EXPERIMENTS AND CFD SIMULATION OF STRATIFIED HORIZONTAL TWO-PHASE FLOW

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1. Introduction

Slug flow as a multiphase flow regime can occur in the cold legs of pressurized water reactors, for instance after a small break Loss of Coolant Accident (SB-LOCA). Slug flow is usually characterized by an acceleration of the gaseous phase and by the transition of fast liquid slugs, which entrain a significant amount of the liquid with high kinetic energy. For the experimental investigation of air/water flows, a horizontal channel with rectangular cross-section was built at Forschungszentrum Rossendorf. Experimental data were used to check the feasibility to predict the slugging phenomenon with the existing multiphase flow models available in CFX-5.

2. The horizontal air-water flow duct

Experiments were carried out at a horizontal duct mounted between two separators (Fig. 1). The two-meter long acrylic glass test section has a rectangular cross-section (height x width: 250 x 50 mm²). A jet pump is driving the water flow, while air is being injected at the top of one of the separators. Both co-current and counter-current tests were performed.

Fig. 1: Schematic view of the horizontal air-water flow duct and modelled part (in red)

The rectangular cross-section was chosen for its optimal optical access in order to observe the flow structure from the side of the duct. A high-speed video camera as well as a PIV-system were used for this purpose. For dynamic pressure measurements, piezoelectric transducers with a rise time of 2 µs were mounted on top of the duct and were synchronised with the high-speed video camera. The dynamic liquid level measurement as well as the analysis of the slug
propagation were achieved by processing the high-speed camera image sequences, both with a time resolution of 100 Hz.

In the following, a selected co-current test run is analysed. It was carried out at a superficial water velocity of $v_L = 0.69$ m/s and a superficial air velocity of $v_G = 2.2$ m/s. The pressure was at an ambient level and the water temperature 16.5$^\circ$C. Under these conditions, a slug flow is generated.

3. CFD model of the duct

The CFD calculation was performed using the software package CFX-5.7 (CFX, 2004). For free surface simulations, the inhomogeneous multiphase model recommended by Frank (2003) was used, where the gaseous and liquid phases can be partially mixed in certain areas of the flow domain. In this case, the local phase demixing after gas entrainment is controlled by buoyancy and interphase drag and is not hindered by the phase interface separating the two fluids. A further decision has to be made regarding the applied fluid morphology and interphase drag law for the multiphase flow. The total drag force $D$ is most conveniently expressed in terms of the dimensionless drag coefficient $C_D$,

$$D = \frac{1}{2} \cdot \rho_{LG} \cdot (U_L - U_G)^2 \cdot A \cdot C_D$$ (1)

where $\rho$ is the fluid density, $(U_L - U_G)$ is the relative speed and $A$ is the projected area of the interphase in flow direction. In (1), $L$ describes the liquid phase and $G$ the gaseous phase.

The fluid-dependent shear stress transport (SST) turbulence models were selected for each phase. Damping of turbulent diffusion at the interface was not considered. The $k$-$\omega$ based SST model accounts for the transport of the turbulent shear stress and gives highly accurate predictions of the onset and the amount of flow separation. The SST model combines the advantages of the Wilcox and of the $k$-$\varepsilon$ model.

To take buoyancy effects into account, a buoyancy production term was applied in the turbulence model and was included in the $k$- and $\omega$-equations for additional turbulence production and dissipation. If the full buoyancy model is being used, the buoyancy production term $P$ is modelled as:

$$P = -\frac{\mu_t}{\rho \cdot Pr_t} \cdot \mathbf{g} \cdot \nabla \rho$$ (2)

where $\rho$ is the density of the fluid, $Pr_t$ the turbulent Prandtl number, $\mu_t$ the turbulent viscosity and $\mathbf{g}$ the gravity vector.

4. Geometry, grid generation and boundary conditions

Due to very high numerical efforts of transient slug flow simulations, the modelling of the complete test facility is not feasible. In order to keep the computational time within acceptable limits, only the horizontal test section with its rectangular cross-section was modelled. The model dimensions are: length x height x width = 2000 x 250 x 50 mm$^3$. The grid was created with CFX-MESHBUILD and transferred to CFX-5 PRE. It consists of $4 \times 10^5$ hexahedral elements, which reduces the computational time and improves the quality of the mesh compared to tetrahedrons.

At the inlet of the channel, air and water velocities are set to constant values over the part of the inlet cross-section that is occupied by each phase. In accordance to the initial water level,
the inlet velocities were set to values that correspond to the gas and liquid flow rates measured during the experiment. These velocities were kept constant in time. The level at the inlet was varied according to the time history of the liquid level measured by the high-speed camera at \( z_f = 0.75 \) m (Fig. 2). The outlet boundary condition has been applied to the cross section at the other end of the horizontal channel and was pressure controlled. The walls of the channel were set as hydraulically smooth walls with a non-slip boundary condition applied to both gaseous and liquid phases.

![Fig. 2: Time-dependent water level during slug flow in the test-section (100 Hz measurement)](image)

5. Results

The image sequence (see Fig. 3) compares the flow observed during the experiment with the corresponding CFD calculation. In both cases, a slug is developing. In the CFD calculation, the slug develops approximately at \( t = 0.90 \) s due to a high peak of the experimental water level at the inlet cross-section. The tail of the calculated slug and the flow behind it is in good agreement with the experiment. The entrainment of droplets in front of the slug could not be observed in the calculation. However, the rolling over and breaking of the wave, characteristic of a slug, are clearly to be seen in Fig. 3. These are created by the high air velocity.

In contrast to the measurement, the slug length is increasing in time in the calculation. This could be a result of the different amount of water in the channel at the beginning of the experiment and the simulation. While in the simulation, the liquid phase covered 78% of the channel, it represented about 70% at the beginning of the experiment. Furthermore, in the experiment, this value was also reduced by a first slug which carries a significant amount of water out of the channel. This first slug could not be simulated. This is probably an effect of the simplified initial conditions assumed in the calculation. Because of the constant initial water level, it took quite a long simulation time to establish a wavy flow along the channel, which is necessary for slug formation. Whereas at the beginning of the measurements, the test channel was already in a fully established intermittent slugging regime.
The slug position extracted from the camera images is compared with the calculation result in Fig. 4. In the experiment, the slug moves along the duct with constant velocity. The velocity of the slug selected for the post-test calculation was 3.7 m/s. In contrast to this, the calculated slug propagation is characterized by an acceleration phase between 0.75 and 0.90 s when the slug is still in the process of formation. In a second phase, starting from $t = 0.90$ s when the wave blocks the whole cross-section of the channel, the velocity of the calculated slug stays nearly constant at 4.4 m/s on average. This is 18% higher than the experimental value.
Fig. 4: Propagation of a slug - comparison between measurement and calculation

Fig. 5 shows the pressure field created by the slug in the CFD calculation. Due to the fact that the slug is driven by the gas pressure, a steep pressure gradient is observed at the slug front. This leads to the typical pressure history recorded by the transducers on top of the channel, which indicate a sudden pressure increase when the slug passes by (Fig. 6). Typical rise times were measured from 2 to 10 ms. An analysis of the camera pictures taken during the pressure measurements could explain the large spectrum of rise times. They are in fact an indicator of the slug length: the longer the slug, the longer the rise time. The pressure decreases simultaneously on both sensor positions, when the slug reaches the outlet separator.

Fig. 5: Calculated pressure field at \( t = 0.95 \) s

The comparison of the time-dependent pressure at both sensor positions for the experiment and the calculation also shows that the first slug observed in the test was not simulated. Therefore, only the second pressure increase can be compared with the calculation. In the simulation, the pressure at the first sensor position increases later than in the experiment. At the second sensor position the increase happens simultaneously. Then the pressure decreases earlier in the calculation than in the experiment. All this is a consequence of the differences in the slug propagation (see Fig. 4).

Furthermore, the calculation overestimated the peak pressure (4.4 kPa) in comparison to the experiment (2.3 kPa). This is due to the different size of the experimental slugs. Since, in the experiment, the first slug removed a certain amount of water from the channel, the second
slug is much smaller than the first one. That is why the peak pressure of the first slug reaches values between 3.6 and 5.0 kPa (respectively at the first and second sensor positions), which is the order of magnitude of the calculated pressure peak.

Fig. 6: Transient pressure at both sensor positions for experiment and CFX calculation

6. Particle Image Velocimetry (PIV) of a slug

A PIV-system was used to show the velocity field inside the slug. The laser-light sheet was focused in the middle of the test section. The PIV camera was directed to the upper part of the duct, in the region of the first pressure sensor.

Fig. 7: Velocity field inside a slug (the vector colour shows the absolute velocity, its length and direction show the relative velocity compared to the propagation velocity of the slug)
A PIV picture of a slug with the measured velocity field is shown in Fig. 7. The slug propagation velocity is approximately 3.8 m/s, which is close to the velocity of the slug analysed in section 5. The vector colour shows that the small leak air flow on top of the slug entrains the water at local absolute velocities of about 6 m/s. The lengths and directions of the vectors show the velocities in a coordinate system that moves with the slug propagation velocity. It reveals the structure of the flow circulation inside the slug.

7. Summary and conclusions

For the investigation of an air/water slug flow, a horizontal channel with rectangular cross-section was built at Forschungszentrum Rossendorf. Optical measurements were performed with a high-speed video camera and were complemented by simultaneous dynamic pressure measurements. By an interface capture method, the water level history can be extracted from the image sequences. The pressure measurements show that the order of magnitude of the pressure level behind the slug is about a few kPa. The pressure increase is fast (2 to 10 ms) and linked to the slug length. Furthermore, the velocity field of a slug was measured using Particle Image Velocimetry (PIV). It reveals the inner flow circulation of the slug, around the point there the slug is rolling over.

A CFD simulation of the stratified co-current flow was performed using the code CFX-5 applying the two-fluid model with the free surface option. The slug flow was successfully simulated with a transient simulation in the horizontal channel, using time-dependent inlet boundary conditions from the experimental data. The behaviour of slug propagation at the experimental setup was qualitatively reproduced, while quantitative deviations require a continuation of the work.

References


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