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INVESTIGATIONS ON FLOW REVERSAL IN STRATIFIED HORIZONTAL FLOW

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ABSTRACT

The phenomena of flow reversal in stratified flows are investigated in a horizontal channel with application to the Emergency Core Cooling System (ECCS) in Pressurized Water Reactors (PWR). In case of a Loss-of-Coolant-Accident (LOCA), coolant can be injected through a secondary pipe within the feeding line of the primary circuit, the so called hot leg, counter-current to the steam flow. It is essential that the coolant reaches the reactor core to guarantee coolability. Due to high temperatures in such accident scenarios, steam is generated which escapes from the reactor core vessel through the hot leg. In case of sufficiently high steam flow rates, only a reduced amount of coolant or even no coolant will be delivered to the reactor core. The WENKA test facility at the *Institute for Nuclear and Energy Technologies (IKET)* at *Forschungszentrum Karlsruhe* is capable to investigate the fluid dynamics of two-phase flows in such scenarios. Water and air flow counter-currently in a horizontal channel made of clear acrylic glass to allow full optical access. Flow rates of water and air can be varied independently within a wide range. Once flow reversal sets in, a strong hysteresis effect must be taken into account. This hysteresis effect was quantified during the present investigations. Furthermore, the test facility is capable to quantify liquid backflow rates very accurately. Lines with constant backflow ratios were added to the flow regime maps. Local experimental data is needed to expand appropriate models on flow reversal in horizontal two-phase flow and to include them into numerical codes. Investigations are carried out by means of Particle Image Velocimetry (PIV) to obtain local flow velocities without disturbing the flow. Due to the wavy character of the flow, strong reflections at the interfacial area must be taken into account. Using fluorescent particles and an optical filter allows eliminating the reflections and recording only the signals of the particles. The challenges in conducting local investigations in stratified wavy flows by applying optical measurement techniques are discussed. Results are presented and discussed allowing a better fundamental understanding of the phenomena of flow reversal.

1 INTRODUCTION

In case of a postulated Loss-of-Coolant-Accident (LOCA) in Pressurized Water Reactors (PWR) it is essential that the coolability of the reactor core can be assured to avoid a core melt accident. LOCAs involve pipe ruptures in the primary and secondary circuits which can lead to a significant loss of coolant. Such a scenario is shown in Figure 1. During such a scenario, coolant is injected by the Emergency Core Cooling System (ECCS) to avoid core uncovering or to reflood the core if already uncovered. In different ECC systems of German and American/Japanese PWRs different injection modes are used, such as cold leg injection, downcomer, upper plenum or combined hot and cold leg injection. During hot leg injection, the coolant is injected through a secondary pipe at the bottom of the feeding line of the primary circuit, the so called hot leg. It is indispensable that the coolant reaches the reactor core. The coolant has to overcome 1.53 meters inside the hot leg before it reaches the reactor pressure vessel (RPV). This design was chosen to prevent high temperature gradients between the point of coolant injection and the hot walls of the RPV. Due to depressurization and high temperatures, steam will be generated in the core. The steam escapes from the reactor core vessel through the hot leg counter-current to the injected coolant. In case of sufficiently high steam flow rates, only a reduced amount of coolant or even no coolant will be delivered to the reactor core independent of the coolant injection rate. This phenomenon is referred to as flow reversal and is also known as counter-current flow limitation (CCFL).

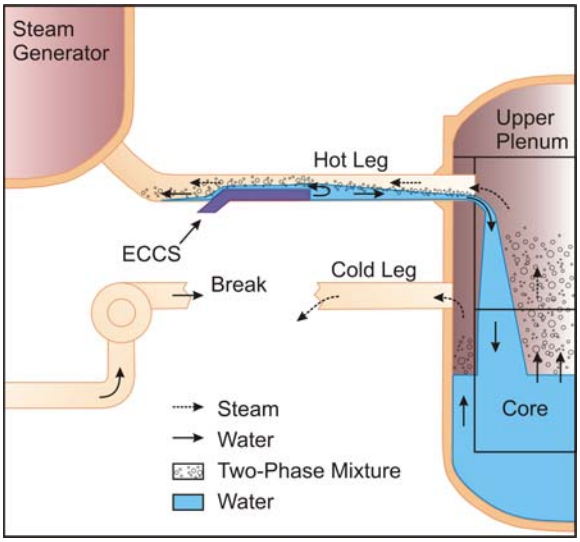

Figure 1**:** LOCA in PWR

Early work was done by Wallis in 1969 [1] and Richter et al. in 1978 [2]. Wallis investigated the stability of counter-current flows in horizontal ducts and the onset of flooding and presented a one-dimensional drift-flux model. Richter adjusted the Wallis correlation constant based on experimental investigations concerning the reflux phase in a scaled down PWR hot leg. During the Three Mile Island Accident in 1979 [3], CCFL prevented cooling water to flow from the pressurizer into the reactor cooling circuit causing the most severe nuclear accident in US-American history. Subsequently, in the field of reactor safety, special interest was taken in CCFL. Most works –both experimental and theoretical– concentrated on reflux condensation cooling (Siddiqui and Banerjee [4], Ohnuki et al. [5], Lopez de Bertodano [6], Wang and Mayinger [7], Wongwises [8, 9] and Navarro [10]). Daly and Harlow [11] focused on CCFL during hot leg injection. They conducted a numerical study and derived a model for counter-current steam-water flows, but no experimental data supported their calculations. Full scale integral experimental investigations on different ECC injection types were carried out in the Upper Plenum Test Facility (UPTF) within the 2D/3D Program [12]. The UPTF tests showed that the liquid in the hot leg was partially reversed for high steam flow rates during hot leg injection. Gargallo [13] investigated the stability of horizontal counter-current stratified flows of water and air to understand and predict the behaviour of ECC during hot leg injection. The experiments yielded flow regime maps for different water inlet heights. A one-dimensional model to predict the occurrence of reversed flow was derived: only if the flow is subcritical and the Wallis correlation is fulfilled, reversed flow sets in. The transition to subcritical flow from an initially supercritical flow occurs suddenly in form of a hydraulic jump. An analytically developed model to predict the occurrence of a hydraulic jump was presented. Furthermore, a strong hysteresis effect was noted by Gargallo [14] and Ralph et al. [15] once flow reversal set in. To return to stable stratified flow again, the air flow rate had to be reduced significantly compared to the air flow rate needed for the transition to reversed flow. Kolev et al. [16] pointed out that the analysis of ECCS flow phenomena with numerical codes is limited due to inappropriate correlations for inertia dominated liquid flows in two-phase flows caused by the lack of available experimental data.

In order to extend appropriate models on flow reversal in horizontal two-phase flows and to include them into numerical codes, local experimental data are needed. As there are still few experimental data available for flow reversal during hot leg injection in PWRs the WENKA test facility has been built at the *Institute for Nuclear and Energy Technologies (IKET)* at *Forschungszentrum Karlsruhe*. The test facility is capable to investigate the fluid dynamics of two-phase flows during a postulated LOCA-scenario with hot leg injection.

2 EXPERIMENTAL FACILITY

The WENKA test facility (Figure 2) is used to conduct investigations in counter-current horizontal two phase flows. In the ongoing investigations water and air have been used as cold simulants for cooling water and steam. The simulants flow counter-currently in a horizontal channel with a geometry analogous to that of a PWR hot leg. Water is circulating in a closed loop and air in an open loop.

Water is pumped from a primary tank (capacity 600 litres) by a centrifugal pump. Before the water enters the experimental channel below a horizontal parallel plate, liquid flow rates are measured by two independent flow meters. The plate can manually be set to heights between 2 and 22 mm. Finally, the water returns to the primary tank through the water outlet.

The counter-current flow of air is fed into the inlet path by a blower, whereby it enters the experimental channel above a manually adjustable inlet plate. The air enters the area of interest smoothly and accurate boundary conditions can be assured. Under the condition of reversed flow, a certain portion of water is carried back over the water inlet plate by the counter-current flow of air. The two phases are separated again by a cyclone upstream the experimental channel. Finally, the air is released to the atmosphere again. The separated water flows down into a secondary tank. For the present investigations, the test facility has been extended by a secondary water loop which connects the secondary tank to the primary tank. Any change of height in the secondary water tank is measured by a capacity level probe. A PID control circuit controls a pump, which conducts the exact amount of water reaching the secondary water tank coming from the cyclone. Subsequently, water flow rates are measured through a system of independent flow meters. Backflow ratios can then be calculated by dividing the amount of water measured in the secondary water loop by the amount of initially injected water into the experimental channel. The accuracy of the backflow measurements using this system lies above 99%.

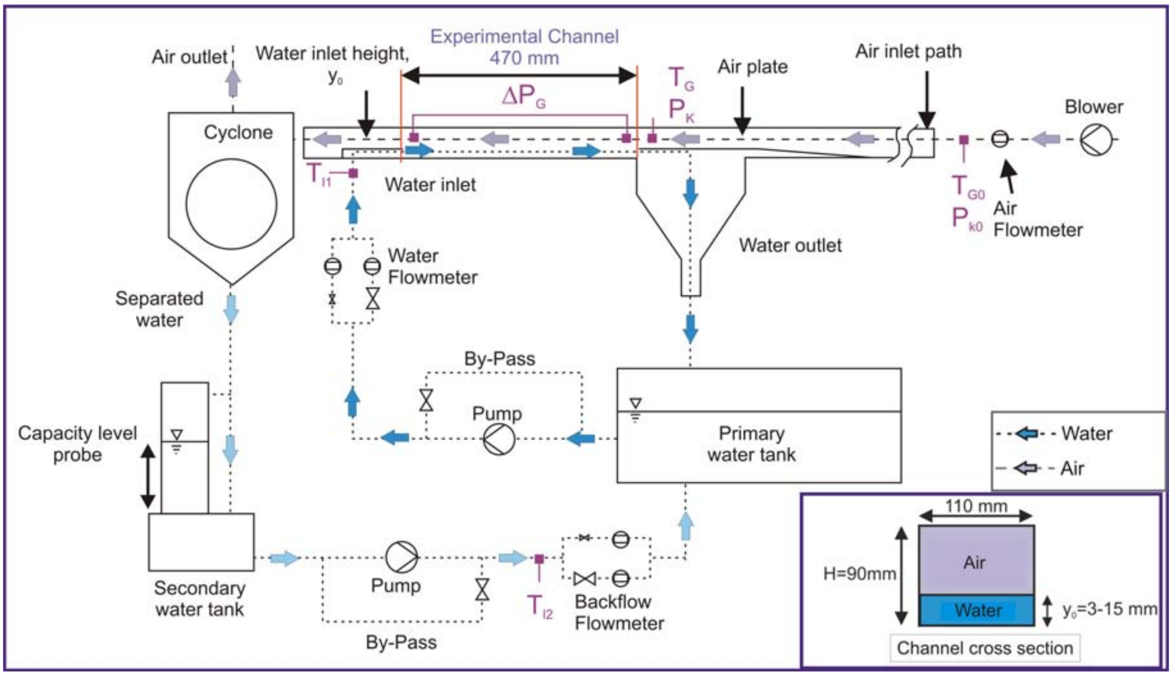

Figure 2: Schematic diagram of the WENKA test facility

Thermocouples (T) are used to measure the temperature variance in both phases. Pressure sensors (P) are used to measure the loss of pressure over the experimental channel, the static pressure of air within the air inlet path and the atmospheric pressure conditions. The data acquisition rate was set to 1 kHz.

The previously described liquid flow measurements consist of two magnetical-inductive flow meters in each water loop. Flow rates can be measured within a total range of 4 to 200 m^3/h. For very low backflow ratios the temporal change in liquid height in the secondary tank can be considered to determine flow rates below 4 m^3/h.

The area of interest of the test facility is the experimental channel, where air and water meet. The channel has a cross section of 90 x 110 mm^2 and a length of 470 mm. To allow full optical access the experimental channel was made of clear acrylic glass.

3 EXPERIMENTAL RESULTS AND DISCUSSION

Gargallo [14] encountered a strong hysteresis effect once partial reversed flow set in. In order to quantify this phenomenon a series of experiments has been conducted. The existing flow regime maps by Gargallo [13, 14] have been extended.

3.1 Flow regime map and hysteresis effect

Figure 3 shows the flow regime map for a water inlet height of y_0 = 9 mm, where the superficial gas velocity u_{GS} is plotted against the superficial liquid velocity u_{LS}. The air inlet plate was set to the same height. The transition to Partially Reversed Flow can be divided into two regions. The region in which the Onset of Partially Reversed Flow (OPRF) has a negative or no slope and the region were it has a positive slope. Beyond the Onset of Totally Reversed Flow (OTRF) the complete injected liquid will be carried over by the air. No liquid will reach the end of the experimental channel. Further details can be found in Gargallo [13, 14]. For values of u_{LS} > 0.115 m/s the OPRF coincides with the OTRF, which means that a stratified flow will immediately change into a totally reversed flow due to the extremely high gas velocities.

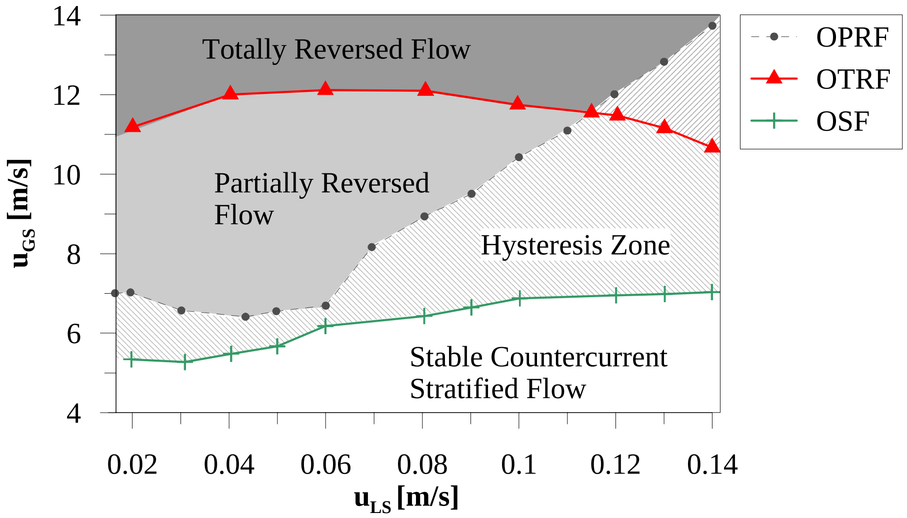

Figure 3: Flow regime map including hysteresis zone for y_0 = 9 mm.

Once Partially Reversed Flow sets in, the flow regime map changes significantly. A strong hysteresis effect affects the behaviour of the flow. The transition from Partially Reversed Flow back to Stable Countercurrent Stratified Flow occurs at much lower gas superficial velocities than the transition into the other direction. The flow regime maps were extended by the curve of Onset of Stratified Flow (OSF). For values of $u_{LS} > 0.115$ m/s, the transition to Totally Reversed Flow will now occur at lower gas velocities than the transition from Stable Countercurrent Stratified Flow to Totally Reversed Flow. This is due to the fact, that waves with high amplitudes in Partially Reversed Flow increase the contact surface of the liquid against the air flow and therefore results in a change of flow regime at lower gas velocities.

Figure 3 represents the conditions for the presented channel geometries. Some correlations to transfer the conditions to the reactor case can be found in Gargallo [13]. The aim of the current research is to describe the flow conditions by applying CFD-methods. Therefore, it is essential to provide local experimental data.

3.2 Measurement of local liquid flow velocities

To expand appropriate models on flow reversal in horizontal two-phase flow and to include them into numerical codes, local experimental data are needed. Laser-optical techniques allow measurements without disturbing the flow. With Particle Image Velocimetry (PIV) the two-dimensional flow field can be obtained by seeding the flow with particles, illuminating these particles with a light source and taking two pictures within a short time. The particle displacement and the knowledge of the time difference between the two illuminations deliver the velocities of the flow field.

Illumination of the liquid flow has been realised by a 50 mJ double-pulsed Nd:YAG laser. The laser light sheet entered the test section from the bottom to ensure uniform light intensity within the flow field. Due to the wavy character of stratified counter-current flows, the laser light will be reflected at the interfacial area. As waves propagate through the channel constantly, the laser light will be reflected into several directions depending on the momentary shape of the interfacial area. In the worst case, the laser light will be reflected directly into the camera lens, causing the destruction of the camera’s CCD chip. Furthermore, no local velocities can be obtained near the liquid surface due to the strong reflections being always present in the obtained pictures. Figure 4 shows two pictures of the same partially reversed flow at different times. As described above, the interface between the two phases changes constantly.

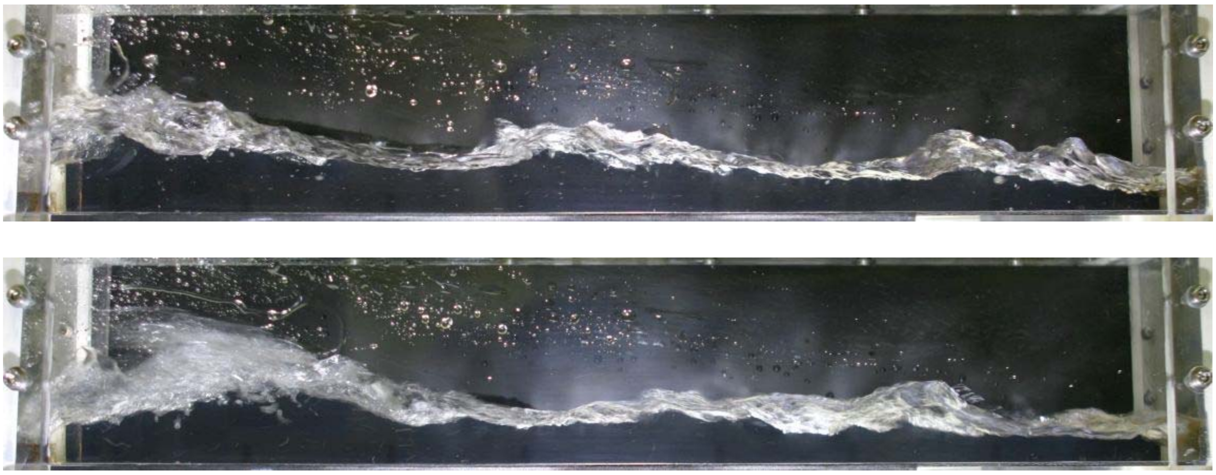

Figure 4: Pictures of partially reversed flow.

By using fluorescent particles and an optical high-pass filter in front of the camera lens, all light of the wavelength of the laser and therefore all reflections at the liquid surface can be eliminated. The signal of the fluorescent particles will pass the optical filter as the fluorescent dye will be excited by the laser light and emit light at longer wavelengths than the laser light wavelength.

In the present investigations PMMA particles dyed with Rhodamine B with a diameter $20\mu m < d_P < 50\mu m$ have been chosen as seeding particles for the liquid phase. A dosing pump connected to the primary water loop is used to adjust the seeding density. A CCD-Camera (ImagerIntense, LaVision) has been used for picture acquisition. Figure 5 shows the vector plot of an instantaneous PIV-recording. As background, the raw image of the recording is shown. The reflections at the interfacial area are eliminated and velocities are only calculated in the regions where fluorescent particles can be seen.

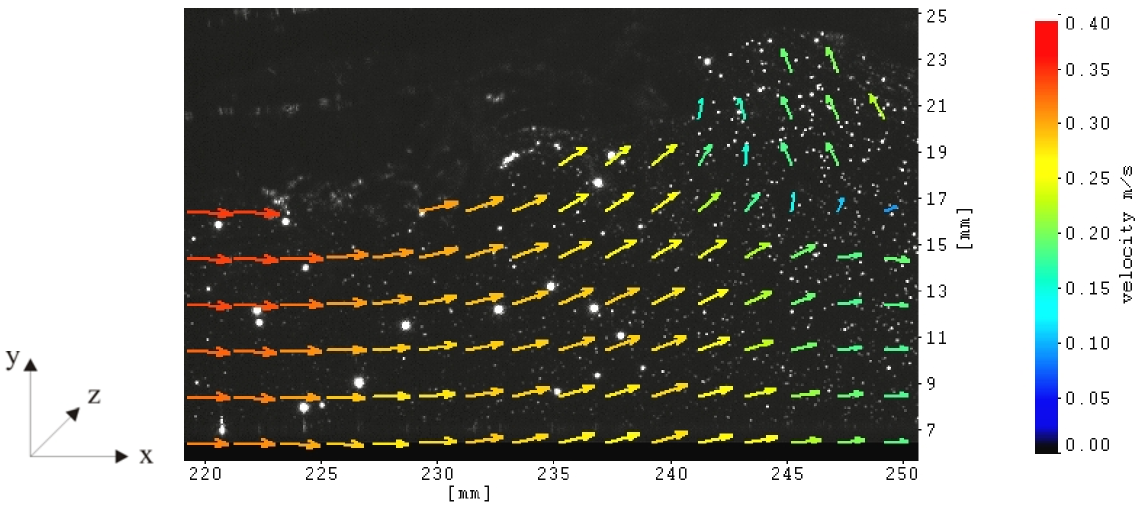

Figure 5: Vector plot of instantaneous PIV-recording.

The aim is to obtain information on the time-averaged flow quantities of the entire process. The single wave is not to be resolved during the present investigations. Therefore, a time-constant triggering mode has been chosen. Consequently, the phase interface will always change its location between the different recordings as waves propagate through the test section constantly. The flow can be separated into three different areas: the lower part of the test section with a constant film of only liquid, the middle part where waves propagate and both liquid and air can be spotted, and the upper part where no liquid can be found. Due to the wavy character of the flow, there will always be fewer particles with increasing channel height when regarding the time-averaged flow field. But to ensure accurate velocity calculations it is necessary to record sufficient particles at any point within the flow field. Therefore, the obtained velocity vector plots were each averaged over 1500 instantaneous images.

As the air in the upper part is not seeded with particles no velocity vectors are obtained during the PIV calculations. Analogously, in the middle part, velocity vectors can only be calculated and validated if liquid is present in the instantaneous recordings. The areas within the different images where no velocity vectors are obtained are locked by software methods and are not included into subsequent averaging procedures. Regarding only the instantaneous images would lead to several different appearances of the flow field due to the constantly changing interfacial area. Averaging all instantaneous velocity plots yielded a flow field where the entire middle part is filled up with velocity vectors, whereas the mean velocities are calculated as

$$\bar{u} = \frac{1}{\Delta t_{ges}} \int_{t}^{t+\Delta t_{ges}} u(\vartheta)\, d\vartheta \approx \frac{1}{N} \sum_{i=0}^{N} u_i \, . \qquad (1)$$

By using this procedure, the time-averaged movement of all waves through the entire field of interest can be caught.

3.3 Results

Figure 6 shows the velocity profiles for the same partially reversed flow recorded with different PIV recordings. The local liquid height y is plotted against the horizontal velocity component v_x in the main flow direction.

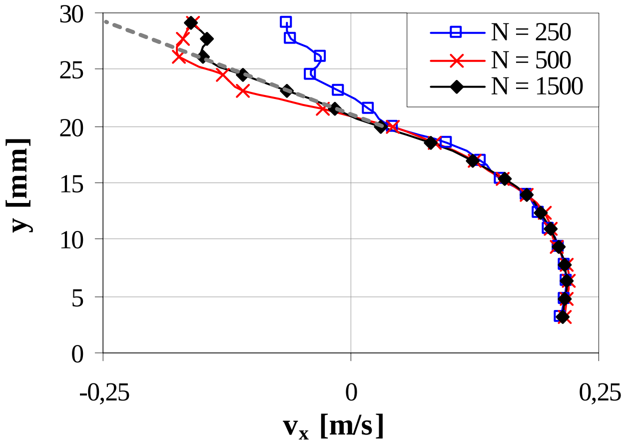

Figure 6: Convergence of velocity profiles

With increasing liquid height a bend must be noted in all lines. With increasing liquid height there will always be fewer particles available for the calculation of the time-averaged velocity profiles because of the wavy character of the liquid surface. It can be seen clearly, that with an increasing number of PIV-recordings N, the bend in the curves occurs nearer to the maximum liquid height. The trend shows that for increasing N the curves converge to the dotted line, which is believed to indicate the real velocity profile for liquid heights near to the maximum liquid height. To obtain curves converging further to the dotted line would require a significantly larger number of PIV-recordings. For the present measurements a total of 1500 PIV-recordings per point were considered as sufficient.

Figure 7 shows liquid velocity profiles for partially reversed flows with different inlet conditions of the superficial velocities u_{LS} and u_{GS} for a water inlet height of y_0 = 9 mm. The measurements were conducted in the middle plane of the channel at a position x = 235 mm downstream the liquid inlet.

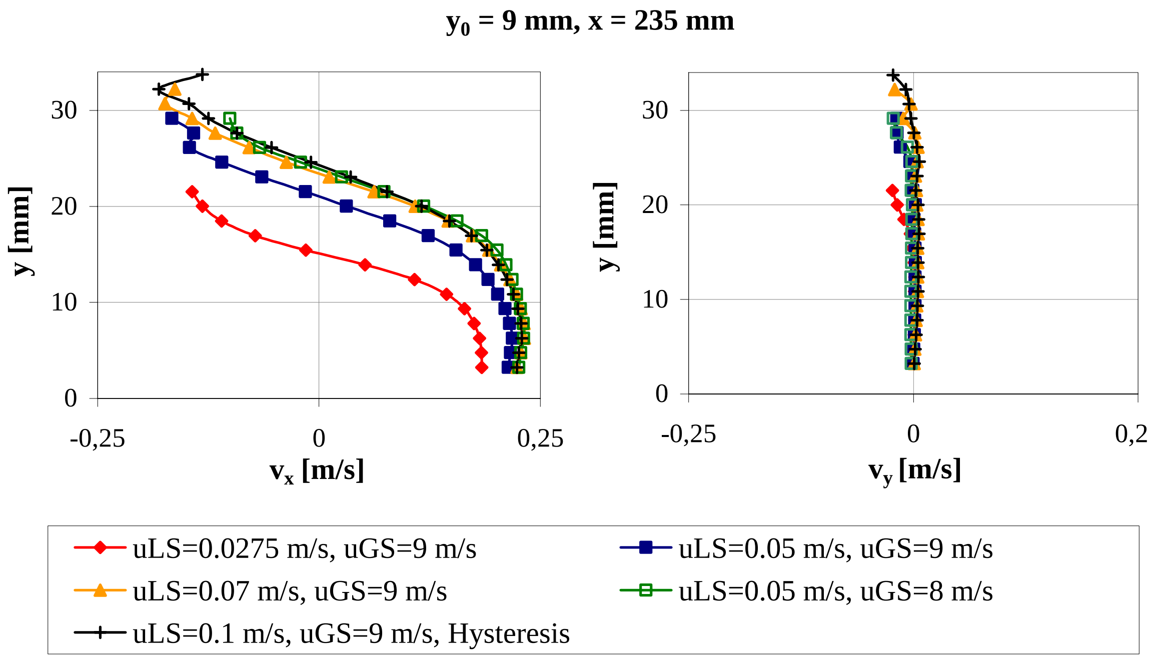

Figure 7: Liquid velocity profiles for partially reversed flows.

With increasing liquid inlet velocities u_{LS}, the local velocities v_x in horizontal direction increase. Additionally, the maximum liquid height increases. A decrease in the gas inlet velocity u_{GS} yields higher local liquid velocities in the main flow direction. It must be noted that for high liquid superficial velocities u_{LS}, a limitation in the maximum values of the local velocities v_x exists. This behaviour is in good accordance with the observation of the hysteresis effect, where a further increase of the liquid inlet flow rate does not affect a higher liquid delivery rate. Furthermore, it has been found that the velocity component v_y in vertical direction shows only low values compared to v_x.

4 CONCLUSIONS

As there are still few experimental data available for the phenomena of flow reversal during hot leg injection a series of experiments has been conducted at the WENKA test facility. The results of the ongoing investigations allow a better fundamental understanding of the phenomena of flow reversal in horizontal two-phase flows.

Once flow reversal sets in, a strong hysteresis effect must be taken into account. The flow regime maps change significantly. The transition from partially reversed flow back to stable counter-current stratified flow occurs at much lower air superficial velocities than vice versa. It has been possible to extend available flow regime maps with the curve describing the onset of stratified flow. The hysteresis zone has been quantified within the flow regime map for y_0 = 9 mm.

The aim of the current investigations is to obtain local experimental data. These data are needed to expand appropriate two-phase models in order to describe the flow conditions for horizontal counter-current flows with CFD-methods.

The challenges of conducting measurements of local velocities in two-phase flows with a variable interfacial area have been discussed. Fluorescent particles have to be used in order to eliminate the strong reflections at the interfacial area. Special attention regarding the camera set-up is necessary to avoid incorrect particle images due to the different refractive indices of water and air.

A large number of PIV-recordings are necessary to obtain the time-averaged velocities in two-phase flows with variable interfacial areas. When increasing the number of recordings, the velocity profiles converge to a line which can be used to estimate the local velocities for the maximum liquid height. A direct measurement would require an enormous number of recordings and is not recommended due to very long data acquisition times and costs for the necessary fluorescent particles.

The local velocities in the main flow direction show a strong dependency on both, the water and the air inlet conditions. Velocities perpendicular to the main flow direction are very low compared with the velocities in the main flow direction.

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