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Coupled 1D/3D method for CFD simulations of liquid-dense gas flows

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Abstract
Due to the high production rates and CO_2 contents observed in the Brazilian Pre Salt, the HISEP separators were developed in order to capture CO_2 at high pressures. CFD simulations of multiphase flows at the operating conditions of the HISEP, which are useful during the equipment design process, pose numerical challenges because of the properties of the dense gas and the length of the domain, which would require high computational costs. A new strategy is proposed in this work, consisting of coupling the results of simplified 1D simulations to 3D simulations: general flow information can be acquired using the 1D Marlim 3® simulator, while detailed information from specific positions, specially near the HISEP feed, can be obtained from high resolution 3D simulations. This method facilitates convergence and the capture of the interface morphology in the 3D high-resolution simulations, providing useful information about the flow conditions provided to the HISEP separator.

Keywords
Dense gas; multiphase flows; Computational Fluid Dynamics

Introduction
The oil reservoirs from the Pre Salt fields show high Gas Oil Ratios (GOR) and productivity indexes, as well as high levels of CO_2 content. If separators used for CO_2 capture were to be built in the topside of the production platforms, they would occupy around 65% of the topside area, not to mention the high construction costs [1][2]. For this reason, Petrobras has been developing the HISEP separators, built at subsea level next to the production wells, operating at high pressures, in order to separate the produced gas, rich in CO_2, and reinject it for Enhanced Oil Recovery (EOR) [1][2].
The operating conditions of the HISEP, consequently, require very high pressures, at which point the gas phase is close to supercritical conditions, with high density and low viscosity [1]. The presence or formation of other components, like hydrates, is also possible in the production line. Characterization of the oil-gas flows preceding and inside the HISEP becomes, thusly, considerably challenging, as there is currently still a lack of comprehensive experimental data for liquid-dense gas multiphase flows. Even for computational simulations using Computational Fluid Dynamics (CFD), difficulties arise when trying to accurately predict the phase distribution, morphology and pressure drop in these flows: firstly, because of the total length of the domain of interest combined with the high grid resolution necessary for accurate interface capture. Secondly, because many known equations of state models have shown inaccurate prediction of properties for rich CO_2 mixtures at near supercritical conditions [3].
One-dimensional simulators such as Petrobras' Marlim 3® are widely used in the O&G industry, providing useful insights into flow information such as pressure drop, phase properties and heat transfer for long pipelines. However, more detailed information about the phase distribution, flow regime and interfacial phenomena, especially near the entrance of the HISEP separator, can only be predicted through a full three-dimensional representation of the flow. These, however, incur high computational costs, which only increase as the length of the simulated domain increases.
In order to make the detailed 3D simulations feasible in terms of time and resources, without compromising the accuracy regarding phase distribution and flow regime, a coupled 1D/3D strategy is hereby proposed. Marlim 3® is employed for large lengths of pipes and generates flow data as input for a 3D CFD simulation of a small portion of the domain where more detailed flow information needs to be predicted. The data obtained from the 1D Marlim simulations can include holdup, phase slip ratio and phase properties. The 3D simulations in the present work are executed in OpenFOAM® v22.12, using

customized boundary conditions in order to establish phase slip within the Volume of Fluid (VoF) model. Preliminary results indicate the feasibility of the proposed method.

Methodology

The process is described in three of its aspects: the 1D simulations, the 1D/3D coupling and the 3D simulations.

One-dimensional simulations

The case simulated in Marlim 3® consists of oil-gas flow inside a 2900 [m] long pipe, with vertical and horizontal sections, as shown in Fig. (1). Pressure and temperature vary along the domain, and phase properties are updated using a PVT table. Each computational cell was 100 [m] long and the simulation ran for 3000 [s], providing data on phase velocities, holdup, slip ratio, properties, GOR, BSW for every 100 [s].

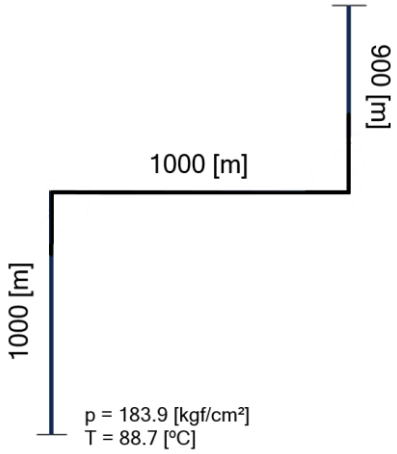

Figure 1. Complete flow domain for 1D simulation.

1D/3D coupling

A position in the middle of the horizontal section of the domain was chosen for the full 3D simulation. The results of the 1D simulation for each time at this specific cell were gathered and used as input data for the 3D simulation in the form of time tables, which are written in the format read by OpenFOAM®.

Three-dimensional simulations

A position in the middle of the horizontal section of the full domain was chosen for the detailed 3D simulation. Considering the pipe diameter of 0.1514 [m], a mesh with 10 diameters of length and an o-grid structure was generated as shown in Fig. (2).

The mathematical model chosen for the simulations was the Volume of Fluid (VoF) model, which is appropriate for capturing the interface movement and flow pattern. In this model, a single velocity (**U**) and pressure (p) field is used to represent the two-phase mixture and a phase fraction field α represents the liquid volume fraction. Equations (1) and (2) represent the transport of mass, momentum and phase fractions (α) using the VoF model.

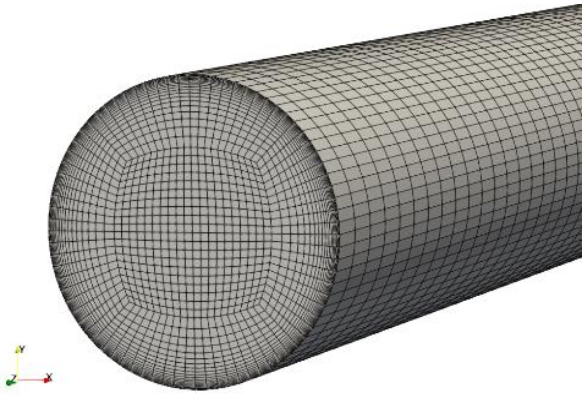

Figure 2. Computational mesh for 3D simulations.

$$\partial_t(\rho\mathbf{U})+\nabla\cdot(\rho\mathbf{U}\mathbf{U}) = -\nabla p +\nabla\cdot(\mu\nabla\mathbf{U}) + (\mathbf{g}\cdot\mathbf{h}_{ref})\nabla\rho + \mathbf{F} \quad (1)$$

$$\partial_t(\alpha) +\nabla\cdot(\alpha\mathbf{U}) = 0 \quad (2)$$

The term $\mathbf{h}_{ref}$ represents the reference height for the calculation of hydrostatic pressure. The properties such as density (ρ) and viscosity (∫) are calculated from the oil and gas properties averaged from the liquid volume fraction as shown in Eqs. (3) and (4).

$$\rho = \alpha\,\rho_O + (1-\alpha)\,\rho_G \quad (3)$$

$$\mu = \alpha\,\mu_O + (1-\alpha)\,\mu_G \quad (4)$$

The term **F** represents the superficial force that acts at the interface, as seen in Eq. (5) [4].

$$\mathbf{F} = 2\sigma\,\rho\kappa\nabla\alpha/(\rho_O+\rho_G) \quad , \quad \kappa = \nabla\cdot\mathbf{n} \quad (5)$$

Geometric interface reconstruction is used through the isoAdvector method [5] implemented in OpenFOAM for VoF simulations in the *interIsoFoam* solver.

A boundary condition developed for OpenFOAM, named *twoPhaseMappedField*, specializes the native *mappedField* condition by allowing the input of time tables for oil superficial velocity (j_O), gas superficial velocity (j_G) and slip ratio (S). These values are used to calculate the average mixture velocity imposed from Eq. (6). This boundary condition maps the velocity field from the outlet of the domain to the inlet, creating a cyclic domain, and adjusts this field to impose the calculated average velocity. The cyclic boundary condition is used in order to impose a fully developed flow in the 3D simulation.

$$\mathbf{U} = [\alpha\mathbf{U}_{in,O} + (1-\alpha)\,\mathbf{U}_{in,G}]\cdot\mathbf{n} \quad (6)$$

$$\mathbf{U}_{in,O} = j_O\alpha_p^{-1}\,[\alpha_p + S(1-\alpha_p)] \quad (7)$$

$$\mathbf{U}_{in,G} = j_G(1-\alpha_p)^{-1}\,[(1-\alpha_p) + S^{-1}\alpha_p] \quad (8)$$

For this preliminary test, and considering the short length of the cyclic domain, the phase properties were considered constant, using values calculated from PVT tables implemented in Marlim 3® for the inlet conditions, as shown in Tab. 1. Given the low variation of pressure and temperature along the horizontal section, this approximation is reasonable.

Table 1. Phase properties fixed in 3D simulations.

Properties	Value
Gas Density (kg/m^3)	256.14
Gas Viscosity (cP)	0.029
Oil Density (kg/m^3)	755.27
Oil Viscosity (cP)	1.063
Surface Tension (N/m)	0.021

The turbulence model used was the 4-equation k-ω SSTLM model [6], with cyclic inlet conditions and its appropriate wall functions.

Results and Discussion

Table 2 summarizes results obtained from 1D simulations in the cell located 1500 [m] after the inlet, which is in the middle of the horizontal section. The flow pattern was predicted as intermittent, with average holdup values reaching a steady value of 40.5%.

Table 2. Results obtained from 1D simulations

Time (s)	Holdup	j_O (m/s)	j_G (m/s)	Flow pattern
100	39.7%	3.22	6.63	Intermittent
500	40.4%	3.30	6.50	Intermittent
1000	40.5%	3.31	6.49	Intermittent
3000	40.5%	3.31	6.49	Intermittent

Fig. 3 shows a plane along the axial direction of the 3D domain for the times of 100 [s], 500 [s] and 1000 [s]. The intermittent flow pattern is captured in the simulations, even though a shorter domain is simulated.

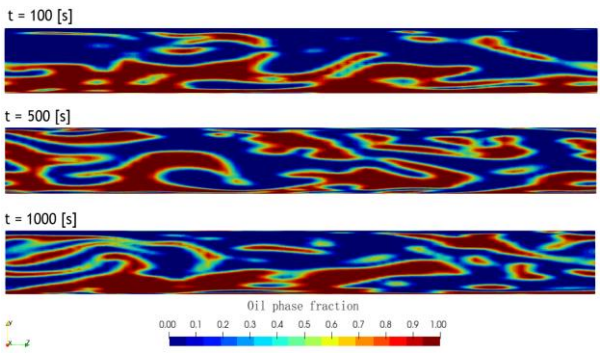

Figure 3. Visualization of the flow pattern in 3D CFD simulations.

Since each computational cell in the 1D domain has a length of 100 [m], the 3D simulations are employed to provide more detailed flow data in a smaller portion of this domain. Even though the phase distribution varies inside the domain, the average holdup measured in the entire 3D domain matches the values obtained in the 1D simulations. Adding to the flow visualization seen in Fig. (3), specific flow information can be probed in locations of interest. Figure 4 shows the variation of the relative height of the interface with time, measured at an axial position at the middle of the 3D domain. The 0 [mm] position marks the initial position of the interface, at the start of the simulation. This analysis can be extended, in real cases, to monitoring flow fields and fluid properties at positions close to the inlet of the HISEP separator, for example.

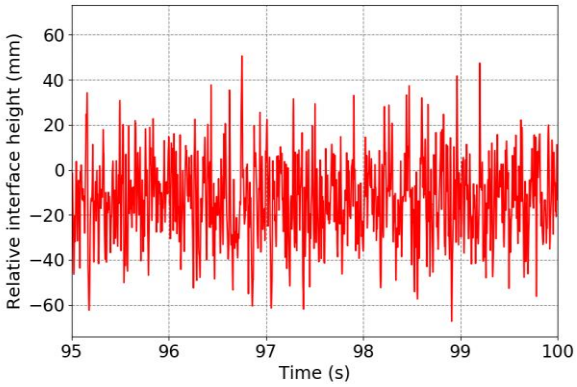

Figure 4. Variation of interface height with time at the center of the 3D domain.

Conclusions

Using the proposed coupling method, the flow through long distances of pipelines can be simulated in a 1D simulator, which uses empirical correlations for closure terms, to obtain general information about the flow, while this data is used as input to a 3D simulator that can provide high resolution information about phase distribution and interaction. This can eventually include mass and heat transfer across the interface, as well as the HISEP separator itself.

Further tests will be conducted on the influence of the length of the 3D domain over the frequencies captured in the interface movement. Accurate thermodynamic models are also planned to be implemented into the coupled 1D/3D simulator, in order to predict the properties of the dense gas mixture, rich in CO_2.

In order to validate the methodology and propose improvements in accuracy for the simulator, a validation study is also being conducted, using the experimental data of oil-dense gas flows from [7], which encompasses different horizontal flow patterns.

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Responsibility Notice

The authors are the only responsible for the paper content.

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