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TOPFLOW-PTS AIR-WATER EXPERIMENTS ON THE PHASE SEPARATION IN THE ECC NOZZLE AND THE ECC WATER MIXING DURING PTS SCENARIOS

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Abstract

In two-phase Pressurized Thermal Shock scenarios several thermal hydraulic phenomena, such as direct contact condensation, entrainment of steam bubbles and multi-scale momentum transfer are involved. The TOPFLOW-PTS experimental assembly represents a 1:2.5 scaled model of a PWR downcomer, cold leg with emergency core cooling injection and a pump simulator. It is build up for the development and validation of CFD models. The setup is highly instrumented – a large number of thermocouples, an infrared and a high-speed camera as well as wire mesh sensors are used to obtain CFD-grade data. As a first step air-water experiments were done with the special aim to investigate the behaviour of the liquid jet from the ECC injection into the cold leg. They indicated that the jet momentum at the impact position is very important for the mixing process and stratification inside the ECC nozzle needs to be considered in CFD calculations.

Introduction

The structural integrity of the Reactor Pressure Vessel (RPV) has to be guaranteed for all imaginable accident conditions. Having in mind that highly irradiated material tends to brittle failure at thermal shock scenarios, the knowledge about thermal stresses is important for the long term safety evaluation of Nuclear Power Plants (NPP). Therefore the local and temporal thermal loads on the RPV wall are an important input for material stress analyses.

In a hypothetical Loss of Coolant Accident (LOCA) in a Pressurized Water Reactor (PWR), the primary pressure drops down to saturation pressure and two-phase flow may occur in the primary circuit. The lost water inventory is automatically compensated by several safety systems, injecting cold water. We speak of Pressurized Thermal Shock (PTS) if this cold water approaches hot walls of pressurized containers. The location of possible thermal shocks depends on the position of the Emergency Core Cooling (ECC) injection and is different for the existing designs of the NPP. The water level in the system next to the ECC injection governs the possible flow patterns and is therefore the most important boundary condition to distinguish between different simulation strategies. In this paper we will discuss the *multiphase flow* which develops when an *inclined ECC injection pipe* inserts cold water into the partially filled cold leg (CL) of a PWR. A potential PTS may occur at the hot RPV wall when the cold water flows into the downcomer. The mixing between the cold injected water and the hot water in the primary circuit controls the thermal loads on the wall.

This mixing process involves a variety of thermal hydraulic phenomena, such as direct contact condensation, stratification between hot and cold water, entrainment of steam bubbles and multi-scale phase momentum transfer. Therefore it is difficult to predict in a simulation. Conventional 1D system codes are not designed to resolve flows, which are governed by 3D multiphase phenomena like this one. Therefore Computational Fluid Dynamics (CFD) codes are currently being qualified for such problems. The models are capable to predict the single thermal hydraulic phenomena as described by Lucas [1] up to now, but they have to be validated for cases in which the interaction between different sub-phenomena has to be considered.

1. TOPFLOW-PTS

A consortium of HZDR, EDF, CEA, AREVA, ETHZ, IRSN and PSI cooperates to conduct several experiments, dedicated on the development of CFD-models, capable of simulating the various PTS-relevant flow phenomena together. A French 900 MWe CPY PWR loop acts as prototype for the 1:2.5 scaled model that covers a pump simulator, the complete cold leg with a 30° inclined ECC injection and the downcomer. Figure 1 shows the model downcomer (DC) in red, the cold leg (CL) in green, the pump simulator (PS) in dark yellow and the media supply and discharge in blue.

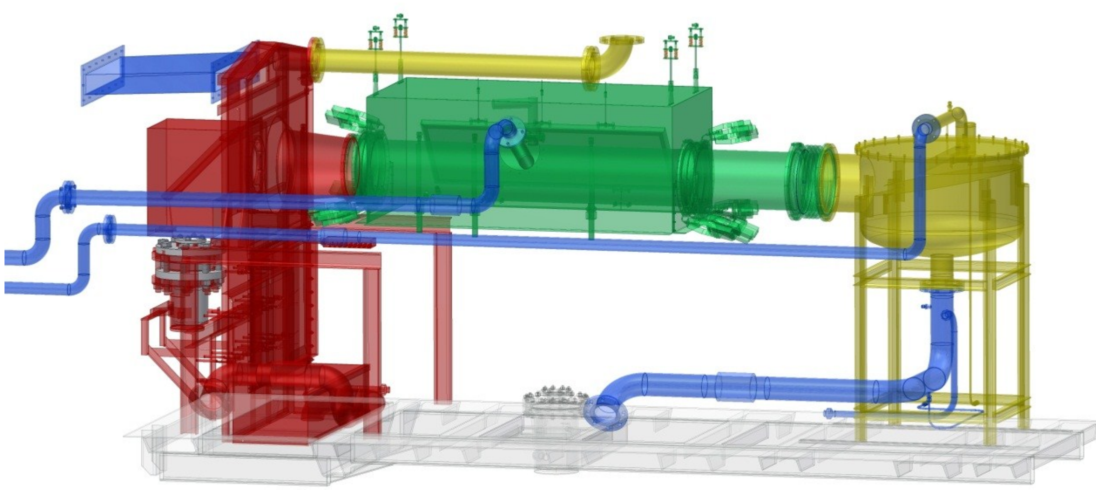

Figure 1 TOPFLOW-PTS test rig

The test rig is instrumented with 196 thermocouples (TC), two pairs of wire mesh sensors (WMS), an infrared (IR) camera and a high speed (HS) video observation along the cold leg. Figure 2 gives an overview of the measurement positions inside the model. A part of the TC is fixed inside a special heat flux probe (HFP), simulating the wall heat transfer from the RPV wall to the fluid. For a detailed description see Péturaud [2].

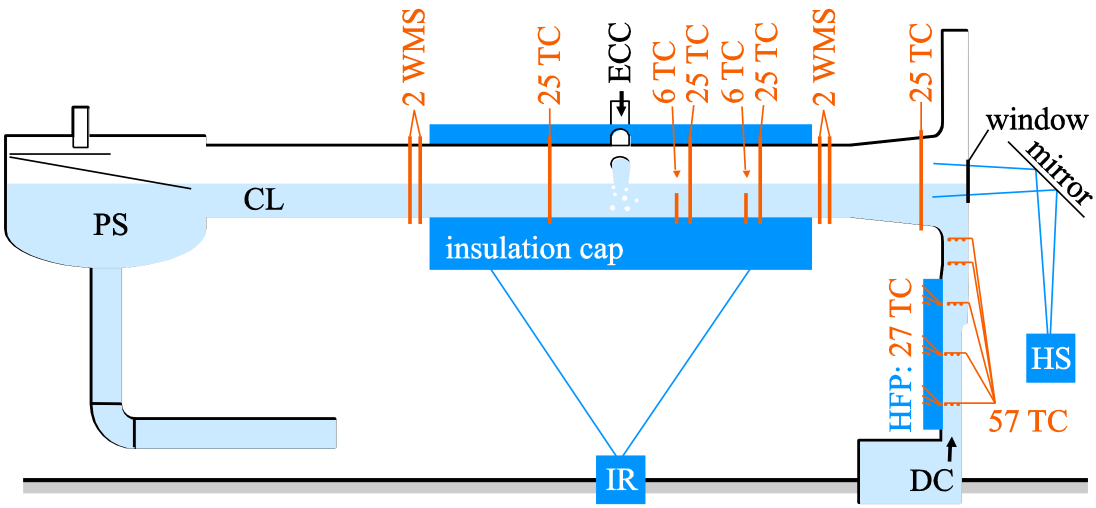

Figure 2 Instrumentation of the PTS rig

For the experiments the TOPFLOW facility of the Helmholtz-Zentrum Dresden-Rossendorf is used. A special pressure tank technology makes it possible to conduct steam/water experiments at pressures up to 50 bars and 264 °C under pressure equilibrium. This allows the use of thin containers with windows. For further reading on the pressure tank technology see Vallée [3].

2. Experiments on Stratification

The first set of experiments was dedicated to the stratification inside the ECC pipe and at the nozzle. To show how important the stratification is, a comparison is visualised in Figure 3. Two cases are to be considered. The momentum I of the ECC jet is well defined in the case of a filled ECC nozzle as shown in Figure 3a) and is $\overline{I_a} = \bar{I}\left(A_a = \frac{\pi}{4} D^2\right)$ in equation (1).

$$\bar{I}(\mathrm{A}) = \dot{m}_{ECC} \cdot \overline{u_{out}}(\mathrm{A}) = \frac{\dot{m}_{ECC}{}^2}{\rho_W \cdot \mathrm{A}} \qquad (1)$$

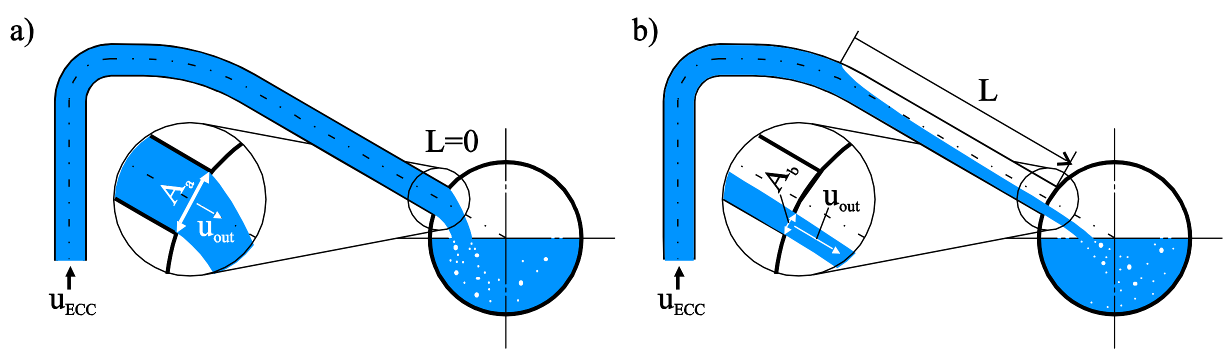

Figure 3 Comparison of the ECC-jet momentum between filled pipe (a) and stratified flow (b)

If the water detaches inside the ECC pipe, a stratified flow establishes as shown in Figure 3b) and the water flow accelerates to supercritical conditions along the inclined section. Assuming a remaining water flow area of $A_b = A_a/4$, the jet momentum and the flow velocity consequently quadruples at the same boundary condition. This results in a different impact point and angle into the water surface. This leads to a significant change of bubble entrainment and turbulence production. Therefore it has a major impact on the mixing process.

For the scaling of the experimental conditions related to original plant scenarios the Froude number Fr_{ECC} is applied. Also it is used to scale the mass flow rate similar to the reactor conditions with the velocity u_{ECC} of the ECC-line input, the density of the fluids ρ_L & ρ_G , the gravitational acceleration g and the ECC pipe diameter D. It will be used as dimensionless flow rate in this paper.

$$Fr_{ECC} = u_{ECC}\sqrt{\frac{\rho_L}{(\rho_L-\rho_G)\cdot g\cdot D}} \tag{2}$$

3. Analysis

Since the TOPFLOW-PTS installation is designed for hot steam-water experiments at pressures up to 5 MPa, it is mainly made of steel and the ECC-pipe is not transparent. To measure the stratification, two approaches have been used. The position of the detachment inside the pipe was measured from the outside by a manual ultrasound probe and the resulting flow pattern in the CL was observed with the high speed camera (c.f. Figure 2). The gas flow field was calculated afterwards with a digital bubble tracking velocimetry of the entrained bubbles below the water level of about 55 % in the CL-simulator.

3.1 Ultrasound measurement

The position of the transition from filled pipe to stratified flow was measured by manually shifting an ultrasound probe along the upper wall as shown in Figure 4. When the pipe is filled, the ultrasound signal shows reflections of the opposite wall (d+D) through the water and a second harmonic (d+2D) reflection. In the air pocket above the stratified flow, the ultrasound is damped, though there is just the signal of the metal/air surface (d).

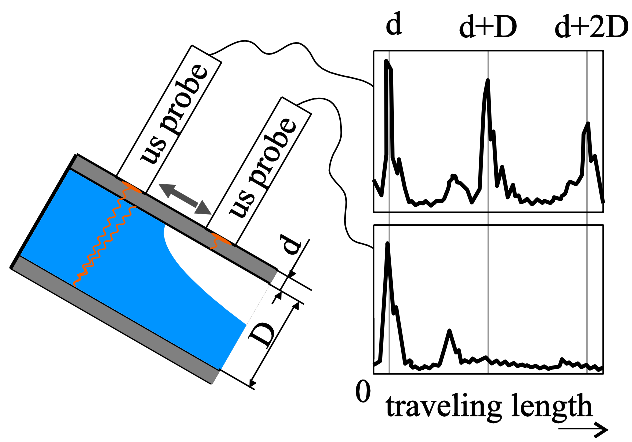

Figure 4 Ultrasound measurement

The positions of the ultrasound measurement in terms of multiple diameters are shown in Figure 5 together with the constructional restrictions. The three locations were the detachment position could not be detected are a flange, the ECC nozzle and the insulation cap (c.f. Figures 1 and 2 to 5).

3.2 Experimental procedure

The measurement was started from an initial state for which the ECC flow rate was larger than $Fr_{ECC.max} = 1.3$. Under these conditions the ECC pipe is completely filled with water and no stratification occurs. Then the mass flow rate was stepwise decreased until $Fr_{ECC,min} = 0.43$. In each of the 25 steps, the detachment position was noted and a set of 1000 high speed camera pictures was taken. Afterwards, the flow rate has been increased similarly with 15 steps. The results in Figure 6 show the first detachment of the pipe flow at $Fr_{ECC} < 0.75$ and a hysteresis between 0.7 and 0.8. With rising flow rate, an instantaneous jump from $7.5D$ to 0 is observed at $Fr_{ECC} \cong 0.8$.

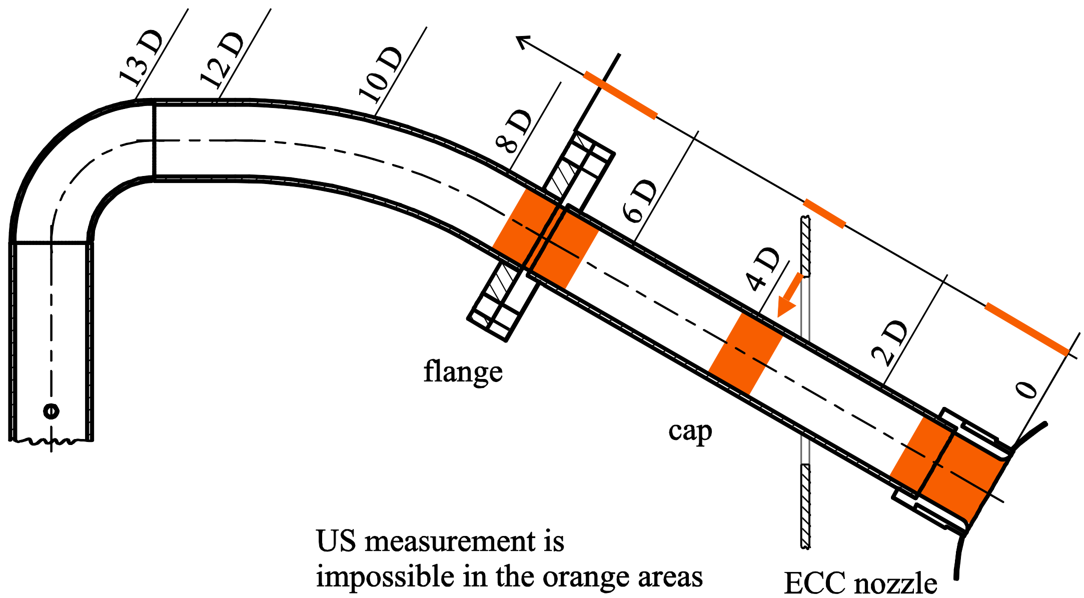

Figure 5 Relative position of the ultrasound measurement with restricted areas

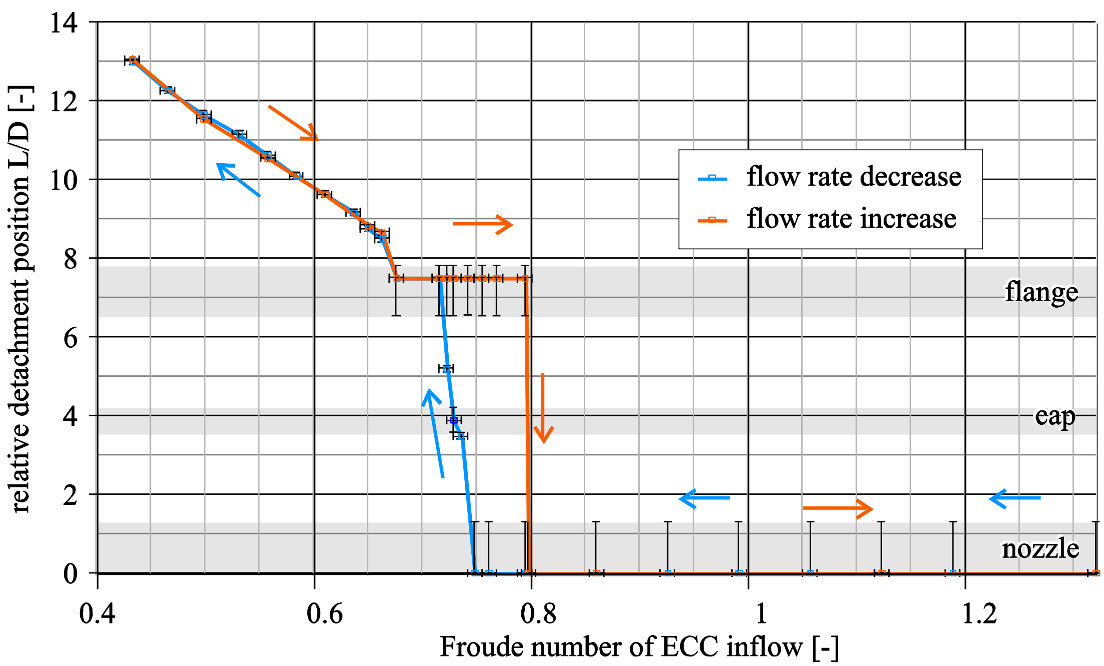

Figure 6 Results of the detachment position ultrasound measurement with hysteresis

3.3 Digital Bubble Tracking Velocimetry

The high speed camera is installed at the downcomer side of the experimental model and is directed into the cold leg, observing the impingement area of the ECC injection (c.f. Figure 2).

Figure 7 shows two exemplary images at the same ECC flow rate. The left was captured with a shutter speed of 200 fps and focused on the nozzle and the free falling ECC jet above the water surface. The bubbles below the water are overexposed and blurred but the jet is clearly visible. The focus plane in the optical medium water is different to the plane in the air, so the camera can either focus on the jet in the air (left image) or on the bubbles at the impingement zone (right image). Furthermore, the illumination comes from the top of the cold leg (see white spot in both images) and has an elliptical form. So the bubbles are better illuminated than the jet and in order to observe and track the bubbles, the shutter speed is set to 700 fps in the right image.

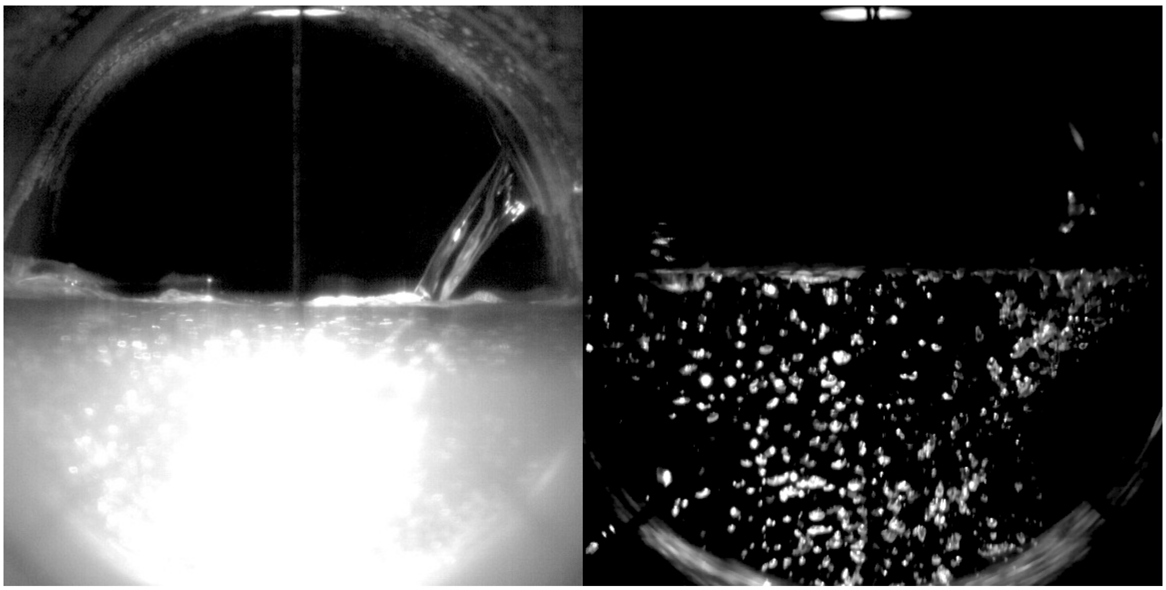

Figure 7 High speed camera images with same mass flow rate and different camera settings, left is for jet observation and the right image is used for bubble tracking

To evaluate the ECC jet stratification using the camera, both observations can be used. The bubble tracking method has been chosen, because it also allows assessing the gas fracture flow field, which results from the stratification.

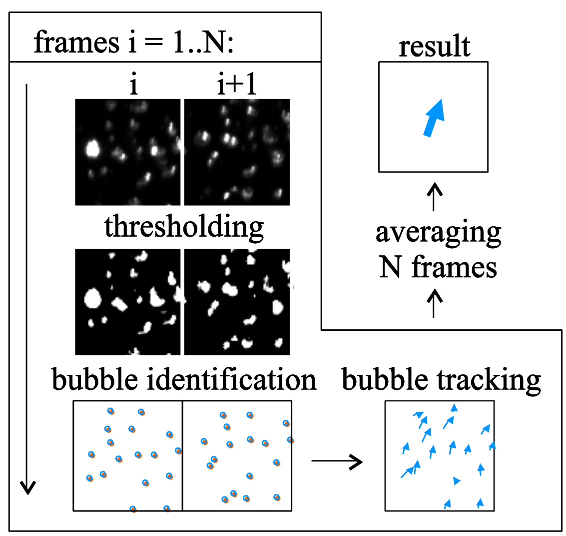

Figure 8 Image processing method

Simultaneous to the ultrasound measurement of the phase separation point in the ECC line, the high speed camera captured $N = 1000$ frames focused to the bubbles below the water at a shutter speed of 700 fps. Afterwards the resulting pictures have been processed with a digital method shown in Figure 8. Every frame was binarized with a local adaptive threshold method according to Bernsen [4] and the bubbles in two subsequent frames were tracked. All the resulting vector fields were averaged in time and in boxes of 36x36 pixels in order to improve the statistical base.

Results are shown in Figure 9 for flow rates outside of the region in which hysteresis occurs (observed in the ultrasound measurement - c.f. Figure 6) and in Figure 10 at one flow rate inside this hysteresis region. Orange arrows always represent the flow rate increase condition and blue arrows the contrairy. The geometrical position of the outer cold leg wall, the ECC injection nozzle and the water level is represented by a green line. Both velocity fields are plotted in one diagram in Figure 9 in order to evaluate the difference between rising and falling flow rates. For $Fr_{ECC} = 1.12$ and $Fr_{ECC} = 0.5$ (Figure 9), the angle and the length of the different colored vectors are similar, so there is no hysteresis effect in these two conditions. The velocity fields in Figure 10 are plotted side by side, because the difference is obvious and hysteresis can be asumed. There are two fundamentally different flow regimes. At flow rates above $Fr_{ECC} = 0.8$ (compare Figure 9 – right) the jet impinges at a point closer to the injection compared to flow rates below $Fr_{ECC} = 0.7$ (compare Figure 9 – left). This implies a naerly vertical falling jet at high flow rates, which is coherent to the observation of a filled ECC line at the ultrasound measurement.

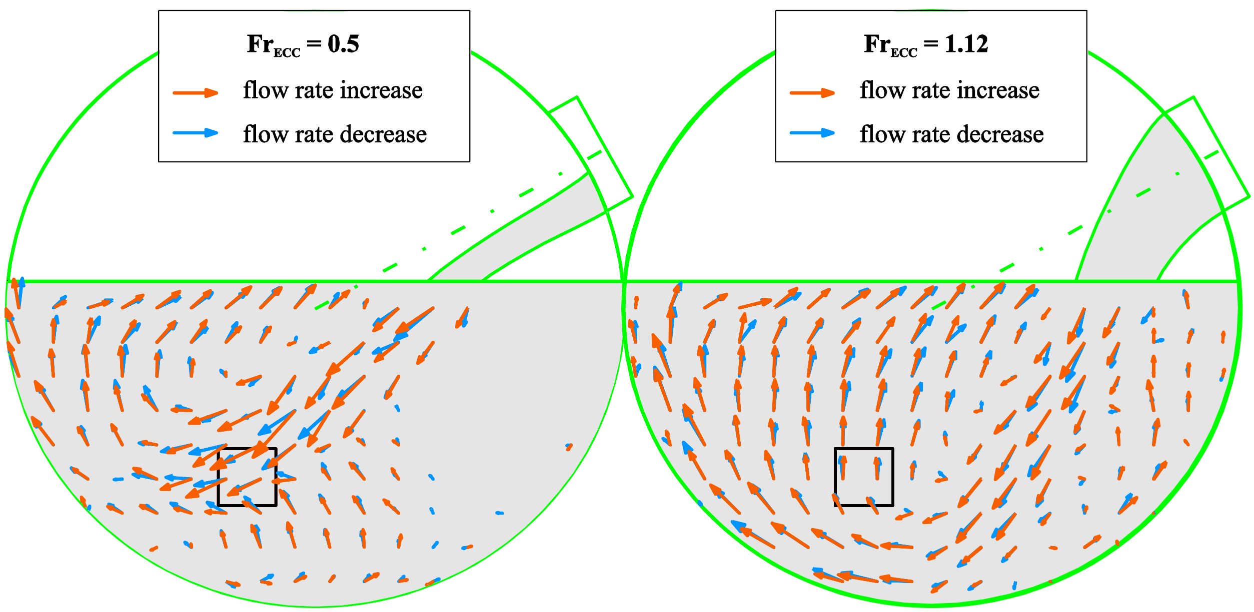

Figure 9 Averaged bubble velocities at Froude numbers above and below the hysteresis

The averaging of different bubble tracks has to be evaluated carefully, because the illumination can not be compared to a light sheet as in particle image velocimetry − it is far thicker. The depth of the illuminated region is big enough to register bubbles rising up in front of others that travel downwards for example. Therefore, the average velocity can just be used to evaluate the overall gas flow pattern, but it can not be compared to absolute gas velocities from a simulation. Principally, it would be possible to calculate different velocities for every averaging area by other statistical approaches, but this was not needed here.

Comparing the advantages of ultrasound and bubble tracking, it is obvious, that a manual method cannot be used in high pressure experiments inside the pressure tank. The installation of some fixed ultrasound probes on the ECC pipe would be useful, but high temperature and pressure-proof probes are not tested at TOPFLOW yet. The bubble tracking method needs no further installation for steam/water experiments and it provides the main information. Different averaging regions may also give other insights.

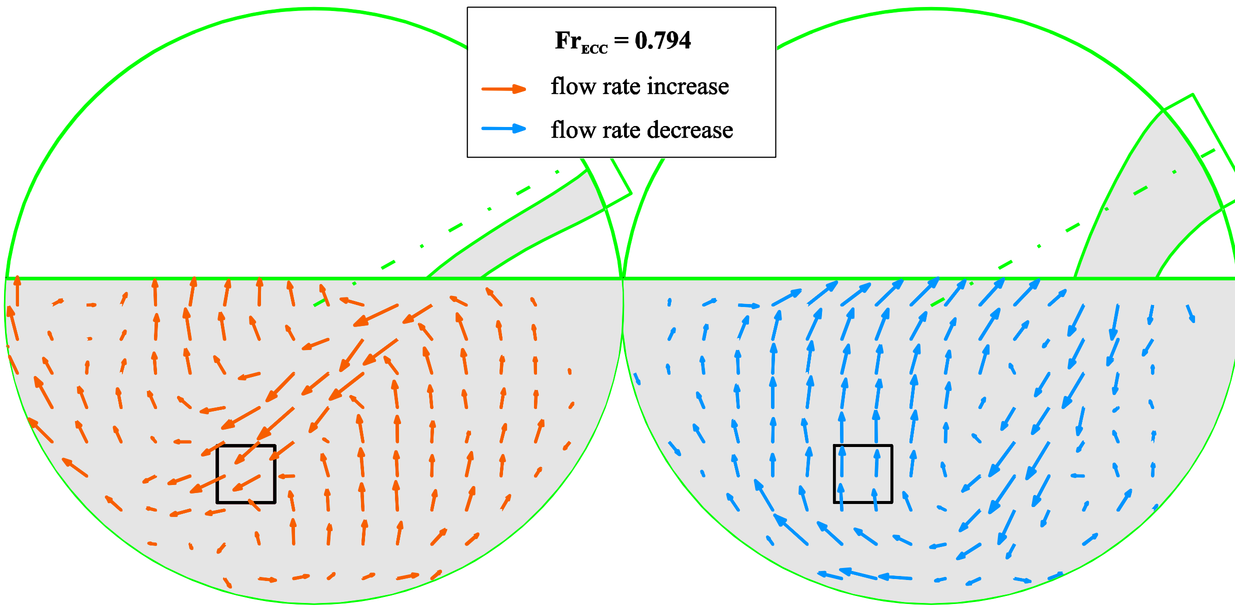

Figure 10 Averaged bubble velocities in the hysteresis area at the same Froude number

3.4 Comparison of Bubble Tracking compared to ultrasound measurement

To compare the two measurement methods for ECC flow separation using all the experiments, the average flow direction angle of a representative region of interest (ROI) in the bubble flow domain was calculated (c.f. black rectangle in Figures 9 and 10). The angle (0 being downward flow) is plotted over the ECC inflow Froude number and compared with the results of the ultrasound method in Figure 11. As in the vector plots, the bubbles rise up in the ROI if the flow rate is above $Fr_{ECC} = 0.8$ and in the hysteresis down to $Fr_{ECC} \cong 0.75$. As soon as the phases separate the free jet elongates and the bubbles travel downwards through the ROI. The changes of direction below $Fr_{ECC} \cong 0.7$ are not significant enough to draw conclusion, but the absence of hysteresis effects can be asumed. At rising flow rates, the angle also jumps up at $Fr_{ECC} = 0.8$, so the hysteresis effect is observed clearly in both methods.

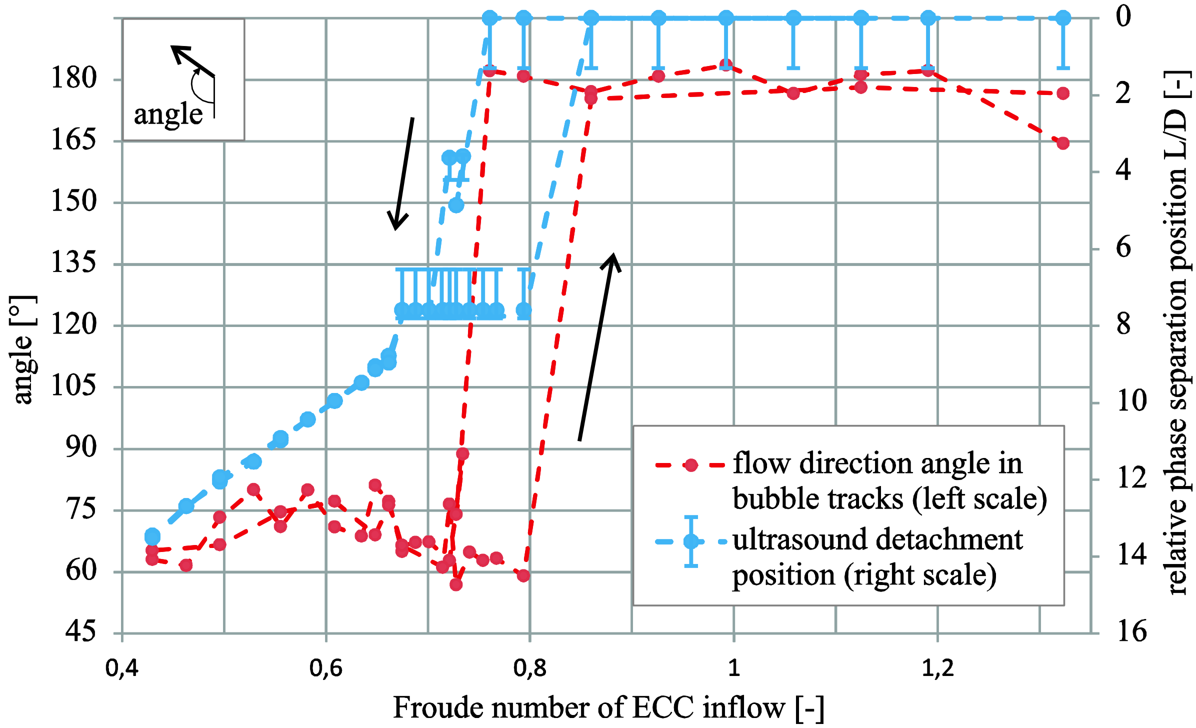

Figure 11 Comparison of flow direction angle in bubble tracking with the relative detachment position measured by the ultrasound method

4. Conclusions

The two selected measurement methods can be used to detect the phase separation in the ECC line. The results obtained from both methods show a good agreement. An accelerated ECC jet due to stratification in the ECC line was observed at flow rates below $Fr_{ECC} = 0.8$ with a hysteresis between 0.7 and 0.8. Since the water separation is situated in the area of a flange in the test rig when the hysteresis occurs (c.f. Figure 5), small gaps or a minimal eccentricity at this position is expected to be the reason. Therefore a difference between the experiment and the ideal model is responsible for the hysteresis and so it is not useful to evaluate the effect further, but to avoid the small flow rate range in the experimental series.

The phase separation inside the ECC line has a significant impact on the flow characteristics in the cold leg, represented by the bubble velocity in this paper. It can be expected that the mixing processes are considerably influenced by such stratification in the ECC line. Therefore it has to be considered as a boundary condition in the CFD validation simulation. According to the present operating experience, hysteresis occurrence is very sensitive to small geometrical differences in the upper ECC line, so it is a considerable factor of uncertainty if it would be part of the simulation.

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References

[1] D. Lucas et al., “Main results of the European project NURESIM on the CFD-modelling of two-phase Pressurized Thermal Shock (PTS)”, Kerntechnik 74(2009), 238-242.

[2] P. Péturaud, U. Hampel, A. Barbier, J. Dreier, F. Dubois, E. Hervieu, A. Martin, H.-M. Prasser, “General overview of the TOPFLOW-PTS experimental program”, submitted to NURETH-14

[3] Vallée, C.; Seidel, T.; Lucas, D.; Beyer, M.; Prasser, H.-M.; Pietruske, H.; Schütz, P.; Carl, H., “Influence of the fluid properties on co-current two-phase flows in a horizontal channel connected to a riser”, 7th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Krakow, Poland, 2009 June 28- July 03

[4] J. Bernsen,”Dynamic Thresholding of Grey-Level Images”, Proc. of the 8th Int. Conf. on Pattern Recognition, Paris, France, 1986 October 27-31