

## EXPERIMENTS ON EVAPORATING PIPE FLOW

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### Abstract

Evaporating two-phase flows were investigated in an 8 m long vertical pipe with an inner diameter of 195.3 mm. The phase transfer was induced by depressurization of the pipe starting from 1, 2, 4 and 6.5 MPa. The pressure relief was done for an upward liquid flow in the test section as well as for stagnant liquid. These experiments complete the extensive CFD-grade database obtained at the same test section for adiabatic two-phase flows and flows with bubble condensation along the pipe. Detailed information on the structure of the steam-water interface was obtained using a pair of wire-mesh sensors. The established database is suitable for the development and validation of CFD.

### 1. Introduction

Two-phase flows occur under normal operational conditions in the primary circuit of Boiling Water Reactors (BWR) as well as in the secondary circuit of Pressurized Water Reactors (PWR). However, such flows have also to be considered in accident scenarios such as during Loss Of Coolant Accident (LOCA) Scenarios in PWR's, i.e., when the system pressure in the primary circuit decreases down to the saturation pressure resulting in the generation of steam. Accident analyses have to show that the short-term as well as the long-term cooling of the reactor core is assured in all design based scenarios. This requires powerful simulation tools for the reliable prediction of two-phase flows. Today so-called system codes (e.g. RELAP, ATHLET, CATHARE, TRACE) are routinely applied to such analyses. They are based on a one-dimensional approach using component-specific empirical correlations derived from large scale experiments up to 1:1 experiments. Therefore, in general the system codes are geometry dependent and valid only within a limited range of scales. In principle, the validation of these codes requires experimental data obtained for the same geometry, similar scale and flow conditions. Large scale experiments are used to adjust such correlations; nevertheless their transferability to different scales, geometries or flow situations is limited. For this reason Computational Fluid Dynamics (CFD) simulations are increasingly used for analyses on special questions in Nuclear Reactor Safety (NRS). While a satisfying status is achieved for 3-dimensional simulations in case of single phase flows still much effort is required to qualify CFD-codes for two-phase flows.

While CFD codes are frequently used for industrial applications on single phase flow problems they are not yet mature for two-phase flows. An overview on the present two-phase

capabilities of CFD-Codes related to Nuclear Reactor Safety (NRS) Research is given by Bestion et al. [1]. The qualification of CFD codes for two-phase flows is one of important requirement of future NRS research. There are different ongoing activities worldwide to meet this goal. In frame of the German Computational Fluid Dynamic (CFD) association activities of different institutions are united to develop and validate CFD codes for their application to nuclear reactor safety assessment. The CFD model development and validation requires experimental data with high resolution in space and time (CFD-grade data). The TOPFLOW facility of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) is designed to provide such data.

In co-operation with ANSYS, HZDR has developed the so-called Inhomogeneous MUSIG-model (Multi Bubble Size Group model) for the simulation of poly-dispersed flows. Recently the model was extended to consider phase transfer [2]. To validate the model approach and related closure models a number of experimental series were run at the TOPFLOW facility. Upward gas-liquid flows in a large vertical pipe were investigated. Detailed data were obtained using the wire-mesh sensor technique [3]. A first database was established on adiabatic air-water flow which provides data especially suitable for the validation of models on the momentum transfer between the phases (bubble forces) and coalescence and breakup [4]. Phase transfer is included in a second experimental series which is on steam bubble condensation in vertical pipe flow. Steam was injected into an upwards flow of sub-cooled water and the condensation of the steam along the pipe was observed [5, 6].

The same setup, i.e. the so-called Variable Gas Injection device of the TOPFLOW facility was used for the new experiments on evaporation caused by pressure relief which are presented in this paper. The test section consists of a 195.3 mm inner diameter pipe with a length of about 8 m. Saturated water is circulated and flows upwards through the pipe. Then at the separator in this circuit a valve is opened leading to a pressure decrease in the system. Consequently evaporation occurs in the test section pipe. In a second series the whole test section was separated from the circuit and pressure relief was initiated by a fast opening valve. For both test series experiments were done for initial pressure values of 1, 2, 4 and 6.5 MPa, respectively.

## **2. Experimental setup and measuring technique**

### **2.1 Test section and measuring procedure**

TOPFLOW is the acronym for **T**ransient **t**wo **P**hase **F**LOW test facility. It is designed for the generic and applied study of transient two-phase flow phenomena in the power and process industries. By applying innovative measuring techniques TOPFLOW provides data suitable for CFD code development and qualification. The facility allows to perform steam-water or air-water experiments. It can be operated at pressures up to 7 MPa and the corresponding saturation temperature of 286 °C. The maximum steam mass flow is about 1.4 kg/s, produced by a 4 MW electrical heater. The maximum saturated water mass flow rate through the vertical test section is 50 kg/s. Different test sections can be operated between the heat source

(steam generator) and the heat sink (cooling systems). Detailed information can be found in [7] and at the TOPFLOW website ([www.hzdr.de/db/Cms?pNid=1003](http://www.hzdr.de/db/Cms?pNid=1003)).

The Variable Gas Injection test section consists of a vertical pipe with an inner diameter of 195.3 mm and a length of about 8 m. Up to 13 ports at different length positions can be used for the injection of air or steam through orifices in the pipe wall. The measuring plane with the pair of wire-mesh sensors is located at the upper end of the pipe (see Fig. 1). The different gas injection ports were used in the adiabatic experiments and the experiments on bubble condensation to vary the distance between gas injection and measuring plane. The aim of these experiments was to investigate the evolution of the flow along the pipe. The gas injection devices were not used in the experiments presented here.

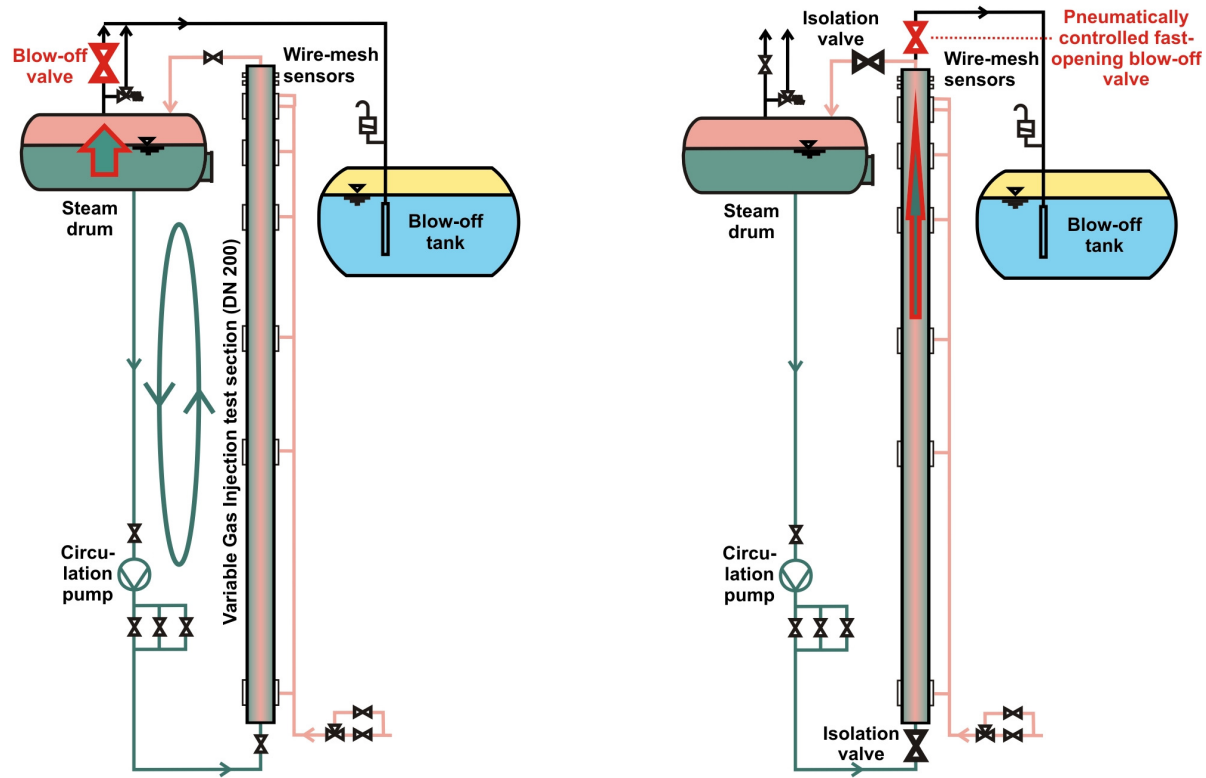


Fig. 1 Schemas of the two experimental procedures (left procedure 1, right procedure 2)

The experiments on pressure relief were done using two different experimental procedures as illustrated at Fig. 1. In case of the first procedure (left-hand side of Fig. 1) water was circulated with a superficial velocity of about 1 m/s and flows upwards through the test section. Before starting the pressure release saturation conditions are obtained in the steam drum, where water and steam are separated. Since the circulation pump is located at much lower elevation the pressure exceeds the saturation pressure at this position. It is important to maintain sub-cooled conditions at the position of the pump also during the pressure relief to avoid cavitation. This condition limits the speed of the depressurization which can be used in the experiments. Therefore, the blow-off valve which is located at the steam drum was only partially opened. According to the rather small pressure gradients also the maximum void

fraction generated in test section by evaporation is limited. The blow-off valve used in the procedure has relative long opening and closing times. For this reason the valve was opened and closed according to the ramp shape shown at the left-hand side of Fig. 2. The relative degree of opening at the plateau and the corresponding durations are shown in the test matrix, Fig. 2. In total there are 8 tests. Each test was repeated using the same conditions to check the reproducibility.

For the second procedure the facility was equipped with an additional blow-off line which was mounted at the upper end of the test section (right-hand side of Fig. 1). After heating up and before the initiation of the depressurization the test section was separated from the loop by valves, i.e. the experiments run from stagnant liquid. The new blow-off line is equipped with a fast opening valve allowing an opening ramp as shown at the left-hand side of Fig. 3. An orifice with a diameter of 20 mm was implemented in the blow-off line to limit the speed of depressurization. Much steeper pressure gradients resulting in much larger void fraction are obtained by this procedure. The test matrix is presented at Fig. 3. As in case of procedure 1 the pressure relief was start from 4 different pressure values. Opening times of 10 and 20 s were used. Again each of the 8 runs was repeated once again.

Both procedures have advantages and disadvantages. The advantage of the first procedure is the relatively large velocity of the fluid at the measuring plane. Previous investigations on the intrusive effect of the wire-mesh sensor have shown that the uncertainties of the measurements increase for small water velocities. Bubbles may be considerably decelerated due to the interaction with the wires for water superficial velocities below 0.2 m/s. For a water superficial velocity of 1 m/s as applied in this procedure this undesired effect is rather negligible and reliable data are obtained. For the second procedure it is expected that the bubbles are also pushed through the sensor due to the boiling up but it is rather difficult to quantify a possible interaction between the sensor wires and the bubbles. Another disadvantage of the second procedure is caused by the fact the valves which separate the test section from the loop (Fig. 1, right) have relatively long closing times. Due to heat losses during the waiting time before the pressure relief is started a slight sub-cooling will be obtained in the test section. Nevertheless the second procedure has the advantage that steeper pressure gradients can be realized leading to higher void fractions.

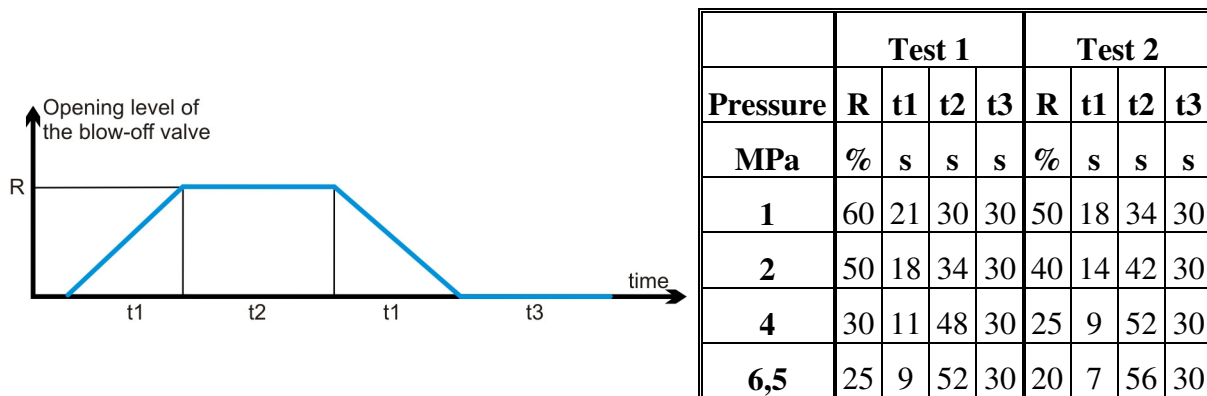
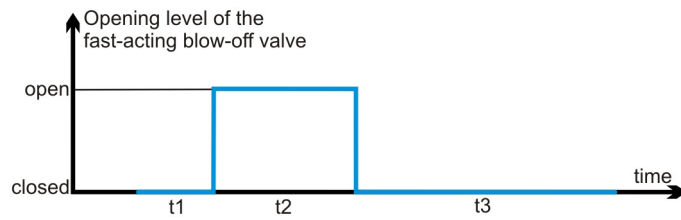


Fig. 2 Test matrix for procedure 1, R is the relative degree of opening of the blow-off valve.



|          | Test 1 |    |    | Test 2 |    |    |
|----------|--------|----|----|--------|----|----|
| Pressure | t1     | t2 | t3 | t1     | t2 | t3 |
| MPa      | s      | s  | s  | s      | s  | s  |
| 1        | 5      | 10 | 35 | 5      | 20 | 55 |
| 2        | 5      | 10 | 85 | 5      | 20 | 75 |
| 4        | 5      | 10 | 85 | 5      | 20 | 75 |
| 6,5      | 5      | 10 | 85 | 5      | 20 | 75 |

Fig. 3 Test matrix for procedure 2

## 2.2 Measuring techniques

Numerous papers were published in the past on the wire-mesh sensor technology (e.g. [3], [7]) and on experiments using the wire-mesh sensor (e.g. [4], [5], [6], [8]). For this reason here only the basic principle is presented. A wire-mesh sensor consists of two grids of parallel wires, which span over the measurement cross-section. The wires of both planes cross under an angle of 90°, but do not touch. Instead there is a vertical distance between the wires at the crossing points. At these points the conductivity is measured. According to the different conductivity of gas and water the phase present in the moment of the measurement at the crossing point can be determined. Many different types of wire-mesh sensors were built and successfully used during the last 15 years.

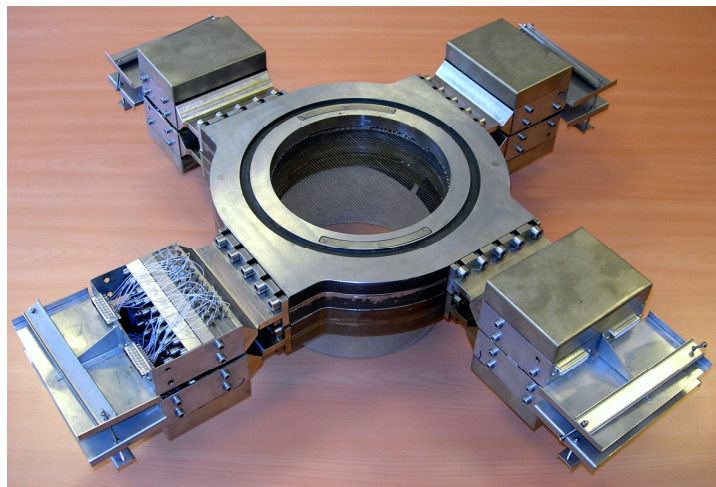


Fig. 4 High temperature wire-mesh sensors used in the present experiments

In the present case, two high temperature wire-mesh sensors (Fig. 4) are employed. They are designed for an operational pressure up to 7 MPa and the corresponding saturation temperature of 286°C. Each plane of the sensors is composed of 64 x 64 wires that have a lateral pitch of 3 mm and thickness of 0.2 mm. The distance between the two grid levels is

app. 3 mm. Due to thermal expansion it is necessary to stress each single wire by a spring. To avoid leakages at high pressures the sensor seals each of the 128 wire electrodes with a single packing box. Inside these boxes a synthetic material is used which allows the electrical and pressure insulation simultaneous up to high temperatures. Additionally, the packing boxes simplify the replacement of damaged wires. Furthermore the body of the sensor is designed modular. This feature reduces the weight of the sensor essential and simplifies the maintenance.

Measurements are done with a frequency of 2500 frames per second, i.e. 2500 pictures of the instantaneous gas distribution in the pipe cross section are obtained. The measuring time was 100 s, i.e. the result of one single measurement is a three-dimensional matrix of  $64 \times 64 \times 250.000$  values of the instantaneous local conductivity. This matrix can be visualized to provide an impression of flow characteristics. More important is the generation of quantitative data by using averaging procedures. Most important is the time averaging.

In case of stationary experiments as presented in [4, 5, 6, 8] the averaging can be done over the whole measuring time. For the transient experiments presented here the measuring time of 100 s was subdivided into 50 time slices of 2 s each. The averaging was done over each time slice. By a calibration procedure (histogram calibration, see [4]) 50 matrices of the dimension  $64 \times 64 \times 5000$  of the instantaneous local volume void fraction are calculated. Time averaging e.g. leads to 50 two-dimensional gas volume fraction distributions in the pipe cross section each of them representing values averaged over 2 s. This averaging time is a compromise between the required statistics and the detailedness regarding the evolution of the flow.

Due to the radial symmetry of the data the statistical error of the two-dimensional distributions of the void fraction can be further lowered by an azimuthally averaging. To do this the cross section is sub-divided into 80 ring-shaped domains with equal radial width. The contribution of each mesh is calculated by weight coefficients obtained from a geometrical assignment of the fractions of a mesh belonging to these rings. In the result radial gas volume fraction profiles are obtained.

For the measurements two sensors were used which measurement planes have a distance of 42 mm. This allows to cross-correlate the gas volume fraction values of the two-planes for all mesh points which are located above each other. From the maxima of the cross-correlation functions the typical time shift of the local void fraction fluctuations can be determined. Since the distance between the measuring planes is known the local gas velocity averaged over the above mentioned period of 2 s can be calculated. The point-to-point two-dimensional gas velocity distributions in the pipe cross section are obtained in the results of this procedure. Again an azimuthally averaging is applied to obtain the radial profiles of the gas velocity. It is important to mention that the second sensor is only used for the determination of the gas velocities. Due to the perturbing effect of the first sensor other data as especially bubble size distributions obtained from the second sensor would be distorted.

The next step of the data evaluation procedure is the identification of single bubbles. A bubble is defined as a region of connected gas-containing elements in the void fraction matrix which is completely surrounded by elements containing the liquid phase. A complex procedure,

described by Prasser et al. (2001), applies a filling algorithm combined with sophisticated stop criteria to avoid artificial combinations as well as artificial fragmentation of bubbles. In the result the same identification number is assigned to all volume elements which belong to the same bubble. Different bubbles receive different identification numbers. These numbers are stored in the elements of a second array. This array has the same dimension as the void fraction array. Combining the information from the void fraction and bubble number arrays together with the radial profiles of the gas velocity characteristic data of the single bubbles as bubble volume, sphere equivalent bubble diameter, maximum circle equivalent bubble diameter in the horizontal plane, coordinates of the bubble centre of mass, moments characterizing asymmetries and others are obtained. Based on these data cross section and bubble size distributions averaged over the above mentioned period of 2 s and radial gas volume fraction profiles decomposed according to the bubble size are calculated. The bubble size distributions are defined volume fraction related, i.e. they present the volume fraction per width of a bubble diameter class (equivalent diameter of a sphere with the measured bubble volume  $V_b$  is considered).

The absolute pressure is measured at the position of the wire-mesh sensors with a frequency of 25 Hz. The pressure difference between this position and 5 length positions along the pipe is also measured. This allows to determine the averaged void fraction within these 5 sections.

### 3. Results

The time-plots of the pressure clearly differ for the two procedures. Due to the slow opening of the blow-off valve in case of procedure 1 the pressure transients are rather smooth (Fig. 5, left). For procedure 2 (Fig. 5, right) a sharp decrease of pressure occurs immediately after the opening of the valve. This leads to a considerable sub-cooling of the liquid followed by a strong evaporation process. During a short period the volume of steam generated by evaporation exceeds to discharge volume leading to an increase of pressure. After closing the valve an increase of pressure is observed which is more pronounced at the 1 MPa experiment compared to the 6.5 MPa experiment. It is caused by the heat input from the walls.

In the following the experiment for procedure 1 at 6.5 MPa and 25 % opening of the blow-off valve is considered more in detail. The opening of the blow-off valve starts at 2 s, i.e. according to the numbers given in Fig. 2 the valve is opened to the desired value (25 %) at 11 s and closing starts at 63 s. The valve is closed completely at 72 s.

Fig. 6 shows the cross section averaged void fraction obtained from the wire-mesh sensor measurement as function of time. The delay of the increase and decrease of the void fraction compared to the opening ramp of the valve results from the delay of the evaporation process but mainly from the fact that the measuring plane is located at the upper end of the pipe. The steam which is produced along the pipe needs some time to travel to the sensor.

This fact is also reflected in the evolution of the bubble size distribution with time as shown at Fig. 7. With the increase of the averaged void fraction increase also the bubble sizes (Fig. 7, top, left). During the period in which a plateau of the averaged void fraction is observed also

the bubble size distributions remain almost unchanged (Fig. 7, top, right). The bubble sizes decrease with the averaged void fraction after closing the blow-off valve (Fig. 7, bottom).

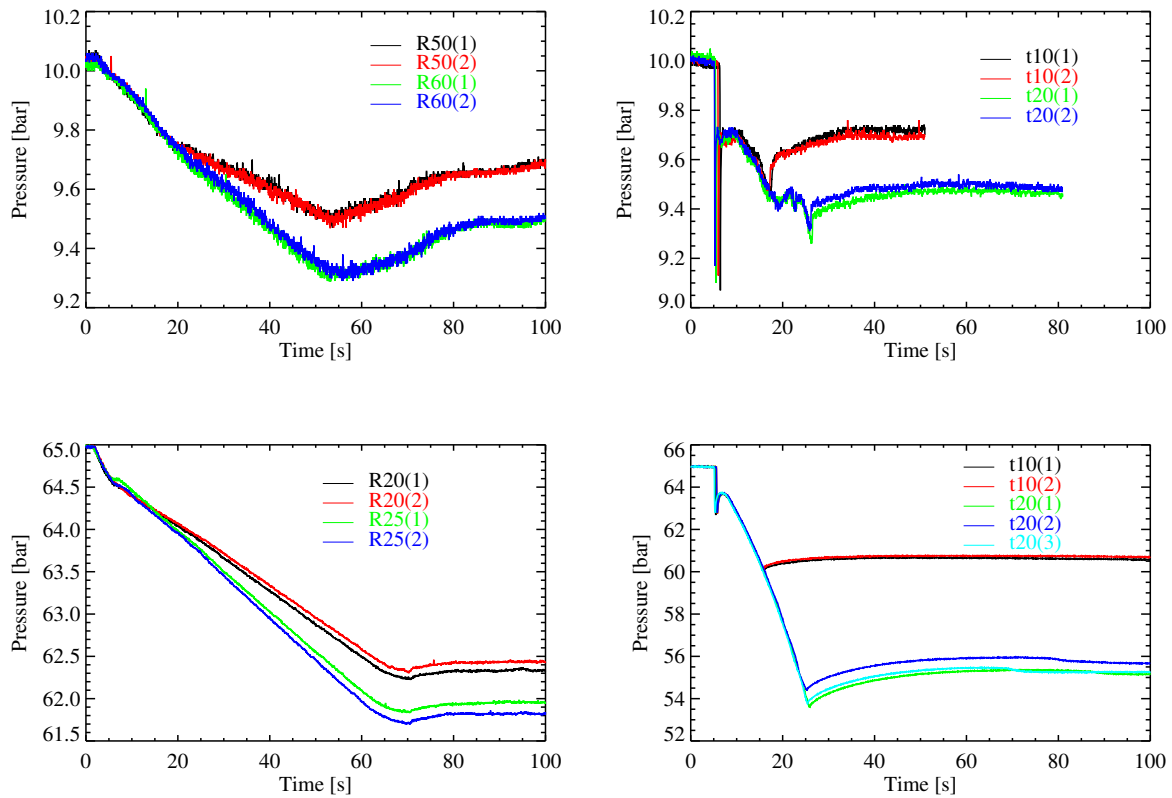


Fig. 5 Time dependent pressure for the two procedures, left: procedure 1, right: procedure 2, top: 1 MPa, bottom 6.5 MPa. The numbers on brackets indicate the first and second realization of the test

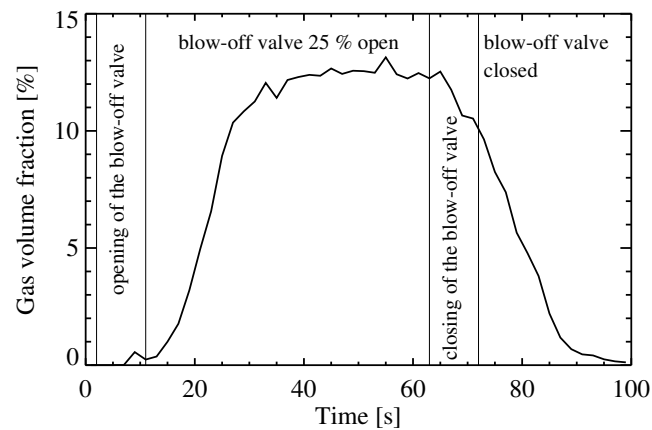


Fig. 6 Cross section averaged void fraction for procedure 1, 6.5 MPa and 25% opening of the blow-off valve

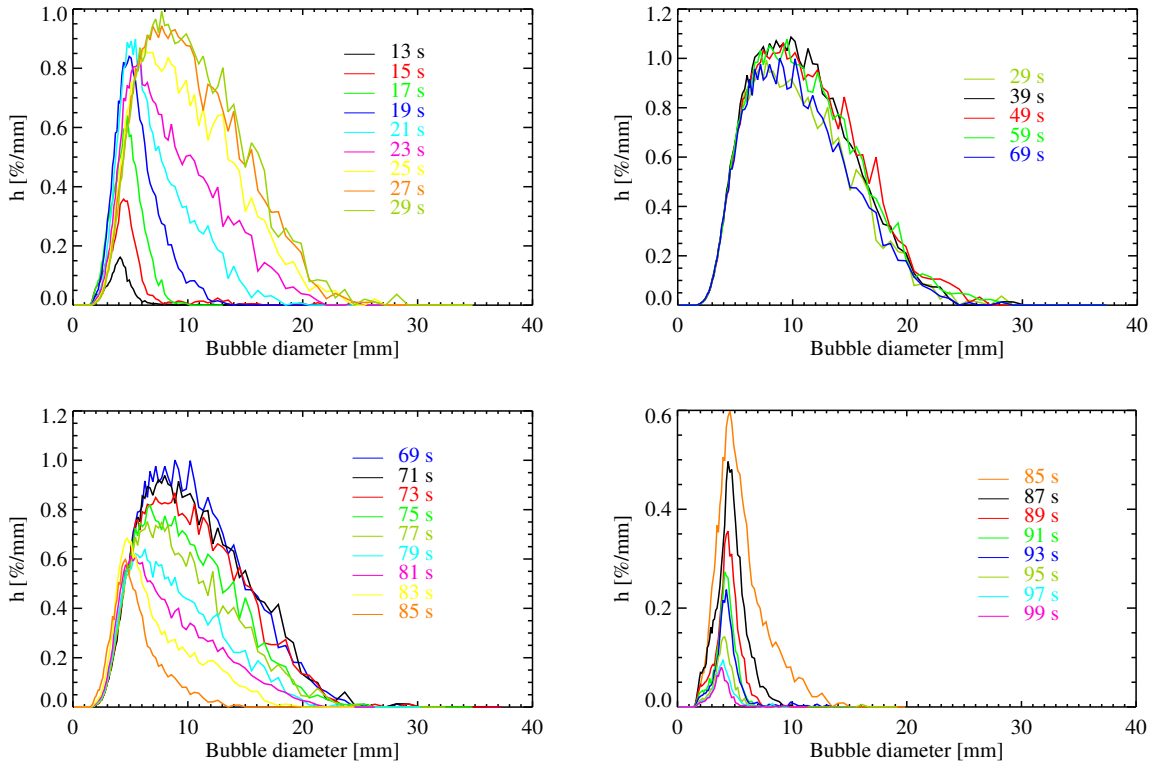


Fig. 7 Bubble size distributions during the transient, procedure 1, 6.5 MPa, 25% opening of the blow-off valve

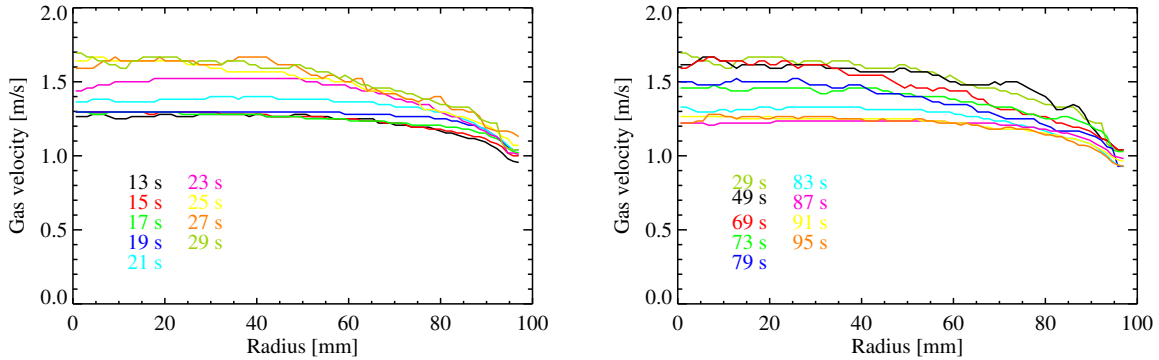


Fig. 8 Radial profiles of the gas velocity during the transient, procedure 1, 6.5 MPa, 25% opening of the blow-off valve

The boiling up during the pressure relief process is also reflected in the radial profiles of the gas velocity which are shown at Fig. 8. Since the first bubbles are generated at the pipe wall (see Fig. 9, top, left) in the first seconds after the start of the blow down the velocity increases first only in the near wall region (up to 18 s in Fig. 8, left). Later on the maximum of the gas volume fraction shifts away from the pipe wall and forms intermediate peaks (Fig. 9, top line – 23 to 69 s). Accordingly the velocity profiles have their maxima in the pipe centre. They are

again flattened with the decrease of the boiling process after closing of the blow-off valve. Starting from about 90 s bubbles are observed only in the near wall region (Fig. 9, bottom, right). Compared to steady state experiments as presented in [4, 5, 6, 8] where the radial profiles and bubble size distributions were obtained from an averaging over the whole measuring time (10 s) here the statistics of the data are not so good. The averaging over periods of only 2 s leads to some fluctuations of the profiles as it can be seen at Fig. 9. The fluctuations are more pronounced in the core region of the pipe compared to the wall region due to the occurrence of few large bubbles.

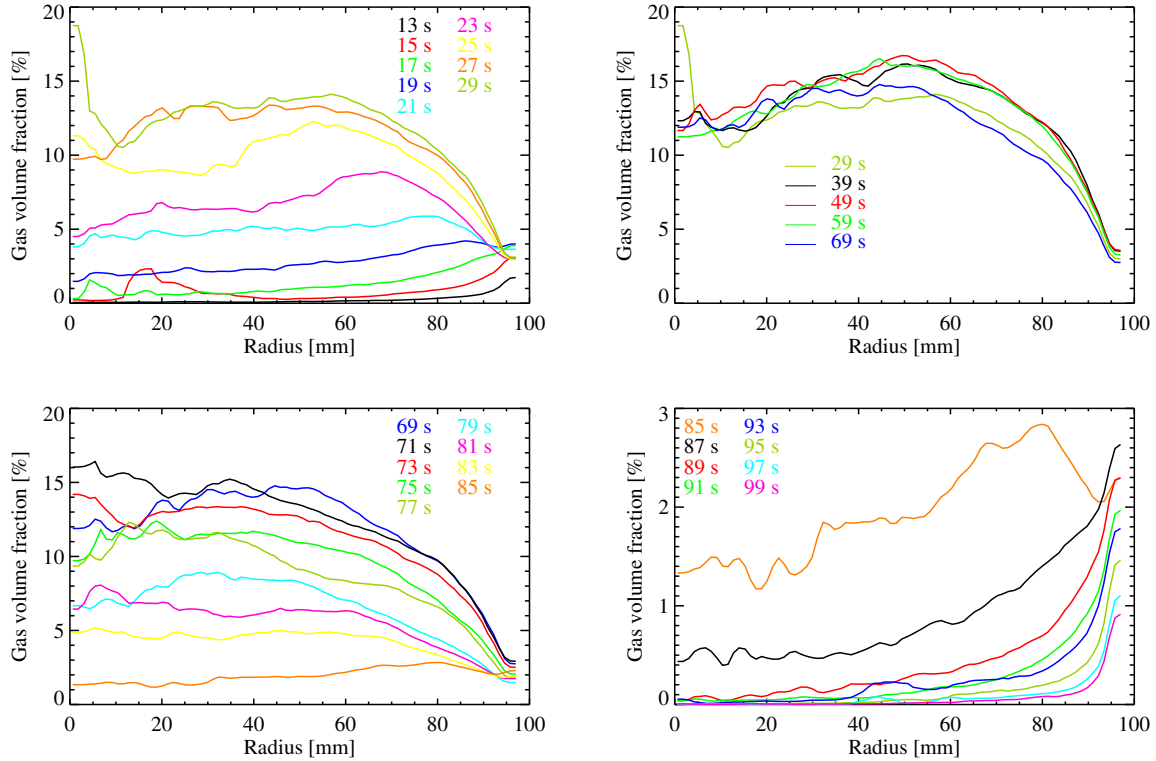


Fig. 9 Radial profiles of the gas volume fraction during the transient, procedure 1, 6.5 MPa, 25% opening of the blow-off valve

During the period of the plateau of the averaged void fraction in Fig. 6 almost stationary conditions are observed in respect to bubble size distributions (Fig. 7, top, right), radial profiles of gas velocity (Fig. 8, right) and radial gas volume fraction profiles (Fig. 9, top, right). For this reason it should be justified to do a time averaging over this period in order to improve the statistics. This is especially important for the radial volume fraction profiles decomposed according to the bubbles size. Such profiles are presented in Fig. 10. Obviously the peak at half of the pipe radius in the total gas volume fraction profiles shown at Fig. 9, top right is caused mainly by bubbles larger than 10 mm sphere equivalent bubble diameter. Smaller bubbles are rather equally distributed over the pipe cross section.

The measured data for the pressure difference recorded for several height positions were used to obtain some information on the axial void distribution along the pipe. Preliminary results

are shown at Fig. 11. Considerable uncertainties arise for these measurements from the fluctuations in signals of the measured pressure differences and from the correlations used for two-phase pressure drop due to friction and acceleration. Compared to the averaged void fraction measured by the wire-mesh sensor (see Fig. 6) some lower values are obtained for the topmost section. In contrast to experiments done at 1 MPa in case of the 6.5 MPa experiment discussed here, steam is also observed at the lowest section between the measurement positions for the pressure difference.

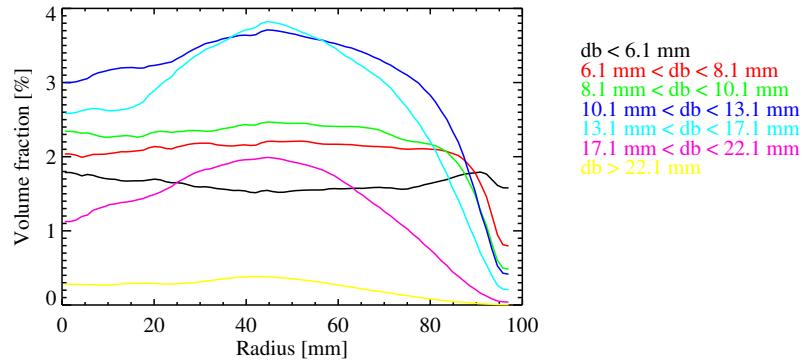


Fig. 10 Radial volume fraction profiles decomposed according to the bubble size and averaged over the gas volume fraction plateau (31 s to 61 s), procedure 1, 6.5 MPa, 25% opening of the blow-off valve

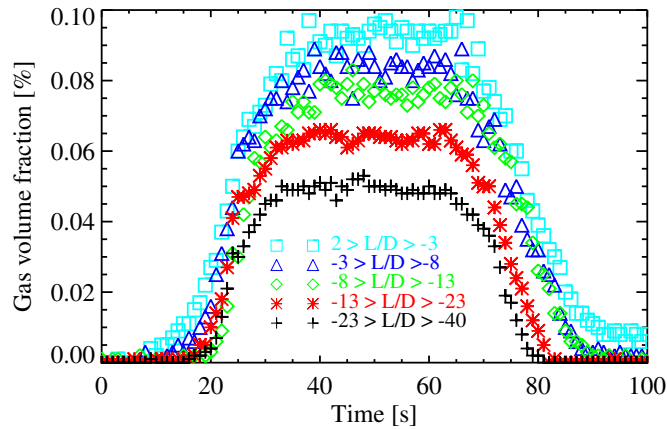


Fig. 11 Volume averaged void fraction for different pipe sections for procedure 1, 6.5 MPa and 25% opening of the blow-off valve. The sections are characterized by length to diameter ratio ( $L/D$ ) measured from the axial position of the wire-mesh sensor.

This observation agrees with the temperature measurement at the lower end of the test section. Before the opening of the valve the water temperature is slightly below the saturation temperature which corresponds to the pressure measured at this position. After the start of the blow-off the measured temperature and saturation temperature agree quite well.

## 4. Conclusions

The experiments presented in this paper complete the database on two-phase flows in a large (195.3 mm inner diameter) vertical pipe. Beside adiabatic flows and cases with steam condensation in sub-cooled water which were conducted for stationary boundary conditions now also transient data on evaporating flows are available. The use of the wire-mesh sensor technology allows the establishment of a CFD-grade database, i.e. data with a high resolution in space and time. This database comprises radial profiles for the gas volume fraction and the velocity as well as cross-section averaged bubble size distributions. Also local bubble size distributions and radial gas volume profiles decomposed according to the bubble size are available.

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