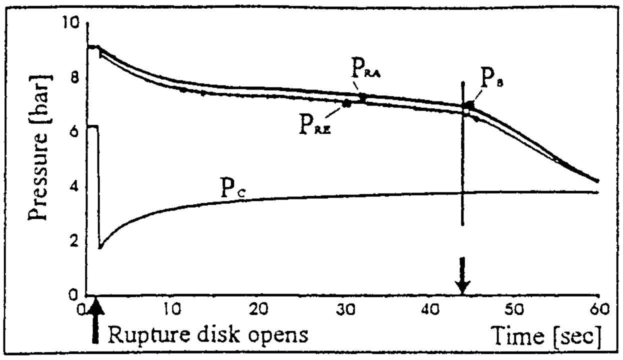
3.1 Propane

As mentioned pressure, temperature, void fraction, momentum of the jet and inventory of the vessel were registered during the blowdown. Comparing pressure and temperature at each location, the grade of thermodynamic disequilibrium could be calculated because the thermocouples measure the temperature of the liquid and this is the phase which is affected to boiling delay during blowdown.

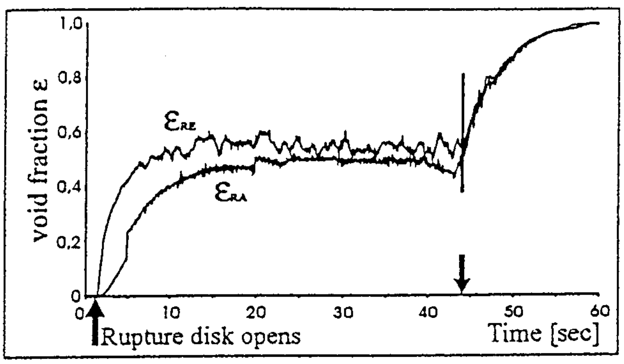
Figure 4 gives an example of such a data set monitored during a blowdown in a pipe with L/D = 110 and Propane as test fluid. The ratio of the cross sections formed by the pipe and by the orifice at the outlet end of the pipe was 4:1. There existed an incipient Propane inventory of 7 kg which filled the pressure vessel up to about 50 %.
The moment when the burst disc opens is indicated by an up ward showing arrow. A second - downward showing arrow marks the moment when the pressure vessel becomes nearly empty and from which on mainly vapour enters the pipe. That is why the void fraction is rapidly increasing from this late moment on and the pressure is falling quicker. Fig. 4 a indicates that the burst disc opens at the moment when the pressure p_C falls in the above mentioned small room due to opening the large ball valve.

There is a long period of boiling delay (approximately 16 s) which is shown in fig. 4 c and d. The thermodynamic disequilibrium reaches approximately 7 K (fig. 4 d). Afterwards, for a period of approximately 28 s, there is equilibrium between liquid and vapour in the pressure vessel (fig. 4 c and d). The deviation of the measured temperature from the saturation line downward from 7 bar is due to the fact that now the thermocouple in the pressure vessel is monitoring the vapour temperature which absorbs some heat from the guard heating system outside of the pressure vessel wall.

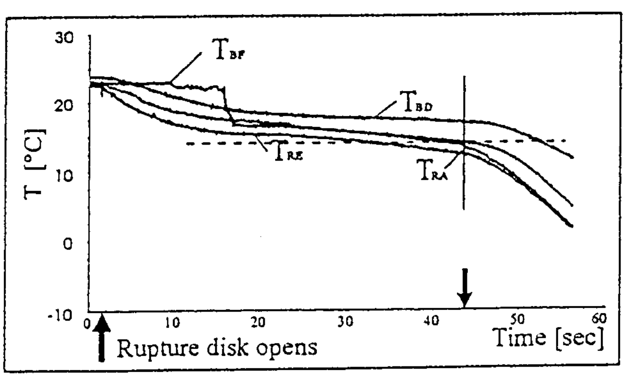
In the pipe there exists always thermodynamic equilibrium along the full flow path. The reason is that flashing already takes place when the fluid leaves the vessel and enters the pipe. Due to the pressure drop in the pipe, the fluid continues to be exposed to flashing on its way downstream to the outlet. This can be clearly seen from fig. 4 b by comparing the void fraction graphs taken at the entrance (RA) and at the exit (RE) of the pipe.



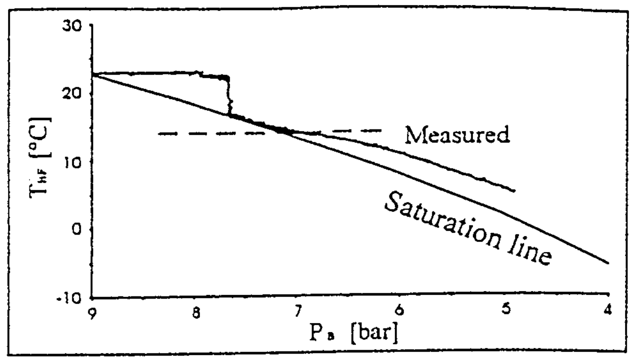
(a) Pressure history



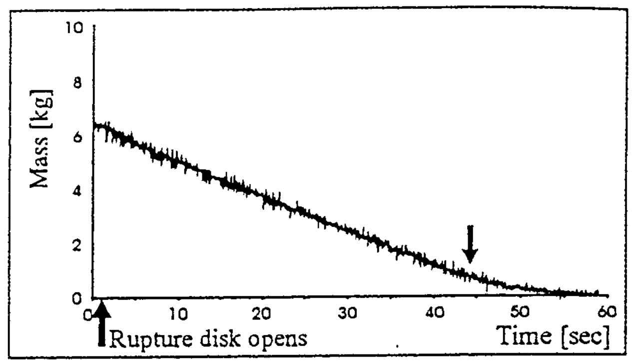
(b) void fraction history



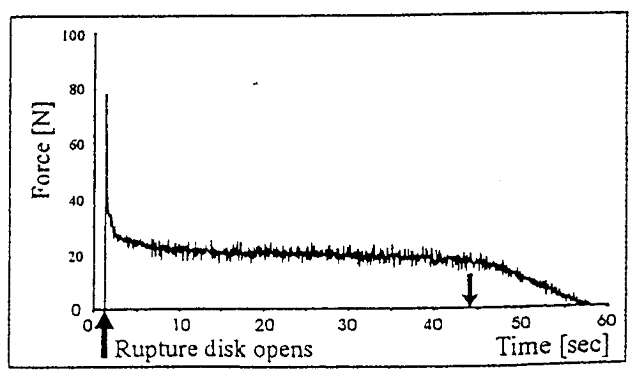
(c) Temperature history



(d) Thermodynamic nonequilibrium of liquid in vessel



(e) Inventory of Propane in the vessel



(f) Impulse force history of outflow

Fig. 4 L/D = 110 ; Dia. of orifice : 5 mm ; Propane

The void fraction sensor at the outlet of the pipe measured strong oscillations (fig. 4 b) after a very first period of blowdown. These oscillations origin from instabilities in the form of density-wave-oscillations resulting from a highly complicated interaction between feeding from the pressure vessel and escaping flow through the orifice. The flow friction in the pipe is a strong function of the void fraction as well-known from the literature. So throttling in the orifice and two-phase-friction in the pipe are in competition.

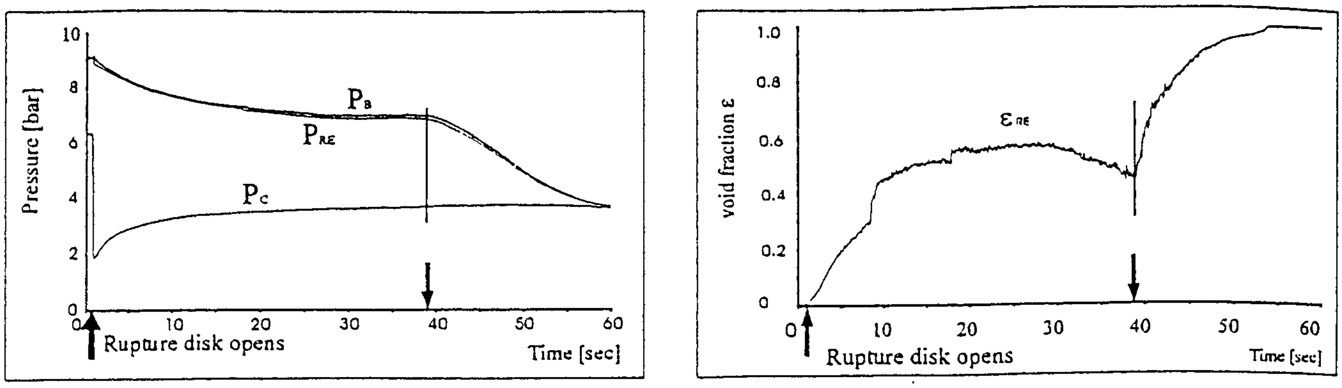
The graphs in fig. 4 e and f show the temporal course of the liquid inventory in the vessel and of the momentum of the flow leaving the orifice. The very first and large peak in fig. 4 f has nothing to do with the momentum of the jet flow. It results from the kinetic energy of the vessel making a very small movement when the blowdown is initiated until touching the force gauge and being supported by it. At the orifice critical flow is probably reached during a long period of the blowdown that is why the fluid inventory in the vessel is almost linearly decreasing versus the time.

Fig. 5 compares readings of the temporal behaviour of pressure and void fraction for 3 different lengths of the pipe. All other parameters were kept constant. To understand the temporal course of the pressure in the vessel and at the different locations along the pipe always the corresponding void fraction has to be taken in account. Increasing void fraction (at the same mass flow rate) produces larger friction pressure drop and therefore in the long pipe (fig. 5 c) there is a remarkable pressure drop between the vessel and the pipe as well as along the pipe. Certainly also the length of the pipe influences the friction-pressure-drop.

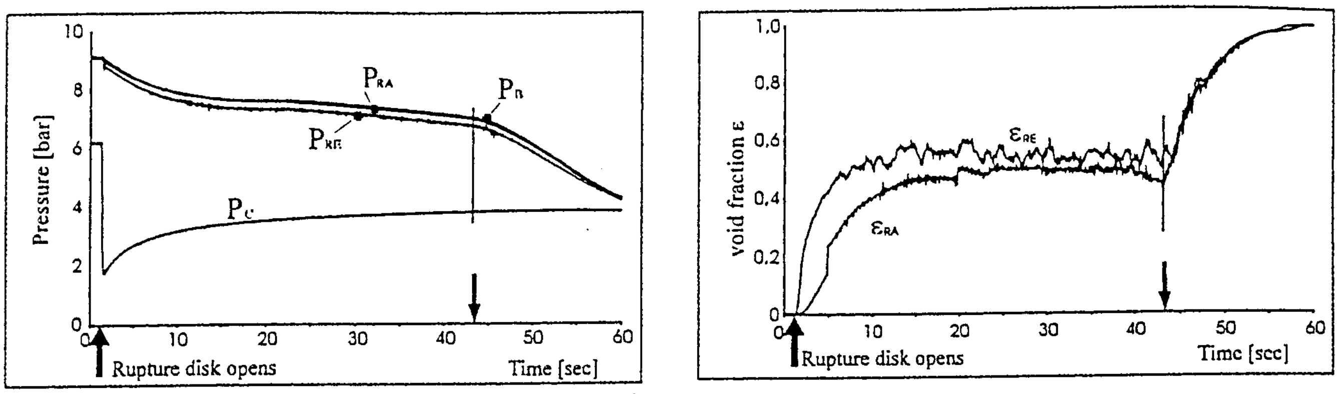
The registered data of pressure and void fraction for the shortest pipe (L/D = 10) prove the well-known fact that in flashing flow the temporal course of the pressure can be closely correlated to the void fraction. Approximately 25 s after beginning of blowdown the void fraction starts to decrease which reduces the temporal pressure gradient. In the longest pipe (L/D = 200) the void fraction sensor positioned in the middle of the pipe indicates the highest fluctuations.

Of course, also the grade of throttling at the end of the pipe influences the fluiddynamic conditions during blowdown. In fig. 6 pressure and void fraction measured in the long pipe (L/D = 200) are compared for 3 different conditions of flow restriction at the end of the pipe. In fig. 6 a the pipe had an open end (no orifice) and in fig. 6 c the flow was restricted at the end of the pipe down to 9% of the pipe cross section (orifice diameter 3 mm). With stronger throttling at the pipe end, the void fraction becomes smaller inside the pipe but is more affected by density-wave oscillations.

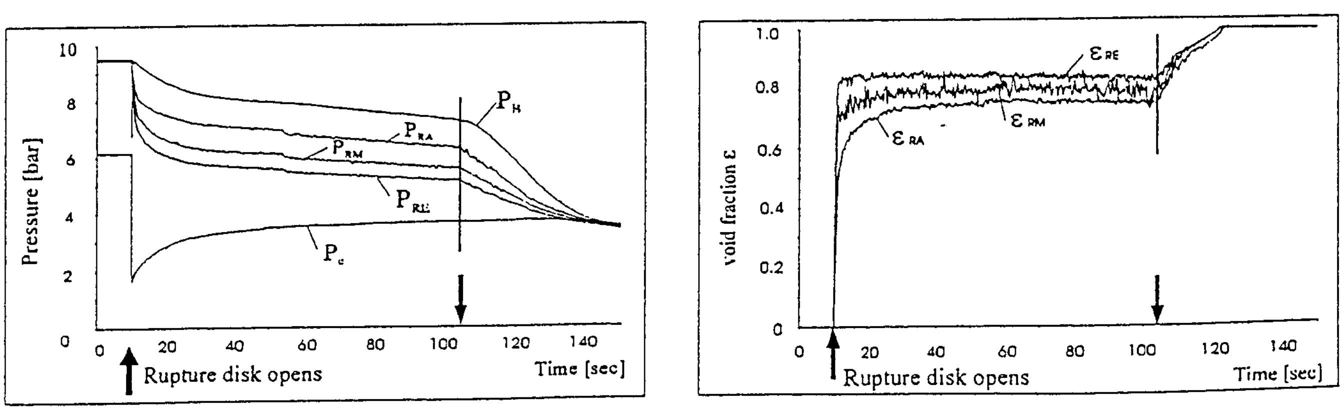
Of course throttling by an orifice at the end of the pipe extends the blowdown time and reduces the instantaneous mass flow rate. The later effect is quantitatively demonstrated in fig. 7. There readings of the momentary fluid inventory in the vessel are compared for different diameters of the orifice and for different pipe length.



(a) L/D = 10

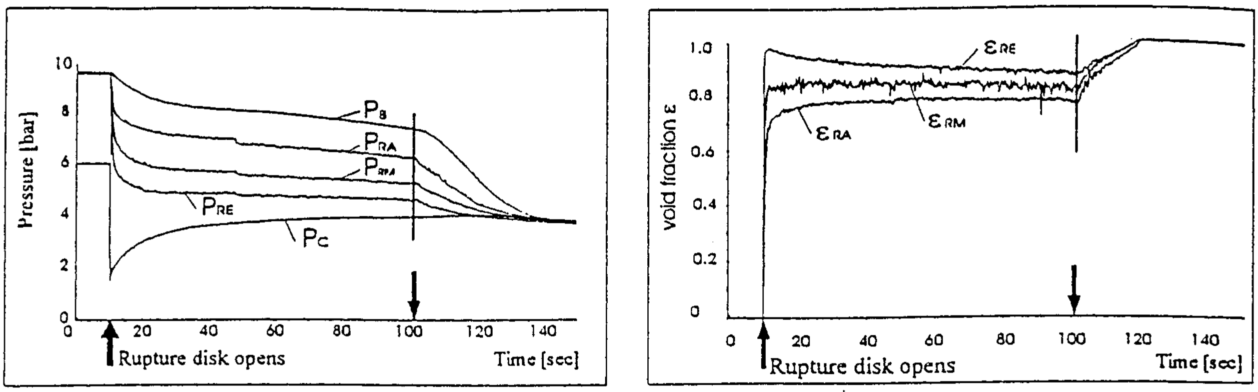


(b) L/D = 110

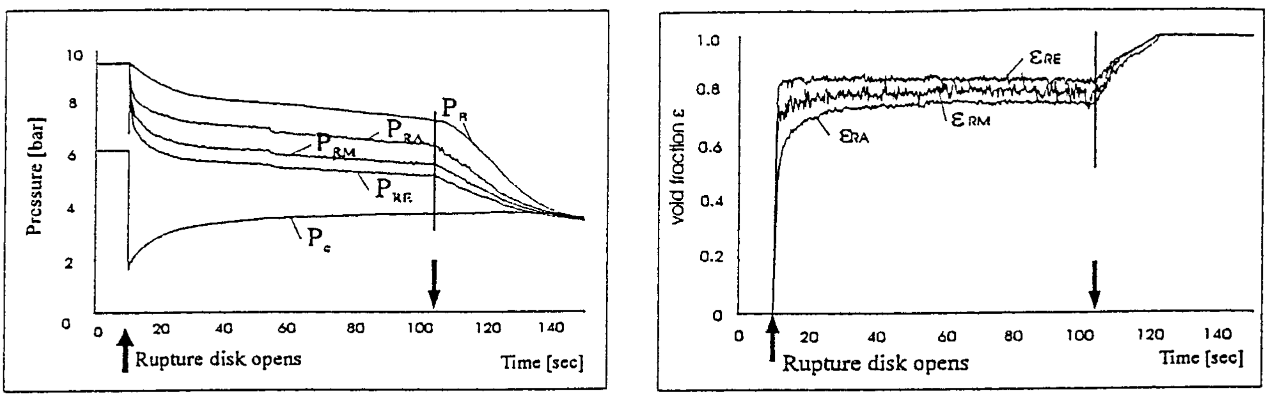


(c) L/D = 200

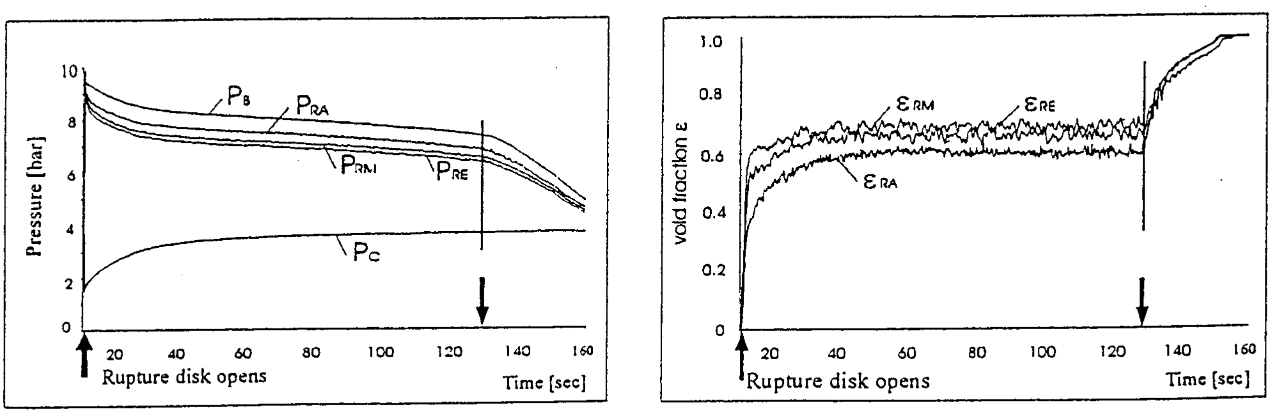
Fig. 5 Comparison of blowdown pressure and void fraction histories for different pipe length
Dia. of orifice : 5 mm, Working fluid : Propane



(a) dia. of orifice:10 mm

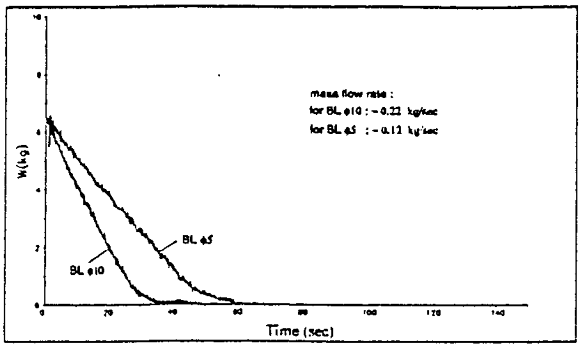


(b) dia. of orifice: 5 mm

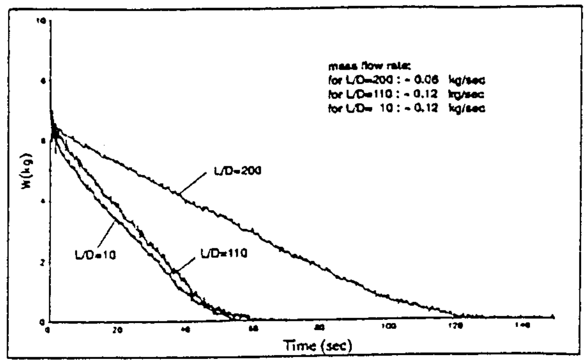


(c) dia. of orifice: 3 mm

Fig. 6 Comparison of the blowdown pressure and void fraction history with different dia. of orifice, L/D = 200 ; Working fluid : Propane



(a) Comparison of mass flow rate with different dia. of orifice. L/D=110, Working fluid: propane



(b) Comparison of mass flow rate with different dia. of orifice. L/D=110, Working fluid: propane

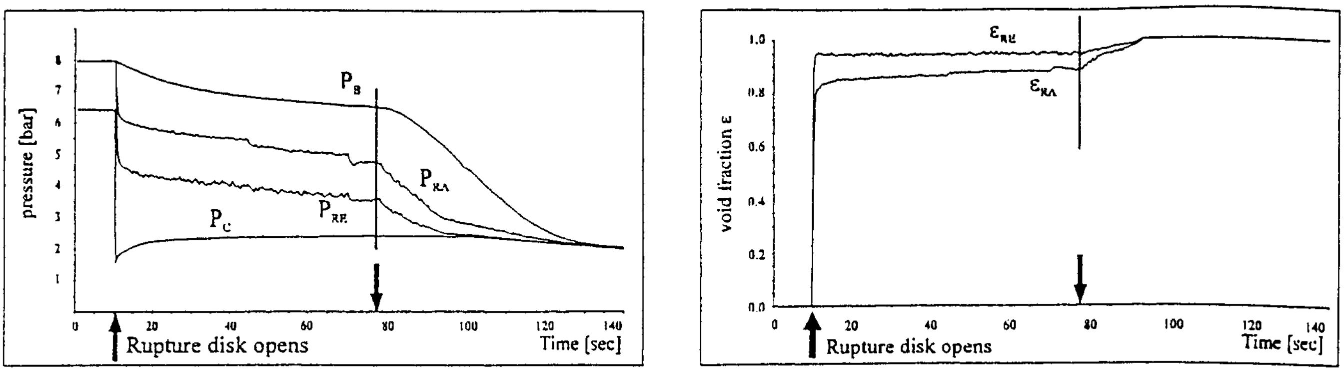
Fig. 7: Comparison of the mass flow rate

3.2 Butane

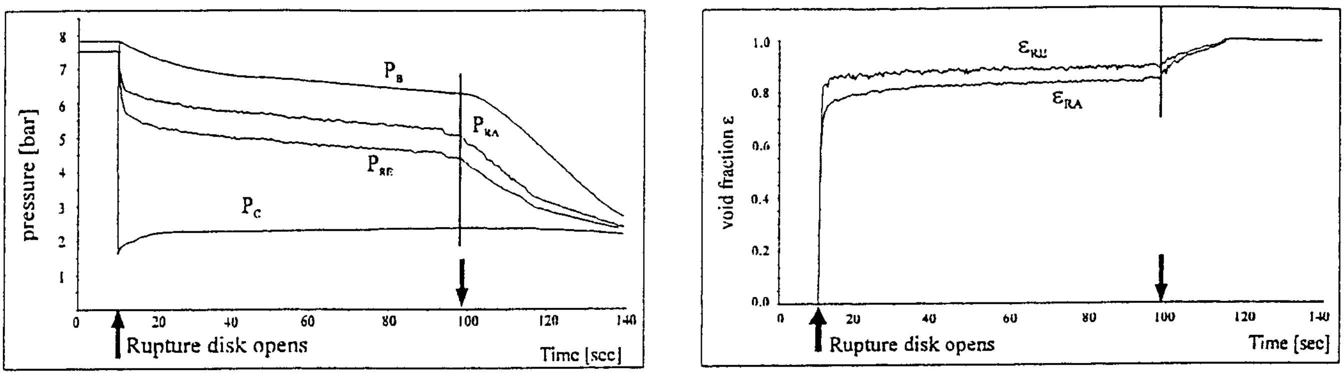
In the experiments with Butane the initial pressure in the vessel was set to a similar value as during the tests with Propane to get comparable results. In the pressure vessel saturated conditions were maintained before initiating the blowdown like with the Propane experiments. However, there was one different condition, namely in the pipe the temperature could not be kept exactly at the saturation value due to a lack of sufficient power of the guard heater. The saturation temperature of Butane is higher than that of Propane at comparable pressures.

These subcooled conditions in the pipe are the reason why the pressure of the fluid in the pipe drops down so rapidly in fig. 8 after the burst disc opens. Fig. 8 compares pressure- and void-fraction-histories during blowdown for 3 different throttling conditions at the end of a pipe having a L/D = 110 ratio. The blowdown- and void fraction behaviour of Butane is similar to that of Propane presented before. However, comparing fig. 8 b with fig. 5 b one realises that with Butane a much higher evaporating rate is reached than with Propane. This is due to the thermodynamic properties of latent heat of evaporation and specific heat of the liquid for both substances.

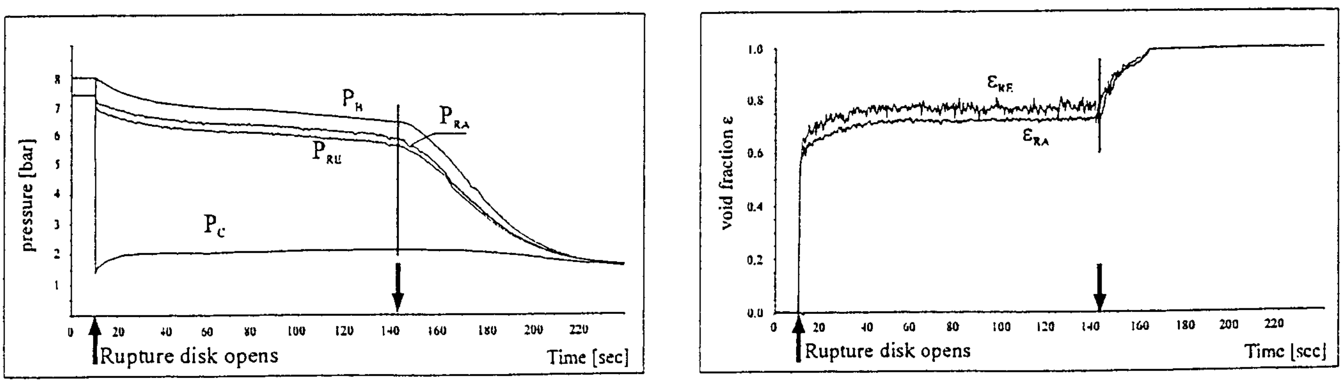
During the Butane experiments 3 thermocouples were located in the pressure vessel at different level-heights (instead of 1 with the Propane experiments). The temperature readings of these thermocouples prove - as shown in fig. 9 a - that the liquid in the vessel mainly evaporates at its upper free surface and a bulk of pure liquid being located between this upper surface and the nozzle leading to the pipe at the bottom of the vessel has almost constant temperature for a long period of blow down, which means it is in thermodynamic nonequilibrium condition. The grade of this thermodynamic nonequilibrium can be depicted from fig. 9 b as the distance from the saturation line. In this figure the temperature is plotted versus the pressure.



(a) dia. of orifice: 10 mm;

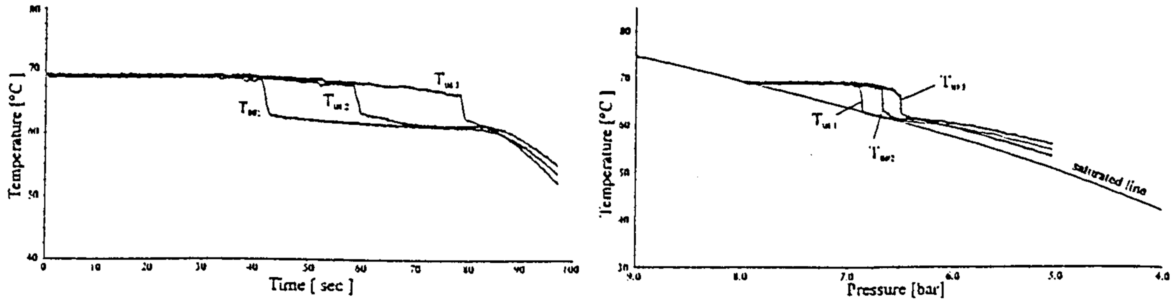


(b) dia. of orifice: 5 mm;



(c) dia. of orifice: 3 mm;

Fig. 8: Comparison of blowdown pressure and void fraction history with different dia. of orifice, pipe length L/D = 110; Working fluid : Butane



(a) Temperature time history
L/D=110, Working fluid: butane

(b) Thermodynamic nonequilibrium
L/D=110, Working fluid: butane

Fig. 9: Liquid temperature at different level-heights in vessel

5. Data analysis by simple calculations

In the most simple form mathematical models describing two phase flow contain the conservation equations for mass

$$\frac{\partial}{\partial t}\left((1-\varepsilon)\rho_F+\varepsilon\rho_G\right)+\frac{\partial}{\partial z}\left((1-\varepsilon)\rho_F w_F+\varepsilon\rho_G w_G\right)=0 \qquad [1]$$

for momentum

$$\frac{\partial}{\partial t}\left((1-\varepsilon)\rho_F w_F+\varepsilon\rho_G w_G\right)+\frac{\partial}{\partial z}\left((1-\varepsilon)\rho_F w_F^2+\varepsilon\rho_G w_G^2\right)+\tau\frac{U_n}{A}=\frac{\partial p}{\partial z} \qquad [2]$$

and for energy

$$\frac{\partial}{\partial t}\left[(1-\varepsilon)\rho_F h_F+\varepsilon\rho_G h_G\right]+\frac{\partial}{\partial z}\left[(1-\varepsilon)\rho_F h_F w_F+\varepsilon\rho_G h_G w_G\right]=q\frac{U_b}{A} \qquad [3]$$

in a lumped way by combining both phases for each conservation law in one equation. For closing this set of equations one needs mathematical models for the void fraction or the slip ($s = w_G / w_F$), for the friction pressure drop and with transient conditions also for the boiling delay or for the thermodynamic nonequilibrium respectively. As demonstrated in the presented experimental data, the boiling delay in the pressure vessel is rather large at the beginning of the depressurisation, however, in the pipe the thermodynamic nonequilibrium between the phases seems to be negligible. With this assumption and by knowing the thermo-fluiddynamic conditions at the entrance to the pipe, the calculation of the transient development of the flow in the pipe needs only information about slip or void fraction and about friction pressure drop.

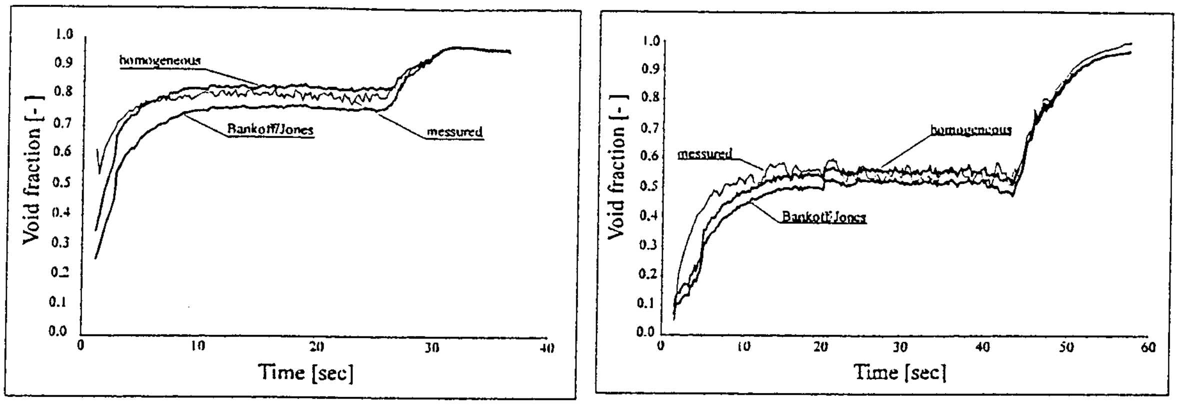
In the literature highly accelerated two-phase flow is frequently assumed to be homogeneous i.e. $s = 1$. We tried to check this assumption by calculating the development of the void fraction along the pipe and by starting this calculation with conditions at the pipe entrance known from the experiments. Two simple void fraction models were used, namely as assumed the homogeneous one and the correlation by Bankoff and Jones /9/ /10/

$$S = \frac{1-\varepsilon}{K^{*} - \varepsilon + \left(1-K^{*}\right)\varepsilon^{r}} \qquad [4]$$

with $K^{*} = 0.71+0.00131\,P$ (P in bar) [5]

$r = 3.33+0.00261\,P + 96.8\text{E-}06\,P^{2}$ (P in bar) [6]

The instantaneous mass flow rate of the mixture was taken from the readings of the weight sensors supporting the pressure vessel.



(a) L/D=110, Dia. of orifice: 10 mm working fluid: propane

(b) L/D=110, Dia. of orifice: 5 mm working fluid: propane

Fig. 10: Comparison of experimental results with two existing models

Fig. 10 shows, that for a rapid depressurisation (L/D = 110, open down stream end of the pipe) almost no slip could develop until the outlet end of the pipe and the homogeneous model predicts the void fraction well. This is also the case if a orifice is placed at the end of the pipe. The L/D is not large enough to allow the developing of a slip flow.

In the very first phase of the depressurisation the curve for the measured data is higher than that for the homogeneous model in fig. 10. This is due to simple assumptions in the calculation, which are not realistic in the very first period of the blowdown phase with highly transient flow. Future calculations within the project will treat the theoretical description of the developing flow in a more sophisticated way and will also compare the experimental results with other void-fraction-models like the drift-flux-model.

In these preliminary calculations, the Chisholm /11 / was used for calculating the friction pressure loss. In future comparisons also other friction models will be used.

Acknowledgement

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Nomenclature

A	Area of the cross section
BL	Orifice
e	Dielectric constant
C_0	Phase distribution parameter
D	Diameter
F	Force
h	Enthalpy
K^*	Coefficient of Bankoff/Jones
L	Length
$\dot{m}$	Mass flux
P	Pressure

q	Heat flux
r	Exponent , eq. [6]
S	Slip ratio
T	Temperature
t	Time
U	Circumference
w	Axial component of the velocity
$\dot{x}$	Quality
z	Axial coordinate

Greek letters

ε	Void fraction
ρ	Density
τ	Shear stress

Subscripts

C	Observation chamber
B	Vessel
BF	Liquid in vessel
BG	Vapor in vessel
F	Liquid
G	Vapor
G	Gravitation
RA	First test section
RM	Second test section
RE	Third test section