DIRECT CONDENSATION AND ENTRAINMENT STEAM EXPERIMENTS AT THE TOPFLOW-DENISE FACILITY

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ABSTRACT

In a hypothetical Small Break Loss of Coolant Accident (SB-LOCA) in a Pressurized Water Reactor (PWR), the Reactor Pressure Vessel wall (RPV) may be exposed to thermal stress, since the Emergency Core Cooling System (ECCS) injects cold water. The loads on the primary loop and RPV walls are determined by mixing processes with the surrounding hot water and by the condensation of steam on the surface.
For the development and validation of Computational Fluid Dynamics (CFD) models, experiments have to meet a high standard of reproducibility, measurement certainty and temporal and local resolution. The pressure tank technology of the TOPFLOW facility allows conducting such experiments at reasonable effort.
The Direct Condensation and Entrainment Installation for Steam Experiments (DENISE) is made for CFD-grade condensation experiments at up to 50 bars pressure. Subcooled water is injected into the DENISE-basin in three different configurations to generate stratified flow, jet and plunging jet (steam entrainment with a jet) experiments with condensation.
The experimental facility is presented along with the high degree of instrumentation. High speed camera, a particular LED illumination, micro thermocouples, coriolis flow meters and movable thermal lances were used.
The available set of experiments is shown together with a number of approaches how to compare the experimental results to CFD simulations. Temperature profiles are used in the water phase of stratified horizontal and downward (jet) flow. Dynamic pressure profiles are measures inside the condensing jet and the plunging jet is mainly observed with high speed camera.

KEYWORDS
direct condensation, experiment, SB-LOCA, thermal shock, PTS, stratified, jet, plunging, entrainment

1. MOTIVATION

In a hypothetical Small Break Loss of Coolant Accident in a Pressurized Water Reactor, the primary system temperature starts at around 300 °C. In the course of the accident, cold water is injected from accumulators through the Emergency Core Cooling (ECC) system. The Reactor Pressure Vessel wall may be exposed to thermal stress, because the injected water is cold. The loads on the primary loop and RPV walls are determined by mixing processes with the surrounding hot water and by the condensation of steam on the free surface (see Bestion et. al. [1] and Lucas [2]) especially in scenarios with an injection into a partly covered cold leg as shown in Figure 1. In this case, the ECC nozzle may form a subcooled liquid jet that flows though the steam environment and hits the present stratified water layer afterwards. It is possible in these cases, that the plunging water jet causes steam to entrain into the water bulk.
In order to use Computational Fluid Dynamics (CFD) Simulations for future safety assessment and design purposes, the associated models need further development and validation. Experiments for that purpose have to meet a high standard of reproducibility, measurement certainty and temporal and local resolution.

The pressure tank technology of the TOPFLOW facility allows conducting such experiments at reasonable effort.

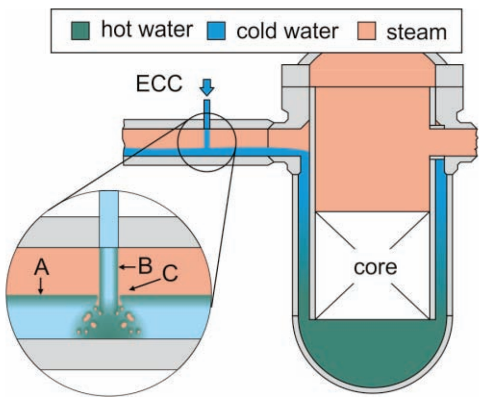

Figure 1: Pressurized thermal shock scenario with partly covered cold leg

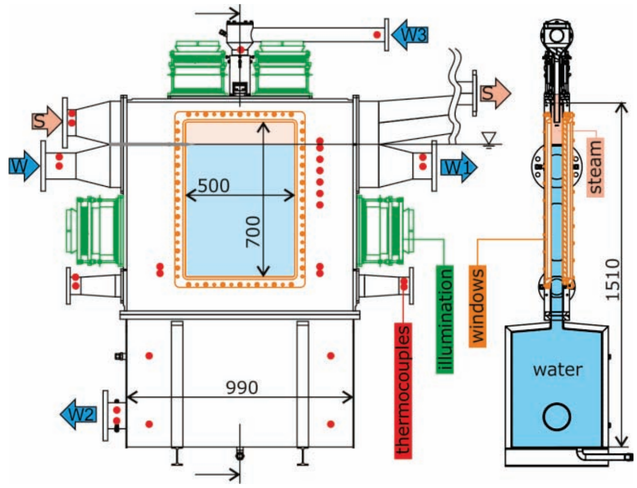

Figure 2: TOPFLOW-DENISE facility with flow directions of steam (S) and water (W)

The Direct Condensation and Entrainment Installation for Steam Experiments (DENISE) was built for CFD-grade condensation experiments at up to 50 bars pressure.
Subcooled water is injected into the DENISE-basin in three different configurations for experimental investigation. The blue arrows in Figure 2 show the water flow ducts for the different experiments:

- stratified flow
- water jet injection
- steam entrainment from a water jet plunging into a stratified surface

The experimental facility is extensively instrumented. The flow inside is observed and controlled with a high speed camera as well as an infrared camera, coriolis flow meters and a set of micro thermocouples. The facility is supplied with a 4-MW electrical boiler producing steam and saturated water, a 30 kW electrical heater and a 2-MW water cooler (see Figure 3).
The pressure tank technology allows observing flows at reactor near states with the mentioned sophisticated measurement technique by working in a pressure equalized way. The whole tank is pressurized with nitrogen and the experiment inside is open to this environment. A special condenser with vertical cooling tubes separates steam and nitrogen. The pressure equilibrium allows building experimental setups with thin walls and large windows. All measurement systems are synchronized using a common trigger-signal and the experiments have been conducted at stationary conditions.

2. STRATIFIED FLOW EXPERIMENTS

The first series are stratified flow experiments comparable to non-adiabatic flow inside hot and cold legs of PWRs. A total of 56 experiments have been carried out according to the test matrix sketched in Table 1.
Two different general flow conditions were investigated. As shown in Figure 4, water has always been injected at the top (W). For pure co-current flow, it has also been withdrawn at the top (W1) and for partly counter-current flow at the bottom (W2) of the basin.

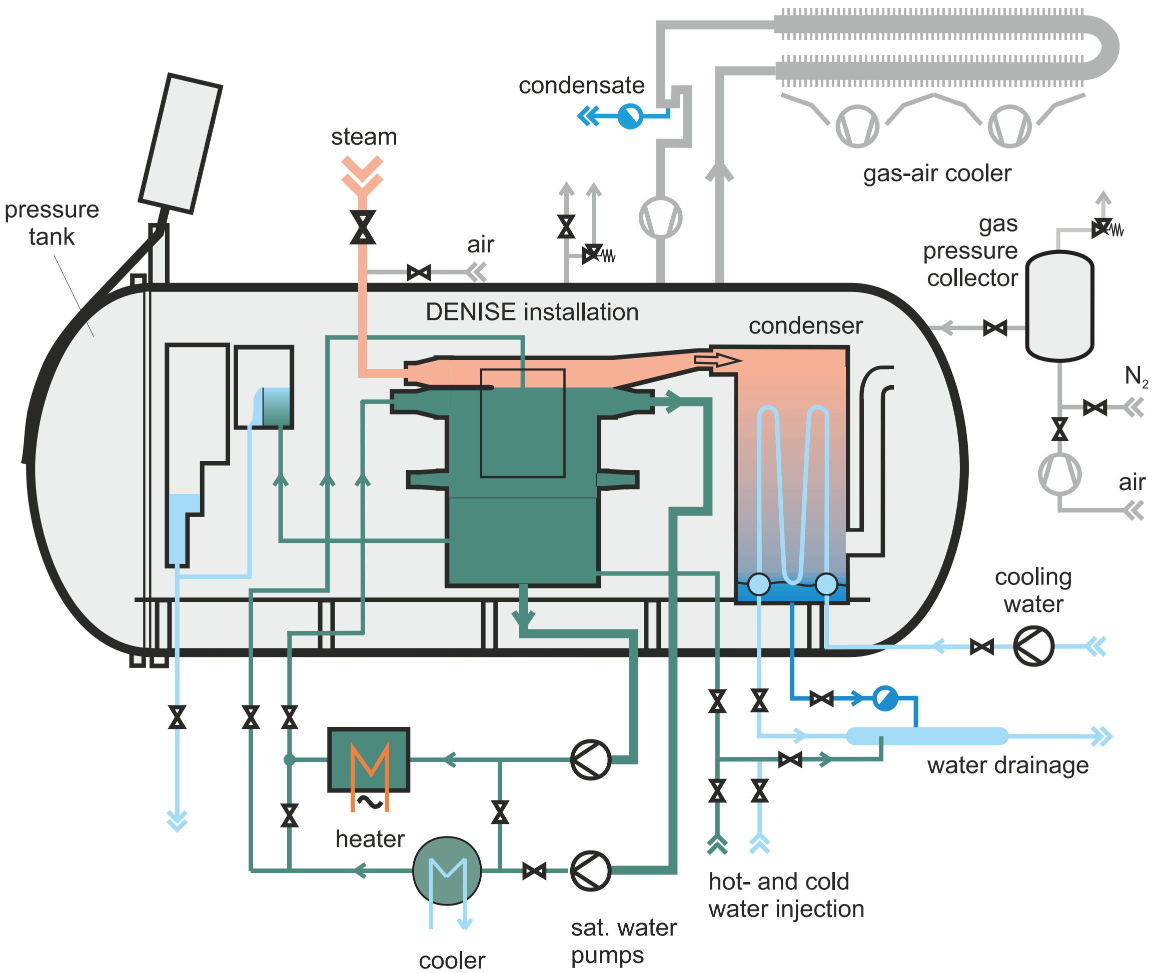

Figure 3: TOPFLOW pressure tank with DENISE installation

Table 1: Experimental matrix for stratified flow experiments

Property	Reference value	Extremes	No. of variations
Pressure	50 bar	25 .. 50 bar	2
Subcooling	100 K	0 .. 150 K	4
Water flow rate	2 kg/s	0 .. 6 kg/s	4
Steam flow rate	250 g/s	250 .. 600 g/s	3
Flow direction (W1/W2)	1/0	1/0 .. 0/1	6

Processed data from these measurements, like the relative temperature profiles shown in Figure 5 and 6 provide comparable results for the development and validation of CFD-models for a series of experiments with sub cooling of 100 K. For co-current flow Figure 5 shows that the effect of steam condensation at the stratified surface is very small if the mass flow rate is high. The hot condensate that builds up at the gas-liquid interface forms a very thin layer and is flushed out of the experimental facility very fast. Therefore, in this case the condensation effect is not well observable with local instrumentation as fixed thermocouples are. Nevertheless, the condensation effect is quantified using overall heat balances of the facility.

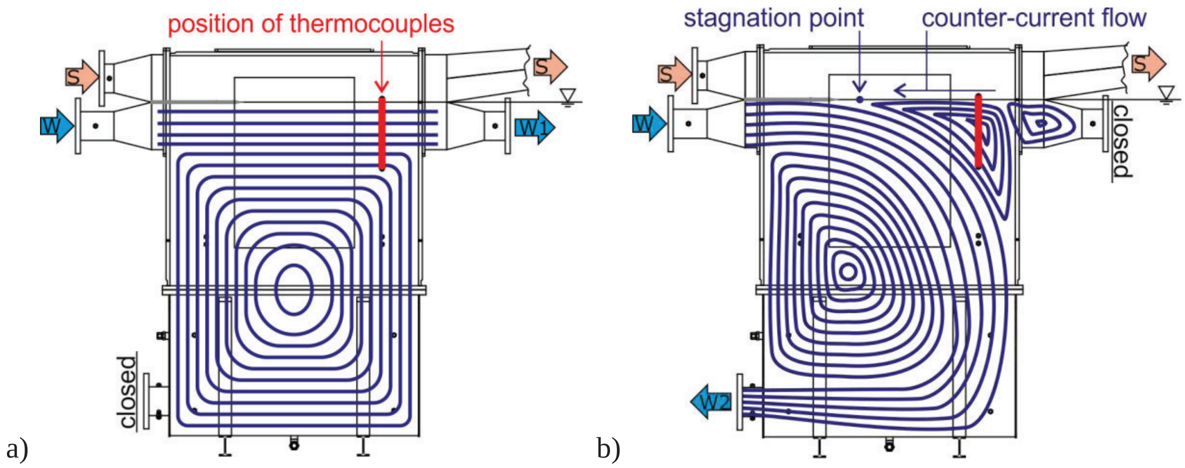

Figure 4: Flow conditions in terms of idealized streamlines for (a) co-current and (b) partly counter-current stratified flow experiments. The red line shows the position of thermocouples presented in Figure 5 and 6.

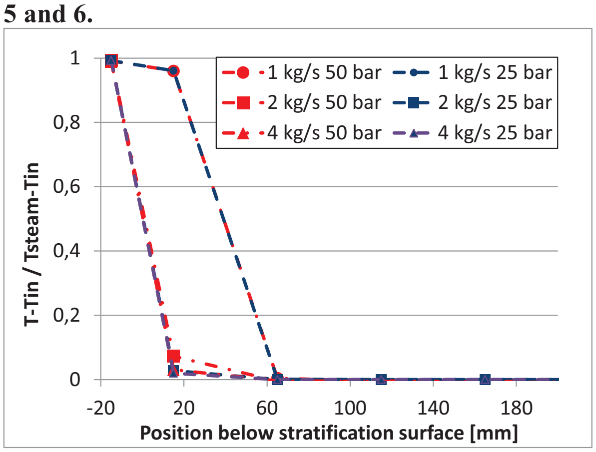

Figure 5: Temperature profiles of experiments with pure co-current flow (Figure 4 a)

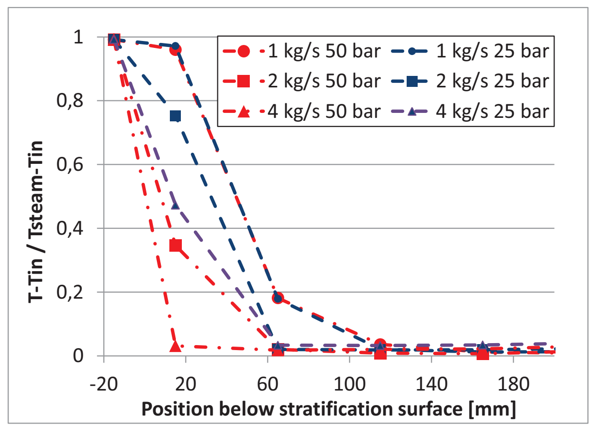

Figure 6: Temperature profiles of experiments with partial counter-current flow (Figure 4 b)

If the injected mass flow rate is low (e.g. 1 kg/s), a thick layer of saturated water forms up at the interface and the condensation is determined by diffusion instead of the water flow turbulence.

In contrast to that, the partly counter-current flow experiments show comparable results. Thanks to a recirculation eddy, condensate is trapped in the top right corner (in Figure 4b behind the stagnation point) and the profile can be analyzed and compared to CFD-simulations for validation purposes, because it shows characteristic results for different conditions.

3. JET EXPERIMENTS

The second set of experiments was conducted in the same facility with a lower water level and with a water injection at the top. The jet nozzle consists of a flow straightener, a conical part and a straight cylindrical nozzle with L/D=10 and a diameter of 19.8 mm. In order to prevent steam cross-flow, a steam guiding wall was installed (see the orange line in Figure 7) with steam opening at the top and strainers (dashed line).

Temperature and dynamic pressure was measured inside the condensing water jets at two different positions - at the jet nozzle exit (z=0 mm) and after z = 500 mm free falling length. A lance (see Figure 8) moves the sensors through the jet and profiles are recorded along a line. Figures 9 and 10 show lance profiles for an experiment with the following parameters: p=25 bar, T_{in} = 174 °C, steam/water, m_{in}=1.5 kg/s.

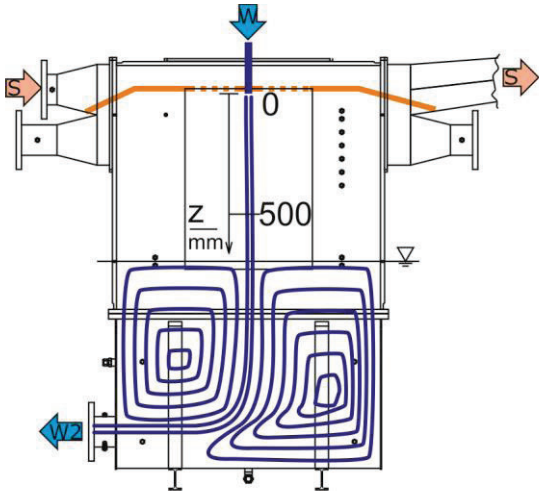

Figure 7: Flow conditions in terms of idealized streamlines (blue) for the jet flow experiments and steam flow guides (orange).

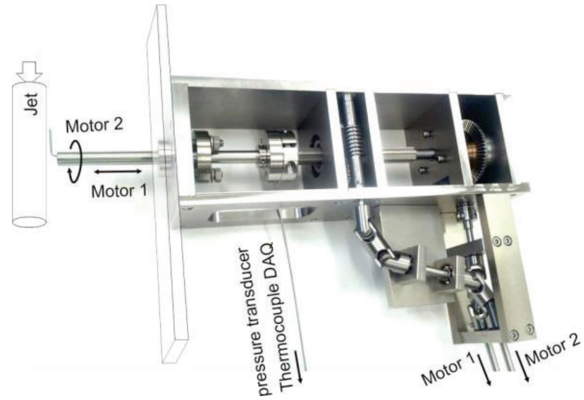

Figure 8: Thermocouple and dynamic pressure lance with gear for measuring profiles inside the condensing jet.

Three components are shown in the plots. Small points represent single measurements of temperature and pressure and the line is a moving average over 1 mm to give an orientation. The most reliable information is given by the box plots. They show a statistical approach for the moments when the lance stopped in order to measure for 5 seconds. In the profiles it is clearly visible, that the jet develops between the two different positions. At the inlet, the velocity profile is a typical developed turbulent type, while the dynamic pressure of the condensed jet is much broader and more fluctuating. The temperature profile shows the effect of condensation and higher surface roughness. The average jet profile shows, that already 60 % of the potential condensate was absorbed in between the two lances.
The experimental matrix is given in Table 2.

Table 2: Experimental matrix for jet flow experiments

Property	Reference value	Extremes	No. of variations
Pressure	50 bar	25 .. 50 bar	2
Subcooling	100 K	0 .. 200 K	6
Water flow rate	1 kg/s	0.25 .. 2 kg/s	5
Steam flow rate	300 g/s	150 .. 800 g/s	(applied)
Gas medium	steam	Steam / air	2

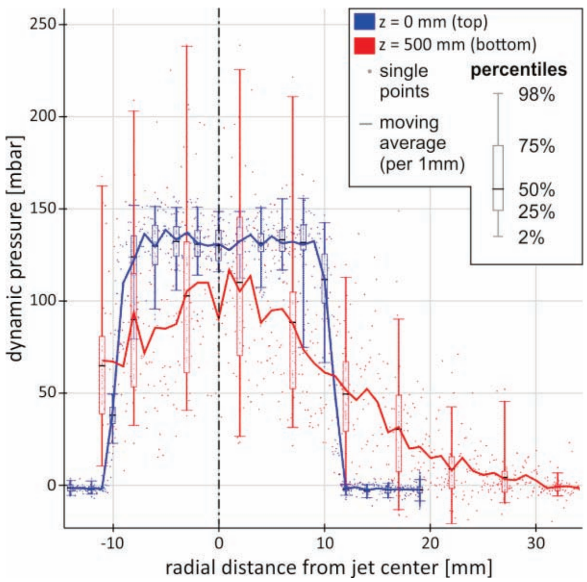

Figure 9: Dynamic pressure profile at two positions inside a condensing jet.

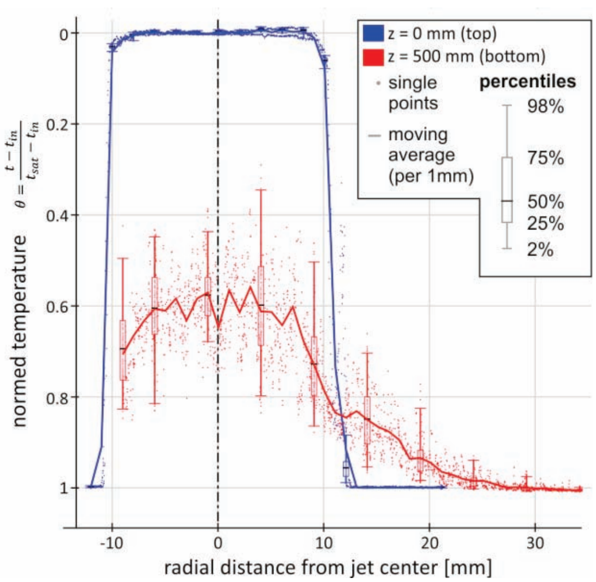

Figure 10: Normed temperature profile at two positions inside a condensing jet

4. ENTRAINMENT EXPERIMENTS

In the third series of experiments, water has been injected at the top of the basin. The water jet falls 100 mm downwards through the steam atmosphere and hits the stratified water surface, carrying steam into the bulk in most cases. 95 experiments have been conducted at conditions shown in Table 3. Figure 11 shows still images of the high speed camera observation for three experiments with the same mass flow rate of 1 kg/s and pressure of 50 bars but different injection temperatures (200 K, 50 K and 1 K sub cooling).

Table 3: Experimental matrix for jet flow experiments

Property	Reference value	Extremes	No. of variations
Pressure	50 bar	25 .. 50 bar	2
Subcooling	100 K	0 .. 250 K	6
Jet flow rate (W)	1 kg/s	0.5 .. 3 kg/s	4
Stratified flow rate (W3)	0 kg/s	0 .. 1 kg/s	2
Steam flow rate	150 g/s	100 .. 300 g/s	3
Gas medium	steam	Steam / air	2

According to the literature (Bin [3]), the entrained steam flow rate mainly depends on the jet velocity. Therefore, the observed differences in gas content below the water surface mainly depend on the condensation at different sub cooling conditions. In order to make experiments comparable and to extract quantitative data from the observation, image processing is used. Figure 12 shows the result of background subtraction, binarization and time averaging treatment on four seconds recorded at 600 fps in terms of interphase frequency distribution. The relative frequency of a gas-liquid interphase along the camera view in each pixel is shown. It can be assumed that a visible interphase is a representation for liquid content if above the water level and for gas if below. Therefore, these images may be compared to integral gas fraction results from CFD simulations, which is useful for developing special models for high shear flow conditions. Many experiments can be compared to each other by extracting the penetration depth from these pictures. Figure 13 shows the comparison of all the experiments with an injection mass flow rate of 1 kg/s.

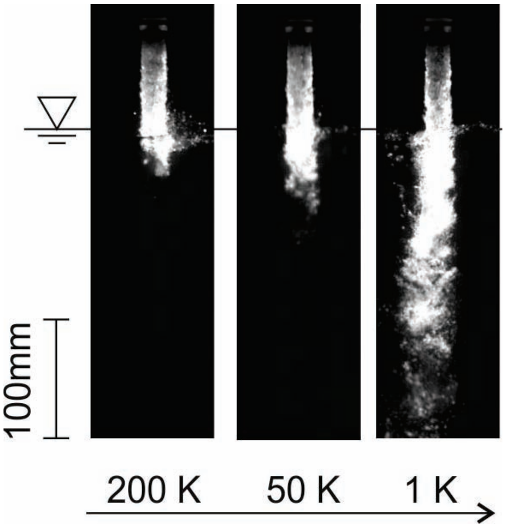

Figure 11: Instantaneous high speed camera images of plunging jet experiments at 50 bar and 1 kg/s injection mass flow rate for three different sub-cooling conditions.

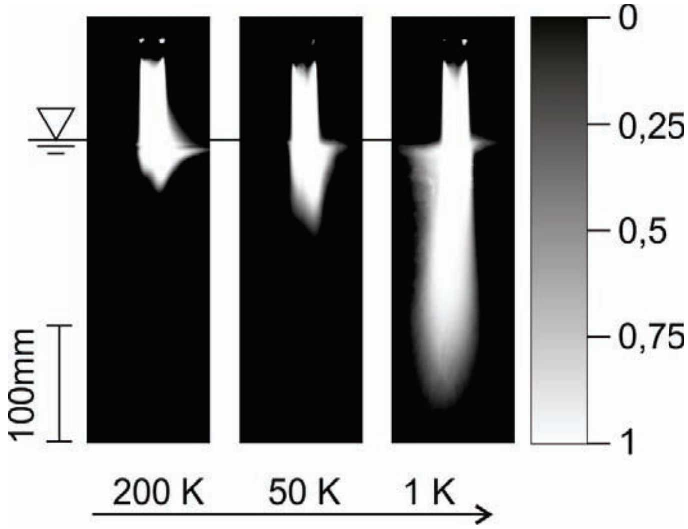

Figure 12: Interface frequency distributions derived from the complete series of images analogue to Figure 11

Furthermore, it is observed that a residual of non-condensable gas is in solution of the water - also during nearly saturated experiments. The visible amount is so small, that it is presumed, not to influence the condensation itself. On the other side, there is a positive effect of the non-condensables. When a steam bubble or meniscus collapses at the plunging point, a very small gas bubble is left over. The diameter is so small, that the bubble has neglectable buoyancy but it is big enough to be visible within the high speed camera. So it may be used as a tracer for the liquid phase velocity measurement, with particle tracking methods. It is possible to use stereoscopy for 3D-reconstruction and statistical methods for turbulence estimation.

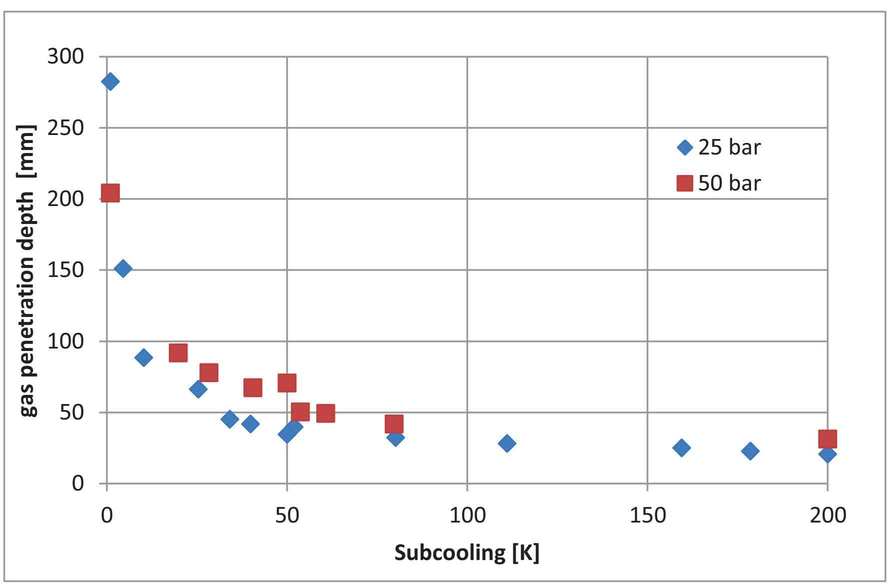

Figure 13: Gas penetration depth of plunging jet experiments with 1 kg/s jet mass flow rate at different pressures and inlet subcooling

5. CONCLUSION AND OUTLOOK

CFD-grade generic experiments have been shown for non-adiabatic stratified steam-water flow, jet flow and for plunging liquid jets. Exemplary analysis approaches have been pointed out to show how the results may be compared to CFD simulations. For stratified flow, the temperature distribution in the condensation layer can be used especially for counter-current flows. For jet flow experiments, lance profiles with dynamic pressure and temperature distributions are a good starting point for comparison. For plunging jets, the visual high speed observation can be used to extract distributions of phase content, velocity and turbulence inside the continuous water phase. Analysis and summary of the measured data is ongoing and promising.

6. REFERENCES

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