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Validation of simulations in multiphase flow metrology by comparison with experimental video observations

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Abstract. One important task in flow metrology is to evaluate the uncertainty in multiphase flow metering. A first important step towards this goal is to establish an accurate computational fluid dynamics (CFD) model of multiphase flows. In this contribution, results of multiphase flow simulations are validated by comparison with experimental data. For the evaluation and quantification of experimental observations, a tool for video analysis has been implemented. This tool extracts the liquid level over time, which is then used for further analysis and comparison with simulation data. Additional relevant parameters are obtained by frequency analysis, which is applied to both, experimental and simulation data. A comparison of the results shows good agreement between experiment and simulation.

1. Introduction

One central aim of multiphase flow metrology is to evaluate and reduce the uncertainty in multiphase flow metering in the oil and gas industries. A well-established reference network with norms and standards is lacking for multiphase flow metrology. Moreover, the level of uncertainty in multiphase flow measurement systems reaches up to 20% [1]. In order to reduce this level of uncertainty the different parameters influencing multiphase flow measurements are investigated. On the one hand, a comprehensive intercomparison of multiphase flow measurement labs is conducted. On the other hand, the process of flow pattern formation and flow behavior as well as the quantitative influence of relevant flow condition parameters is studied by computational fluid dynamics (CFD). Therefore, gas-liquid flow through an at least 10 meter long horizontal pipe followed by a relatively complex measurement unit is examined experimentally and numerically. A lot of test cases with different oil, water, and gas flow rates are considered in order to model industrially relevant configurations. Depending on the prescribed superficial velocities of the different phases, different flow patterns are observed at the end of the horizontal inflow section.

2. Multiphase flow simulation

The multiphase flow simulations were performed using the commercial CFD solver ANSYS FLUENT. The interface between the different phases was modeled by the volume of fluid (VOF) method [2], which was applied within a mixture model. An unsteady RANS (Reynolds-averaged

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Navier-Stokes) approach was used for turbulence modeling. The k-ω-SST (shear stress transport) model [3] was applied because it allows the inclusion of turbulence damping. Turbulence damping is required if there are high velocity gradients at the interface between the different phases to model such flows correctly [4,5]. Further details about the numerical modeling can be found in [6]. Figure 1 shows the resulting flow pattern for one of the test cases, which has also been investigated experimentally. The corresponding material parameters and superficial velocities of the two phases, nitrogen and brine water, are summarized in table 1. The figure displays the volume fraction of nitrogen at the end of the horizontal inflow section after ca. 40 seconds. One observes slug flow, which is in good agreement with the pattern in the corresponding experiment.

Table 1. Material parameters and superficial velocities of the two phases.

Brine water-nitrogen flow	Nitrogen	Brine water
Density in kg·m^{-3}	10.8	1011
Viscosity in Pa·s	$1.7 \cdot 10^{-5}$	$8.8 \cdot 10^{-4}$
Superficial velocity in m·s^{-1}	1.399	1.144

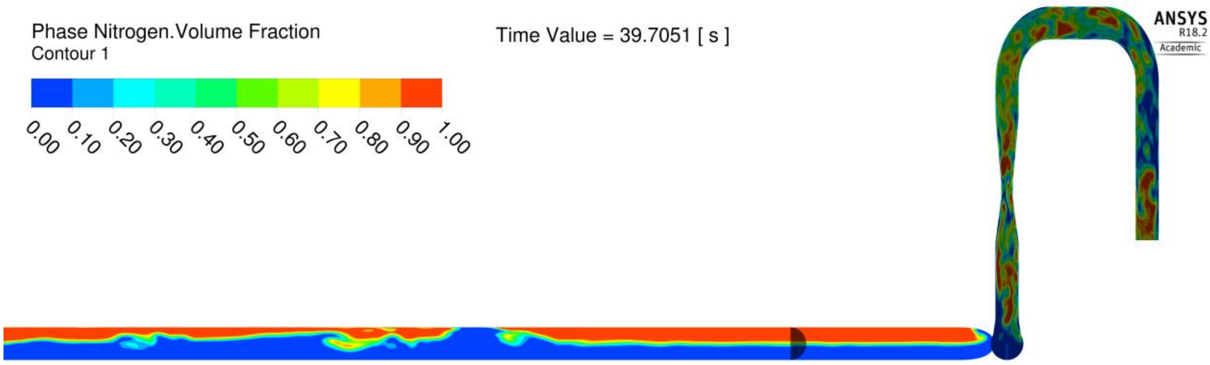

Figure 1. Gas volume fraction of brine water-nitrogen flow obtained by a CFD simulation.

In the experiments, a glass viewing section has been installed at the end of the horizontal inflow section in order to observe the flow pattern with a video camera. A qualitative comparison between the simulation results and pictures that have been extracted from these video observations shows that the structure of the slug is reproduced well by the numerical simulation [6]. However, for a quantitative comparison between experiment and simulation, more than pictures are needed. Therefore, we developed a tool, which extracts the liquid level at a certain position in the pipe over time by identifying the interface between the liquid and the gas phase from the video observations.

3. Liquid level extractions from experimental video observations

For the evaluation of the CFD simulations, quantitative parameters are required. Therefore, additional video and image processing was done in MATLAB to extract the liquid level from the experimental video observations.

3.1. Oil-gas flow

For the extraction of the liquid level from the videos, the pixel values of a region of interest (ROI) are selected over time, where the ROI is defined as a vertical line through the pipe (see figure 2). Since every pixel value consists of a vector of three components (RGB), three two-dimensional pictures are obtained. For oil-gas flow with a yellowish-brown Paraflex oil and transparent nitrogen, the blue component is of particular interest, since the blue content in the yellow oil is low. Hence it can be used to distinguish the two phases. On the blue component frame, morphological filters are applied to enhance contrast, homogenize and identify two regions, which characterize the areas of the two phases. Then the interface between these regions can be tracked by edge detection. After smoothing, this interface represents the liquid level. The bottom picture in figure 2 shows the extracted liquid level on top of the original picture. One can see that the tool is identifying the liquid level very well.

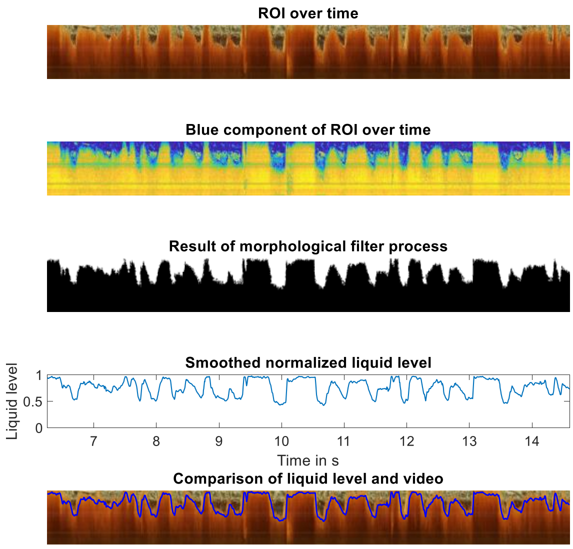

Figure 2. Visualization of the different steps from the raw picture to the extracted liquid level for Paraflex oil-nitrogen flow.

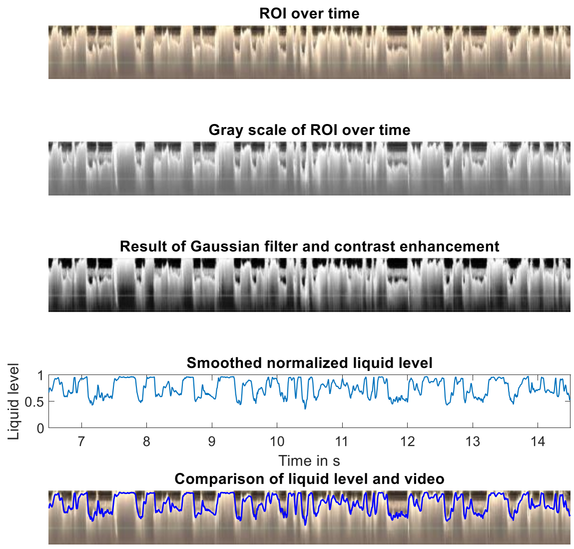

Figure 3. Visualization of the different steps from the raw picture to the extracted liquid level for brine water-nitrogen flow.

3.2. Water-gas flow

For the water-gas flow test cases, the algorithm is slightly different. Since the liquid is also transparent and colorless, a separation by color information is not purposeful. Therefore, we use the grayscale gradients and apply Gaussian smoothing and contrast enhancement filters before edge detection (see figure 3).

4. Results and discussion

The approximated liquid level from the experimental video observations is used to validate the CFD simulation results. We compare relevant parameters characterizing flow patterns, namely the average of the liquid level as well as its fast Fourier transform (FFT) and power spectral density (PSD). This provides a quantitative description of the dynamics of the multiphase flow. Here, the results for one typical brine water-nitrogen test case (see table 1) are presented. Since the CFD data is given for the whole three-dimensional domain, we average the liquid volume fraction in a cross section and calculate the corresponding circular segment height, which can be identified with the liquid level. Then, this value is compared with the extracted liquid level from the experimental video observations. For better comparability, the extracted liquid level shown in the top picture in figure 4 is only plotted for a short section of 25 seconds. However, the frequency analysis (shown in the middle and bottom pictures of figure 4) has been performed for the complete video observation of 120 seconds. Figure 5 shows the corresponding results for the data from CFD. For the PSD, we used a window averaging with 16 segments and 50 % overlapping. As seen in figure 4 and 5, the average liquid level from the CFD simulation is very close to the experimental one with a relative difference of 8 %. Furthermore, the frequencies of the highest amplitudes of the FFT are quite similar. Thus, the dynamics of the flow pattern are reproduced in a reasonable manner. However, the amplitudes of structures in the profile of the liquid level are too small in the CFD simulations.

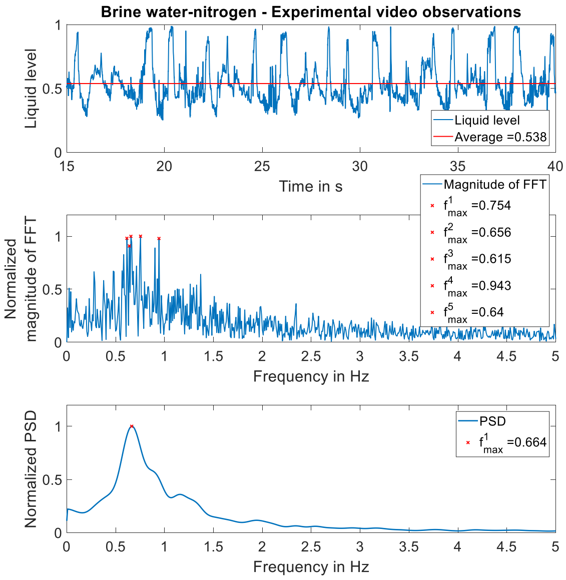

Figure 4. Extracted liquid level from experimental video observations for brine water-nitrogen flow with corresponding FFT and smoothed PSD.

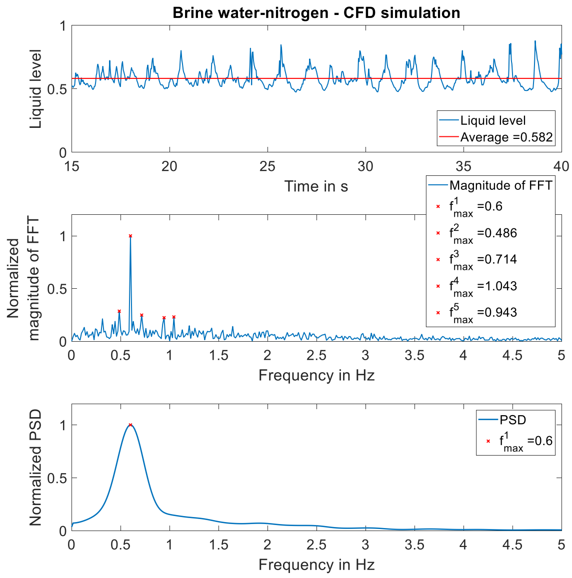

Figure 5. Liquid level from CFD for brine water-nitrogen flow with corresponding FFT and smoothed PSD.

Altogether the presented tool allows the extraction of the liquid level from experimental video observations. Frequency analysis shows reasonable agreement between simulation results and experiments, especially for the dynamics of the liquid level.

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