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LedaFlow model improvements for three-phase gas dominated flows

Jørn Kjølaas[1*], Vanessa Richon[2]
[1]SINTEF, Norway
[2]TotalEnergies EP Norge AS

Abstract

This work concerns the simulation of three-phase gas dominated flows at low to moderate flow rates, which are conditions typically encountered in mature gas-condensate production systems. At low flow rates, liquid starts to accumulate in uphill pipe sections, potentially leading to unstable flow, increased pressure drop due to the gravitational effect, and consequently severe operational difficulties. This onset of liquid accumulation determines what is called the turndown or minimum flow through the pipeline. Successful prediction of this turndown requires accurate multiphase flow models to forcast when problems will occur, and what remedies could be applied. In an effort to improve LedaFlow predictions for mature gas-condensate production systems, a large scale experiment campaign was launched at the SINTEF Multiphase Laboratory, conducting multiphase flow experiments in a 194 mm pipe with 1° inclination. The system pressure was 60 bara, and the flow rates were selected to be representative of typical gas-condensate production systems. In this paper we share some key results and findings from this campaign. Furthermore, we demonstrate how these experiments can be used to improve the closure laws in LedaFlow, yielding more accurate predictions for the new laboratory data.

Keywords

Multiphase flow; Experiments; Modelling

Introduction

The lifetime of offshore gas-condensate fields is often limited by the onset of flow instabilities [1], where large variations of the produced liquid can make phase separation troublesome to the point where production may have to be suspended until mitigation mechanisms are put in place. A common remedy for the challenges encountered in mature offshore gas-condensate systems is subsea compression [2]. However, this requires years of effort in planning and execution, hence accurate forecasts on when operational difficulties will arise are needed to implement mitigation strategies in a timely manner.

To obtain accurate forecasts of flow assurance challenges, high-quality multiphase flow models are needed, meaning that the closure laws applied in multiphase simulators must be accurate. In low-rate gas-condensate systems, the gas/liquid interfacial shear stress tends to be the most important closure law, which is why a great deal of effort has gone into calibrating this closure law in LedaFlow [3]. These efforts have however mainly targeted two-phase gas/liquid systems because three-phase data with sufficiently precise phase fraction measurements have been lacking. To amend this situation, a large scale experiment campaign (financed by TotalEnergies) was launched at the SINTEF Multiphase Laboratory, conducting multiphase flow experiments in a 194 mm pipe, covering both two- and three-phase flows. The pipe was equipped with pressure sensors, several gamma densitometers, and a quick-closing valve system to measure phase fractions accurately.

The results from the experiment campaign were compared to predictions by LedaFlow, and while the predictions were for the most part quite good, significant deviations in holdup and pressure drop were found in the so-called turndown-region, where the flow changes from gravity-dominated to friction-dominated. In this work we discuss the possible origin of these disparities, and how they can be amended.

Experiments

The experiments were conducted in a 94 meter long pipe with internal diameter of 194 mm, and an inclination angle of 1°. The nominal system pressure was 60 bara, and the fluids used were Nitrogen gas, Exxsol D60 oil, and tap water. The thermodynamic properties of the phases are listed in Table 1. The flow regime in these experiments was mainly stratified flow, but with large waves or pseudo-slugs at the lowest gas rates.

Table 1. Thermodynamic properties

Properties	Value
Gas density	60 kg/m^3
Oil density	790 kg/m^3

Water density	1000 kg/m^3
Gas viscosity	0.18 cP
Oil viscosity	1.4 cP
Water viscosity	1.0 cP
Oil/gas surface tension	26 mN/m
Oil/water surface tension	38 mN/m
Gas/water surface tension	71 mN/m

The main instrumentation included six pressure sensors to measure the pressure gradient, five vertically mounted gamma densitometers to measure the liquid height, one traversing gamma densitometer to measure average density profiles, and a 63.55 meter quick-closing valve section for high-precision phase fraction measurements.

Figure 1 shows the liquid holdup plotted versus the superficial gas velocity USG for USL=0.05 m/s and 0.2 m/s and water cuts 0% and 25%. The dashed lines in the graphs represent predictions obtained using LedaFlow. We observe that the measured liquid holdup is higher for the three-phase data (WC=25%) compared to the two-phase data (WC=0%). LedaFlow does predict this trend rather well for USL=0.05 m/s, but for USL=0.2 m/s, the measured three-phase effect is significantly larger than the predicted one. This suggests that the interfacial shear stress between the gas and the oil layer is affected by the presence of the water layer, and that this is not fully accounted for in the model.

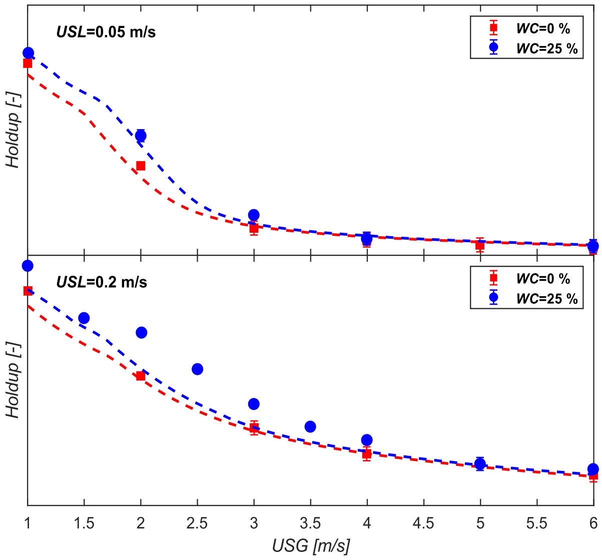

Figure 1. Liquid holdup plotted versus *USG* for *USL*=0.05 and 0.2 m/s, and water cuts WC=0% and 25%. The markers represent measured values, and the dashed lines are LedaFlow predictions.

Model improvements

In LedaFlow, the interfacial shear stress between the gas and the oil is calculated as:

$$\tau_i = \frac{1}{2} f_i \rho_{go} \left| u_g - u_o \right| \left(u_g - u_o \right) \qquad (1)$$

where u_g is the gas velocity, u_o is the oil velocity, and the interface density is defined as:

$$\rho_{go} = \sqrt{\rho_g \rho_o} \qquad (2)$$

The friction factor f_i is calculated according to the expression:

$$f_i \equiv f_{i,smooth} \cdot \left(1 + WF \right) \qquad (3)$$

where $f_{i,smooth}$ is the friction factor for a smooth interface, and *WF* is the so-called "wave factor", which represents the effect of waves on the interface. The respective expressions for these parameters are described in [4] and [3].

We observed in the previous section that LedaFlow does predict slightly higher holdups in three-phase flows compared to two-phase flows. The reason for this is that the oil layer travels faster than the water, leading to a lower gas/oil slip velocity, and subsequently to interfacial lower shear stress (see Eq. 1). However, for the case with USL=0.2 m/s, this effect is not sufficient to explain the large deviations between the three-phase and two-phase results, hence it appears that the presence of a water layer can reduce the effective roughness of the gas/oil interface. Specifically, it may be that the waves on the oil/water interface dampen the gas/liquid waves through a type of destructive interference.

A fully mechanistic description of this mechanism is out of reach for a 1D model; hence we need to come up with a heuristic model amendment to the interfacial shear stress model that captures our experimental observations. Some of the main observations were:

1) The three-phase effect appeared to increase with the oil/water slip velocity.
2) The three-phase effect is greatest for "moderate" liquid holdups, and smaller for low/high liquid holdups.

Based on these observations we came up with the following expression for the three-phase wave factor WF_{3P}:

$$WF_{3P} = \frac{WF}{1 + \frac{C_1 \alpha_L}{1 + C_2 \alpha_L^{1.5}} \cdot \max\left(\frac{\left| \Delta u_{ow} \right|}{u_{VKH}} - 1{,}0 \right)} \qquad (4)$$

Here, *WF* is the original wave factor [3], C_1 and C_2 are undisclosed model coefficients, α_L is the liquid holdup, Δu_{ow} is the oil/water slip velocity, and u_{VKH} is the wave onset velocity for the oil/water interface [4]. It may be noted that the max-expression in Eq. 4 essentially represents the waviness of the oil/water interface [4], which is consistent with the notion that the three-phase effect is a product of destructive interference between the oil/water waves and the gas/oil waves. This expression guarantees that the model amendment is only active for separated oil/water flows with oil/water waves.

In the following section we show the results obtained by introducing Eq. 4 in LedaFlow, and discuss the findings.

Results and discussion

Figure 2 shows the three-phase experimental data along with liquid holdup predictions before (dashed lines) and after (solid lines) the model improvements. We observe that the new holdup-predictions are in better agreement with the measured values, at least for intermediate gas rates. At low gas rates, LedaFlow predicts pseudo slug flow, and the holdup is no longer a function of the interfacial shear stress, which is why the before/after results are the same in that region. At high gas rates, LedaFlow predicts fully dispersed oil/water, leading to zero oil/water slip, and subsequently no three-phase effect on the shear stress.

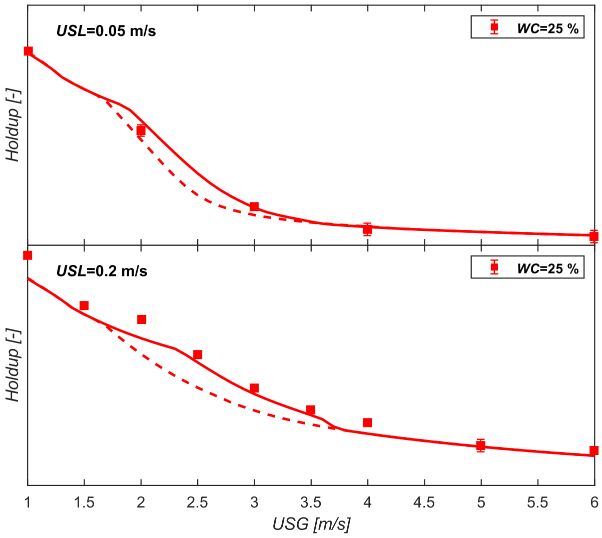

Figure 2. Liquid holdup plotted versus *USG* for *USL*=0.05 and 0.2 m/s, and 25% water cut . The markers represent measured values. The dashed lines are LedaFlow predictions before the model changes, and the solid lines are LedaFlow predictions after the changes.

For *USL*=0.2 m/s, the three-phase predictions would be even better if the onset of pseudo slug flow and the transition to fully dispersed oil/water were slightly shifted to the left/right, respectively. This is illustrated in Figure 3, where we have included simulations for which the gas/oil/water are assumed to be separated (red dashed lines). Here, we observe that the separated model is more accurate for the points close to the two flow regime transitions, at USG=2 and 4 m/s.

We should however keep in mind that the pipe might not be long enough to accurately pinpoint the onset of slugs/pseudo slugs, hence the data points in that transition region might not be fully developed. Regarding the oil/water flow regime, it is known that predicting oil/water dispersions in three-phase flows has uncertainties, hence it is arguably expected that the oil/water flow regime is not predicted perfectly.

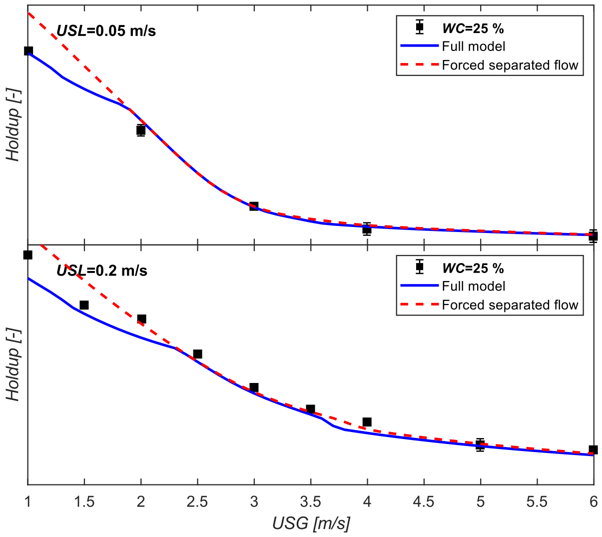

Figure 3. Liquid holdup plotted versus *USG* for *USL*=0.05 and 0.2 m/s, and 25% water cut . The markers represent measured values. The blue solid lines are LedaFlow predictions after the model changes. The red dashed lines are LedaFlow predictions with the same model, except that the gas/oil/water are assumed to be fully separated.

Conclusions

A set of large scale experiments were conducted at the SINTEF Multiphase Laboratory in a 194 mm pipe with 1° inclination at 60 bara pressure with flow rates representative of typical gas-condensate production systems. The data showed that the liquid holdup can be significantly higher in three-phase flows compared to two-phase flows.

LedaFlow was able to predict the three-phase effects for the lowest liquid rate (*USL*=0.05 m/s), but for the highest liquid rate (*USL*=0.2 m/s), the holdup predictions were found to be too low. We suspect that the reason for these discrepancies may be due to destructive interference between waves on the two interfaces, which is included in the LedaFlow shear stress model.

Using the new experimental data, we derived a three-phase amendment to the LedaFlow shear stress model, significantly improving the agreement with the measurements in three-phase flows.

Acknowledgments

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Responsibility Notice

The authors are the only responsible for the paper content.

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