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Numerical simulation, validation, and analysis of two-phase slug flow in large horizontal pipes

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Abstract

Multiphase flow, especially two-phase gas-liquid flow, is of great importance for a variety of applications and industrial processes, for example in the nuclear, chemical, or oil and gas industries. In this contribution, we present simulation results for gas-liquid slug flow in large horizontal pipes. Six test cases with different oil, water, and gas flow rates are considered, which cover a wide range of different slug flows. The numerical predictions are validated by comparison with experimental data obtained from video observations, which have been recorded at NEL as part of the European research project "Multiphase flow metrology in oil and gas production". The relative error of the mean liquid level between experiment and simulation is less than 10.8 per cent for all but one test cases. Furthermore, a frequency analysis is performed. The single-sided amplitude spectrum as well as the smoothed power spectral density are calculated. For both, experimental and simulation data, one observes an increase of the dominant frequencies if the ratio of liquid and gas superficial velocity is increased.

1. Introduction

One central issue in subsea oil and gas production is the evaluation and reduction of uncertainty in multiphase flow measurement. While for single-phase flow metrology there exists a well-established reference network with norms and standards, such a network is lacking for multiphase flow metrology. This leads to a high level of uncertainty in multiphase flow measurement systems reaching up to 20 per cent [1].

The main objective of the European research projects "Multiphase flow metrology in oil and gas production" (MultiFlowMet I) and "Multiphase flow reference metrology" (MultiFlowMet II) is to reduce this level of uncertainty. Therefore, a comprehensive experimental intercomparison on multiphase flow is conducted on one hand. On the other hand, the process of flow pattern formation as well as the quantitative influence of relevant flow condition parameters are studied by computational fluid dynamics (CFD). The great advantage of CFD is that it gives insight into areas that are hardly accessible by experiments. Therefore, simulations can help to understand flow pattern formation as well as their influence on the measurement process. However, before CFD simulations can be used for predicting flows, they need to be validated first.

In this contribution, we present simulation results for two-phase slug flow in horizontal pipes, which have been investigated during the MutliFlowMet I project. The numerical predictions are validated by comparison with experimental data obtained from video recordings at NEL.

The paper is organized as follows. Section 2 gives a description of the considered geometry as well as of the material properties and superficial velocities of the investigated test cases. Furthermore, the numerical modeling is shortly summarized. In Section 3, the simulation results are compared with experimental data. First, the mean value and standard deviation of the liquid level are considered. Second, a frequency analysis is performed. Finally, conclusions are drawn in Section 4.

2. Multiphase flow simulation

In the following, we present simulation results for six test cases with different oil, water, and gas flow rates, see Table 1, which were all classified as slug flow in the corresponding experiments.

Table 1: Superficial velocities of the considered test cases.

Name of test point	Superficial velocities in m/s		
	Nitrogen	**Paraflex oil**	**Brine water**
TP 01	7.063	0.294	-
TP 03	1.399	1.144	-
TP 05	0.545	1.635	-
TP 77	7.063	-	0.294
TP 79	1.399	-	1.144
TP 81	0.545	-	1.635

The material parameters of the different fluids are summarized in Table 2.

Table 2: Material parameters of the different fluids.

	Nitrogen	**Paraflex oil**	**Brine water**
Density in $kg \cdot m^{-3}$	10.8	815.8	1011
Viscosity in $Pa \cdot s$	$1.75 \cdot 10^{-5}$	$7.84 \cdot 10^{-3}$	$8.82 \cdot 10^{-4}$

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 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 nitrogen-oil test cases (TP 03, see Table 1). It displays the simulated gas volume fraction in a longitudinal section through the middle of the pipe after ca. 30 seconds. One observes slug flow, which is in accordance with the pattern recorded in the corresponding experiment.

3. Comparison with experimental data

The numerical predictions are validated by comparison with experimental data obtained from video observations, which have been recorded at NEL during the MultiFlowMet I project. For the quantitative evaluation of the experimental observations, a tool for video analysis has been implemented [7], which extracts the liquid level over time from the recorded video observations.

Since the pipe wall has a thickness of several millimeters, the light rays inside and outside the pipe are displaced relative to each other. This leads to a distortion of the observed liquid level. To account for this, the liquid level has been corrected using Snell's law together with basic formulas for the height of a circular segment in geometry, see [8].

Furthermore, due to the installation of the viewing section, the recorded videos do not show the whole inner pipe. Only 94 per cent of the inner diameter are visible in the experimental observations, whereas the lowest and highest 3 per cent of the pipe cannot be seen because of tie bars. Since in general we cannot decide whether the unseen area is covered with liquid or not, we decided to use only the visible part for the comparison with the CFD results. To obtain a reasonable comparison between experiment and simulation, we "reduced" the simulation results in the same way. This means that we consider only the (inner) 94 per cent of the pipe for the analysis shown in the following subsections.

3.1 Liquid level

In the following, we compare the mean value and standard deviation of the liquid level derived from the experimental video observations with the corresponding data from CFD.

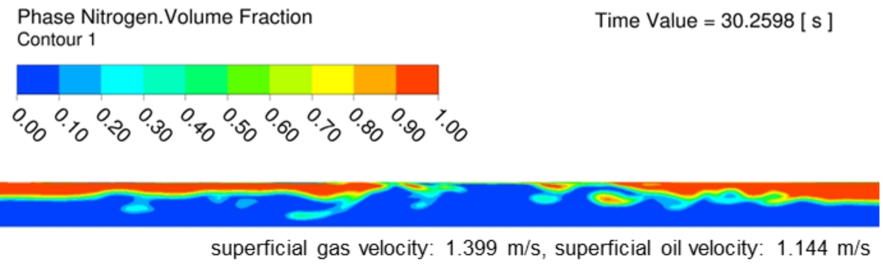

Figure 1: Slug flow observed for one of the test cases (TP 03) after ca. 30 seconds. The picture shows ca. 2 meter of the longitudinal section through the middle of the pipe.

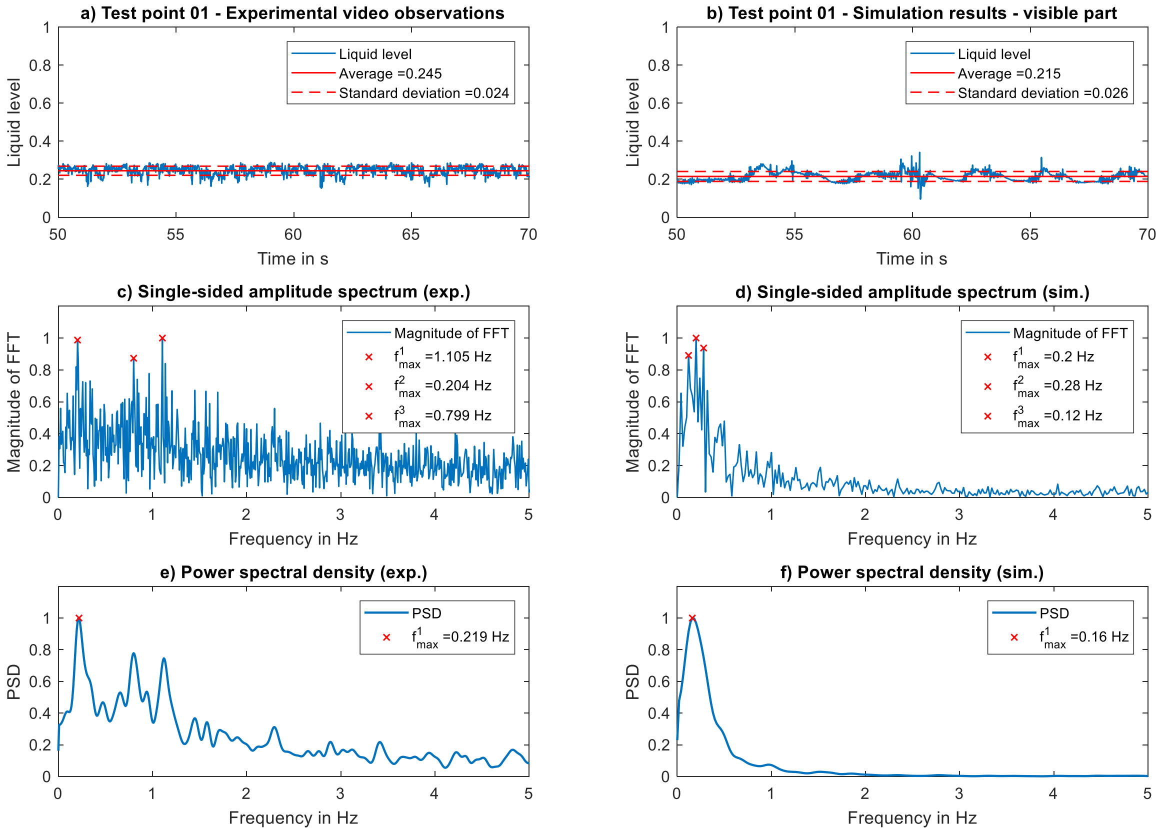

Figure 2: Comparison of the extracted liquid level (mean value ± standard deviation), its single-sided amplitude spectrum obtained by FFT as well as its smoothed PSD (pictures on the left) with the corresponding data from CFD (pictures on the right) for TP 01.

While the mean value gives an impression of the general proportion of liquid in the pipe, the standard deviation describes how much this value changes. A higher standard deviation implies larger fluctuations in the distribution of the phases, for example due to higher waves or more slugs.

Note that it does not make sense to directly compare the extracted experimental versus the computed liquid level at one fixed point in time. The reason for this is that slug flow is intermittent. Therefore, only statistical data should be compared.

Figure 2 a) shows the liquid level over time that has been extracted from the experimental video observation of one of the nitrogen-oil test cases (TP 01, see Table 1). Note that, for better illustration, only 20 seconds of the recorded time interval are displayed in the figure. However, the mean value and standard deviation stated in the legend nevertheless represent the mean value and standard deviation for all data recorded. Figure 2 b) shows the corresponding data from CFD. One observes good agreement for both, the mean value as well as the standard deviation of the liquid level.

Figure 3 a)+b) show the same analysis for a nitrogen-water test case (TP 81, see Table 1). This test case has a much lower gas and a much higher liquid superficial velocity leading to a higher liquid level and more slugs than in the previous test case. A comparison between the liquid level extracted from the video observations with the one from the CFD simulation shows good agreement. However, the standard deviation of the simulated liquid level is much smaller than in the experiment. One reason might be the larger time step size used in the evaluation of the simulation data (because the flow field was saved only every 100 time steps).

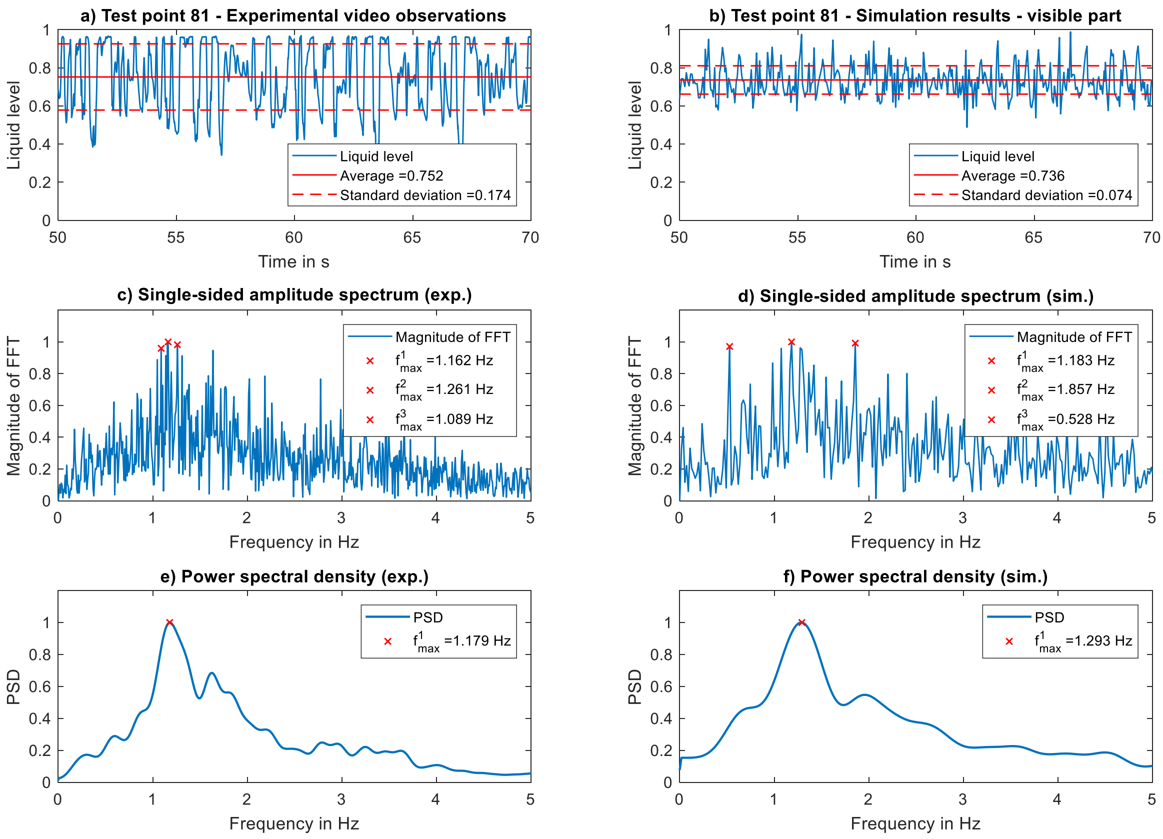

Figure 3: Comparison of the extracted liquid level (mean value ± standard deviation), its single-sided amplitude spectrum obtained by FFT as well as its smoothed PSD (pictures on the left) with the corresponding data from CFD (pictures on the right) for TP 81.

In Figure 4, the mean value and standard deviation of the experimental liquid level are compared to the corresponding simulation results for all six considered slug flow test cases, see Table 1. One observes that a higher liquid superficial velocity leads, as expected, to a higher liquid level in the pipe. Except for one case (TP77), the relative error of the mean liquid level between experiment and simulation is less than 10.8 per cent.

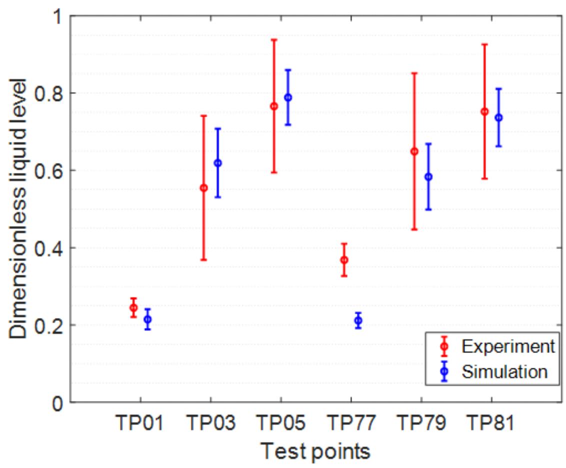

Figure 4: Comparison of the liquid level (mean ± standard deviation) extracted from experimental video observations (red) and simulation results (blue).

3.2 Frequency analysis

A classical parameter for distinguishing different slug flow cases from each other is the so-called slug frequency, i.e., the number of slugs occurring in a certain time interval. In theory, one would say that there is a slug if the pipe is fully filled with liquid at a certain position. In practice, however, slugs usually contain some gas (e.g., in the form of bubbles), which means that even in the core of the slug the liquid level might not be equal to one. This means that a threshold for the liquid level needs to be defined, above which a slug is counted. However, inspecting different slug flow cases shows that such a threshold is not universal.

Therefore, we use a frequency analysis instead. We apply the fast Fourier transform (FFT) to both, experimental and simulation data, and compare the resulting frequencies as well as the peaks in the corresponding smoothed power spectral

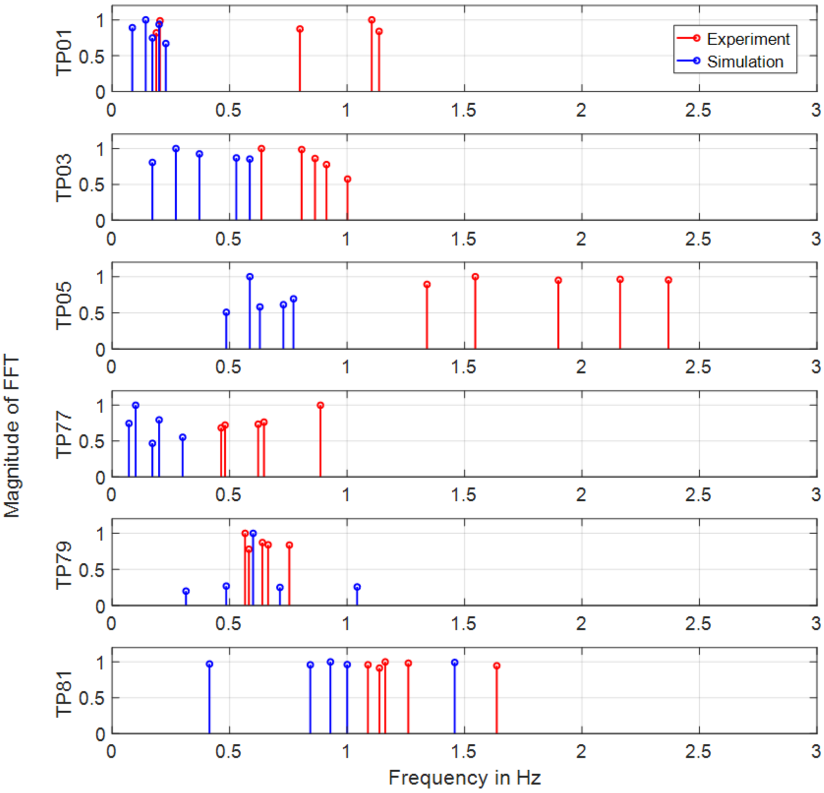

Figure 5: Comparison of the five most dominant frequencies from experimental video observations (red) and simulation data (blue).

density (PSD). Even though the frequencies identified by FFT do not necessarily represent the slug frequency, they nevertheless provide a quantitative description of the dynamics of the slug flow. Hence, they can be used for comparison between experiment and simulation.
Figure 2 c)+d) show the (normalized) single-sided amplitude spectra of experimental and simulation data, respectively, for the nitrogen-oil test case TP01 (see Table 1). For the simulated liquid level, the most dominant frequencies are all around 0.2 Hz. This value can also be found as one of the most dominant frequencies in the FFT of the experimental liquid level. However, in the experiment, the amplitude spectrum has further peaks around 0.8 and 1.1 Hz. This can also be seen in the smoothed PSD, see Figure 2 e)+f), which has been calculated using the Matlab function `pwelch`.

The same analysis (FFT and PSD) is shown in Figure 3 c)+d) and e)+f), respectively, for the nitrogen-water test case TP 81, see Table 1. For this test case, the three most dominant frequencies of the FFT are centered around ca. 1.2 Hz in both, experiment and simulation. This is also reflected by the peak in the PSD, which is ca. 1.2 Hz in the experiment and ca. 1.3 Hz in the corresponding simulation.

Figure 5 displays the five most dominant frequencies of the FFT spectrum for all test cases, see Table 1. The experimental data is shown in red, the simulation data in blue. Note that the amplitudes of the FFT spectra have been normalized to one in all cases. In general, the observed frequencies in the simulation are lower than in the experiment. On the other hand, the increase of the frequencies with higher superficial liquid velocity can be seen in both, experiment and simulation. For one case (TP 79), the dominant frequency of approximately 0.7 Hz observed in the experiment is reproduced almost exactly by the numerical simulation. In other cases (TP 01, TP 03, and TP 81) at least some of the dominant frequencies observed in the experiment can also be found in the simulation.

4. Conclusion

In this paper, we presented simulation results for different slug flow test cases. The numerical predictions have been compared with experimental data obtained from video observations, which have been recorded at NEL during the MultiFlowMet I project. The relative error of the mean liquid level between experiment and simulation is less than 10.8 per cent for all but one test cases.

Furthermore, a frequency analysis has been performed. The single-sided amplitude spectrum as well as the smoothed PSD have been calculated for both, experimental and simulation data. Even though the observed slug frequency (which can be determined by counting slugs, for example) usually cannot directly be identified with the highest frequencies obtained by FFT, neither in the experiment nor in the simulation, these frequencies provide a quantitative description of the dynamics of the slug flow. For both, experiment and simulation, one observes an increase of the dominant frequencies if the ratio of liquid and gas superficial velocity is increased.

However, for a better comparison between experiment and simulation, further analysis is necessary. Methods like proper orthogonal decomposition (POD) [9,10] can be applied to identify typical structures in the flow that are characteristic for a specific pattern. Simulation data can then be validated by comparison with experimental data with respect to these relevant structures. Furthermore, commonly used flow pattern categories can be changed or extended according to the identified characteristics.

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