Petroleum 5 (2019) 133–140

Contents lists available at ScienceDirect

Petroleum

journal homepage: www.keaipublishing.com/en/journals/petlm

Slug catcher finger-type CFD simulator for two-phase flow separation

Alessio Pierro*, Simone Spadoni, Francesco Chiappetta, Francesco Ferrini

Techfem SpA, Italy

A R T I C L E I N F O

Article history:
Received 16 August 2017
Received in revised form
23 October 2017
Accepted 12 December 2017

A B S T R A C T

Slug catcher is an important and costly equipment in the up-stream assets, but is the less supported by research or commercial simulation software in terms of design and sizing criteria.

The purpose of this paper is to present a simulation model based on the open-source software for computational fluid-dynamics OpenFOAM®, which can assist during the preliminary sizing, made by the usual simplified methods, proving the fluid-dynamic behaviour and drive the process engineers to an optimum final design by checking all the expected production profiles of the related oil/gas field, for a comprehensive and safe operation all along the reservoir life.

The slug catcher main function is to ensure the separation of the phases within the acceptance specifications dictated by the process units of downstream CPF (Central Production Facility).

The optimization of the slug catcher could allow the reduction of the equipment overall dimensions, that is essential to reduce the capital expenditure and make the installation more flexible.

The graphic output is a strong tool in the hand of engineers, following the fluid-dynamic response of the slug catcher in the gas-liquid separation section, in function of the flow pattern at the entrance and superficial velocities of the phases.

1. Introduction

Slug catcher is a static equipment in the upstream assets, which has to cope with continuous changes of the incoming multiphase flow rates at various flow patterns, due to:

(1) ramp-up and slow-down of production rates;
(2) terrain and hydrodynamic slugging along trunklines/flowlines;
(3) pigging of trunklines/flowlines.

Moreover, the slug catcher has to face the hydrocarbons production profile due to reservoir depletion.

The slug catcher, located at the end of a production pipeline and upstream of field process facilities, is intended to separate the phases and to provide temporary storage for liquid received, acting as a buffer tank for the incoming liquid phase. The finger-type slug catcher is usually composed of three main sections:

(1) Entrance section;
(2) Gas/liquid separation section;
(3) Liquid storage section.

The separation section is the most complicated of those summarized above, from the engineering point of view. A detailed analysis of separation section is necessary to define correctly the finger dimensions required to obtain a stratified flow. This is crucial to reduce the capital expenditure (namely number, size and sloping length of fingers) and make the construction simpler, with benefits in terms of support structures.

Particularly in offshore production fields, the dimension reduction and consequently an overall lower weight is crucial, since the equipment shall be carried to the installation site and deployed subsea.

Actually, there are not commercial tools for the sizing of slug

* Corresponding author.
E-mail addresses: a.pierro@techfem.it (A. Pierro), s.spadoni@techfem.it (S. Spadoni), f.chiappetta@techfem.it (F. Chiappetta), fr.ferrini@techfem.it (F. Ferrini).

Peer review under responsibility of Southwest Petroleum University.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.petlm.2017.12.006

catchers. Usually, its sizing is dictated by the maximum liquid volume that has to be stored. However, it must be able to intercept the larger possible slug size received from the multiphase pipeline at any moment, according to the worst scenarios in terms of surge liquid incoming volumes.

In case of unpiggable trunklines, the design of the slug catcher is dictated by changing production profile (ramp-up) or by intermittent flow due to pipeline elevation profile. Consequently, the slug catcher is sized to accommodate the hold-up volume changes between the previous steady state flow and the final flow figure. Instead, in case of piggable trunkline, it can be sized according to the amount of liquid hold-up expected to be accumulated along the line during pigging intervals.

The purpose of this paper is to present a simulation model based on the open-source software for computation fluid-dynamics OpenFOAM®, to provide to engineers a new approach for the sizing of slug catcher finger-type handling different flow conditions. This is useful to improve the knowledge of phenomena, studying also the distribution of different flow patterns inside the equipment. The purpose is to reach a detailed final design improving the classical empirical methods approach, with a fluid-dynamic analysis using as input the actual conditions that the slug catcher is demanded to face.

Since the computational time is quite high, the analyses require a proper modelling and a dedicated workstation. However, it enables the process engineer to analyse a high number of case, simply changing the input parameter as the production profile variations require.

A computation fluid-dynamic approach has been already proposed by Frank and Hans Bos, [1,2]. The limit of these studies is that they analyse only single section of the slug catcher, the inlet header in Ref. [1] and a single finger in Ref. [2]. Instead in this paper, the slug catcher is studied in a single complete model (see Fig. 3), excluding the storage section.

2. Basic data - case of study

The models that, at the moment, we have developed by OpenFOAM® are relevant to existing slug catchers, dimensioned in former times with classic empirical method and currently in operation. In this paper, it is presented the model of a slug catcher built for Western Libya Gas Project.

It was studied for the slug removal which would occur in different operating conditions, but at the end it was sized to accommodate the liquid storage volume after pigging.

The previous studies have brought to the selection of an 8-finger slug catcher with a finger diameter of 36”.

The present analysis takes into consideration only the design cases, i.e. pigging and hydrodynamic slugs from most critical trunkline. The input data used for simulations, in terms of hold-up and phase superficial velocity, are obtained with OLGA® software. The resulting data correspond to the years characterised by the highest liquid hold-up.

General physical properties of phases, used in the simulations, are reported in Table 1.

Table 1
System physical properties.

	Symbol	Value	Unit
Oil density	ρ_{oil}	850	kg/m^3
Oil kinematic viscosity	ν_{oil}	10^{-4}	m^2/s
Gas density	ρ_{gas}	0.85	kg/m^3
Gas kinematic viscosity	ν_{gas}	$1.48 \cdot 10^{-5}$	m^2/s
Pressure	P	25	bar
Trunkline diameter	D	20	inch

2.1. Pigging case

Fig. 1 shows the hold-up trend and the phase superficial velocity versus time at the input section of the slug catcher, resulting from the pigging case.

2.2. Hydrodynamic slug case

Fig. 2 shows the hold-up and the phase superficial velocity versus time at the input section of the slug catcher, resulting from a hydrodynamic slug case. The hydrodynamic slug takes into account also the terrain slug caused by the pipeline elevation profile.

3. Model description

As shown in Fig. 3, the symmetry of the slug catcher allows to study only a half, in terms of finger number and length. This is to reduce the computational time. It is not a limitation because the model is focused on separation section, which is the core of this paper.

Due to the large amount of calculations, a dedicated workstation is required to obtain the final results in a brief period. About 36 h were required to complete each simulation, so the model optimization and the adequate machine are crucial to reduce the computational time. Anyway, through the OpenFOAM®post-processor Paraview®, it is possible to check the simulation during the run, monitoring the flow evolution and just in case make a corrective intervention, without waiting the end of the CFD calculation.

The advantage of a CFD approach is the possibility to build a “tailor-made” model for the specific project, exploring all the selected production conditions, based on the actual input data in terms of production rate and flow patterns, and according to construction requirements.

3.1. CFD model

The CFD modelling has been performed by means of the open-source software OpenFOAM®. The software is based on a finite-volume approach. First order schemes are used for space and time discretization. A Preconditional Conjugate Gradient (PCG) solver has been used to get the pressure field, while a Smooth Solver has been used to get the velocity fields [3].

The computational domain is illustrated in Fig. 3, with the used patch highlighted as shown in the legend. The symmetry of the slug catcher allows to study only half model. In wireframe are reported the parts of the finger type slug catcher not analysed in this work.

A mesh sensitivity, with different levels of refinement, has been carried out in order to optimize the grid. For all models, a good compromise between representative results and computational time has been obtained with cell dimension of $D_{finger}/10$. For the grid independency study see Appendix A.

The boundary conditions are respectively:

(1) inlet: Dirichlet boundary condition on α_v and velocities, zero gradient conditions on pressure;
(2) symmetry: plane of symmetry, default function implemented in OpenFOAM®;
(3) outlet_o: Dirichlet boundary condition on pressure; zero gradient conditions on α and velocities;
(4) outlet_g: Dirichlet boundary condition on pressure; zero gradient conditions on α and velocities;

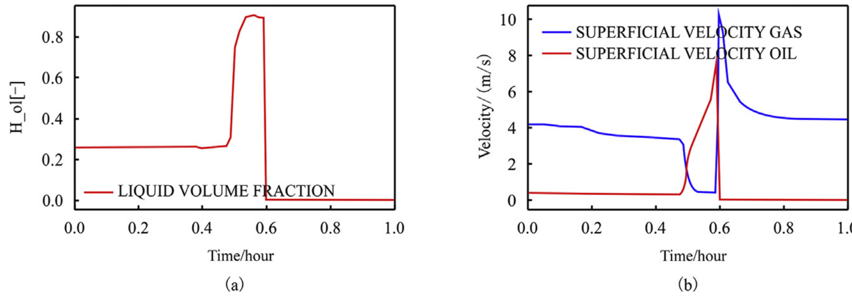

Fig. 1. (a) Hold-up trend for pigging case. (b) Superficial velocities of gas and oil phase.

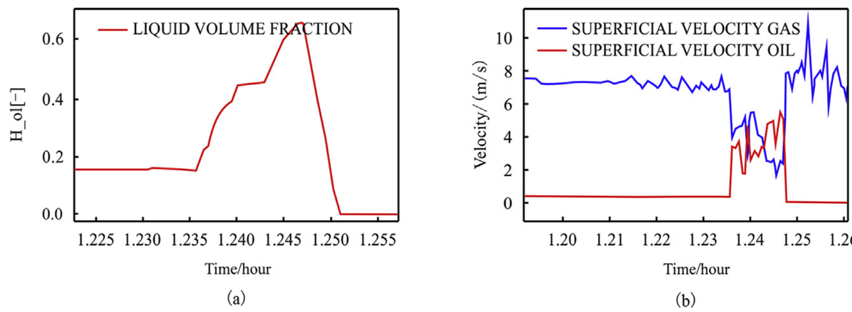

Fig. 2. (a) Hold-up trend for hydrodynamic slug case. (b) Superficial velocities of gas and oil phase.

(5) pipe: zero gradient boundary condition on α_v and pressure, no-slip condition for velocities.

α_v is the volume fraction of each phase, calculated as:

$$\alpha_v = \frac{V_{\varphi 1}}{V_{\varphi 1} + V_{\varphi 2}}$$

In order to simulate correctly the dynamic of the problem, the boundary condition on α and velocity at inlet are time varying, see Ref. [3].

The timestep is variable along the simulations, in order to respect the Courant stability condition:

$$Co = \frac{\delta t \cdot |U|}{\delta x} \leq 1$$

where δt is the timestep, δx is the grid cell size and U is the maximum velocity. To guarantee the stability of the simulations, a maximum Courant number of 0.5 has been used.

The Reynolds number at the slug catcher inlet, based on pipe diameter, is $Re = 2535$ for liquid phase, and ranges between 137000 and 257000 for gas phase depending on slug case.

The residuals are in the order of 10^{-5} along all the runs.

3.2. Governing equations

The multi-phase flow is simulated by solving the Navier-Stokes equation for multiphase flow, [4]. Only the basic governing equations are listed here.

The continuity equation reads:

$$\frac{\partial}{\partial t}\alpha_k \rho_k + \nabla \bullet \left(\alpha_k \rho_k \overline{U_k}\right) = 0$$

The momentum equation reads:

$$\frac{\partial}{\partial t}\alpha_k \rho_k \overline{U_k} + \nabla \bullet \left(\alpha_k \rho_k \overline{U_k}\,\overline{U_k}\right) + \nabla \bullet \left(\alpha_k \rho_k \overline{R}_k^{eff}\right) = \alpha_k \nabla p + \alpha_k \rho_k g + \overline{M}_k$$

where k denotes the phase, α the volume fraction and ρ the density of the respective fluid. $\overline{R}_k^{eff}$ is the combined Reynolds (turbulent) and viscous stress, $\overline{M}_k$ denotes the average momentum transfer between the phases, which may include drag forces, lift forces, turbulent dispersion, etc.

3.3. Interfacial properties

OpenFOAM® needs the specification of the *interfacialProperties* dictionary to simulate the interface between the two phases, particularly it is necessary to define the drag model. The drag model used is the "Schiller-Naumann" model, [3]:

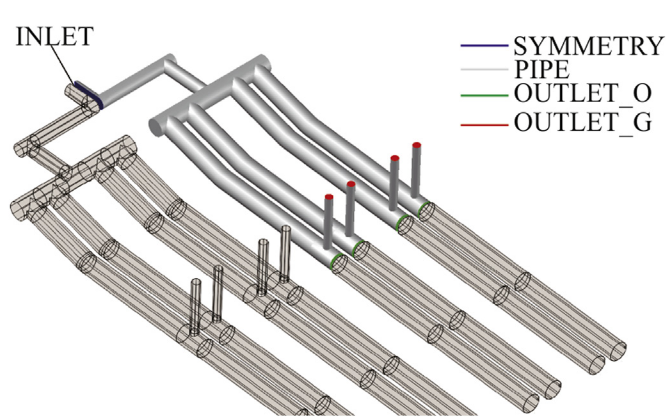

Fig. 3. Typical domain for the CFD runs.

$$C_D = \frac{24}{Re_p} \cdot \left(1 + 0.15 Re_p^{0.687}\right)$$

where Re_p is the relative Reynolds number for the continuous phase (c) and the dispersed phase (d):

$$Re_p = \frac{\rho_c U_r d_d}{\mu_c}$$

where ρ_c and μ_c are respectively the density and viscosity of the continuous phase, U_r is the relative velocity between phases, defined as $U_r = U_c - U_d$ and d_d is the particle diameter of the dispersed phase.

For flow Reynolds number larger than 1000, the drag coefficient is approximately constant: $C_D = 0.44$.

3.4. Turbulence model

The turbulence model used for simulations is the k-equation model for “Large Eddy Simulation” (LES), see Ref. [3].

4. Results and discussion

This section presents the results obtained from different simulations, with the purpose to optimize the separation section of a finger-type slug catcher. Section 4.1.1 and 4.1.2 report respectively the results for pigging and hydrodynamic slug for the analysed cases, with the purpose of sizing optimization. Section 4.2 analyse the liquid carry-over problem.

4.1. Finger sizing

In order to optimize the sizing separation section, the following slug catcher configurations have been analysed:

(1) 8 fingers with nominal diameters 28”;
(2) 4 fingers with nominal diameters 28”;
(3) 8 fingers with nominal diameters 24”;
(4) 4 fingers with nominal diameters 24”;
(5) 8 fingers with nominal diameters 22”.

Table 2 summarizes the main dimensions, in terms of nominal diameter and length, of each single model analysed. Table 2 reports the full-size dimensions for entrance section, but only reduced model has been simulated (see Fig. 3):

The model 8 fingers with diameter 22″ has been analysed only for liquid carry over investigation, see section 4.2.

4.1.1. Pigging case

Fig. 4 and Fig. 5 refer to the same timestep 0.57 h (see Fig. 1), when the incoming liquid volume fraction is maximum.

From Fig. 4(d) it is possible to see that the solution 4 fingers with diameter 24″ does not ensure the phase separation. In fact, the

Table 2
Model dimensions for each analysed case.

	Splitter	Inlet Header	Downcomers_1	Downcomers_2
8 fingers, D = 28”	D = 20″, L = 7 m	D = 28″, L = 5.2 m	D = 28″, L = 3 m, slope = 15°	D = 28″, L = 5.5 m, slope = 4%
4 fingers, D = 28”	D = 20″, L = 7 m	D = 28″, L = 3.2 m	D = 28″, L = 3 m, slope = 15°	D = 28″, L = 5.5 m, slope = 4%
8 fingers, D = 24”	D = 20″, L = 9 m	D = 24″, L = 4.5 m	D = 24″, L = 2.5 m, slope = 15°	D = 24″, L = 4.5 m, slope = 4%
4 fingers, D = 24”	D = 20″, L = 9 m	D = 24″, L = 2.5 m	D = 24″, L = 2.5 m, slope = 15°	D = 24″, L = 4.5 m, slope = 4%
8 fingers, D = 22”	D = 20″, L = 9 m	D = 22″, L = 4.2 m	D = 22″, L = 2.5 m, slope = 15°	D = 22″, L = 4.5 m, slope = 4%

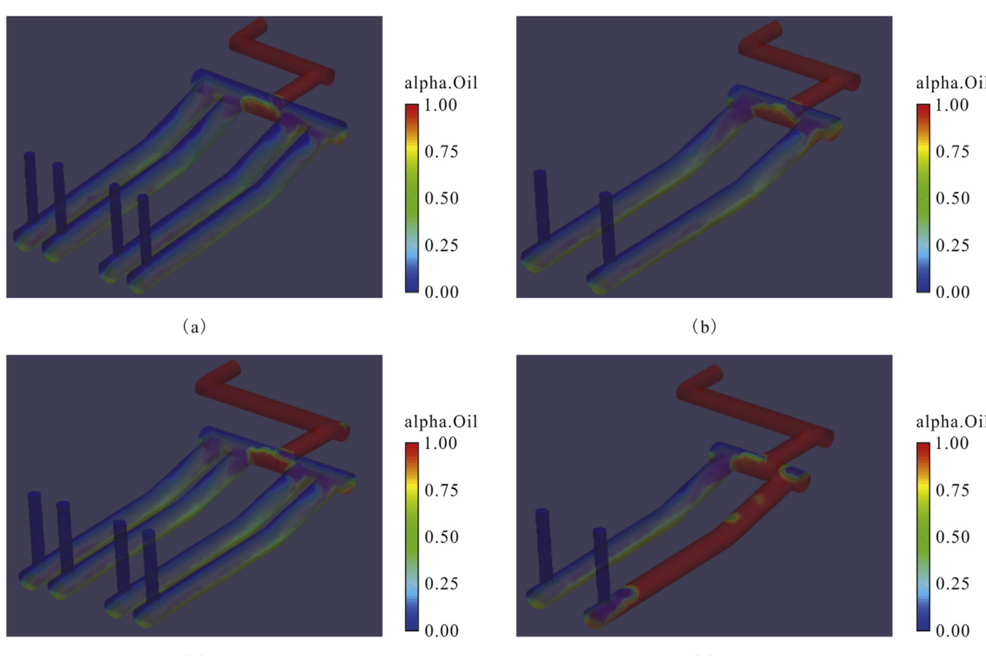

Fig. 4. (a) Oil volume fraction for slug catcher 8 finger, D = 28”. (b) Oil volume fraction for slug catcher 4 finger, D = 28”. (c) Oil volume fraction for slug catcher 8 finger, D = 24”. (d) Oil volume fraction for slug catcher 4 finger, D = 24″.

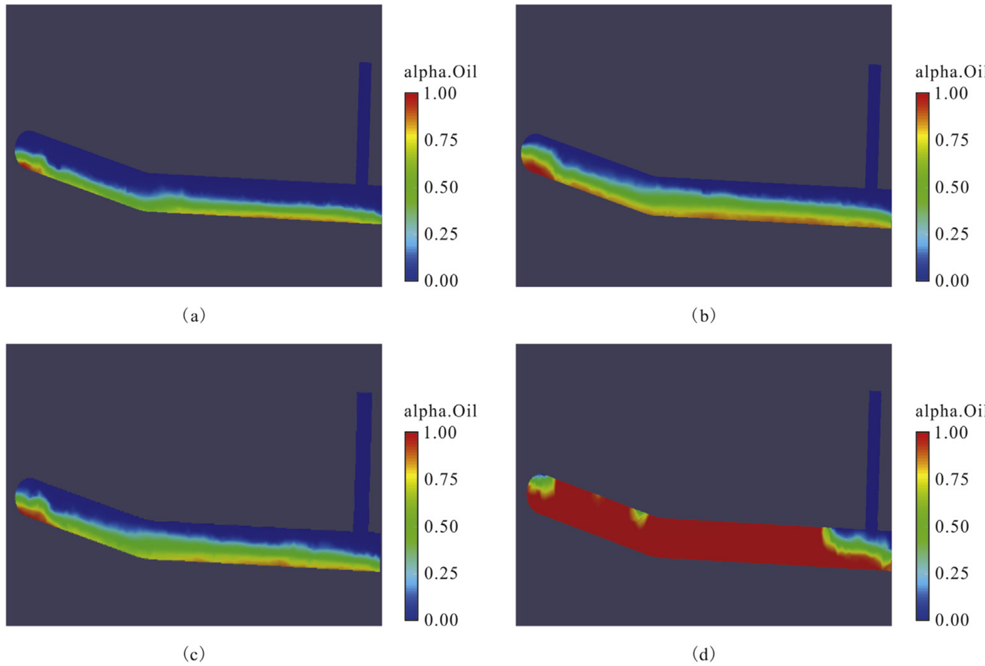

Fig. 5. Finger section: (a) Oil volume fraction for slug catcher 8 finger, D = 28”. (b) Oil volume fraction for slug catcher 4 finger, D = 28”. (c) Oil volume fraction for slug catcher 8 finger, D = 24”. (d) Oil volume fraction for slug catcher 4 finger, D = 24”.

finger dimensions are not sufficient to absorb the slug volume.

Since the length between the splitter and the inlet header is too short, the flow can't be straightened, so it tends to maintain the right side of the slug catcher, and it explains the reason why the flow distribution between the fingers is not symmetric, like in the other cases. Fig. 6 shows the asymmetric distribution of oil velocity (Y component) inside the inlet header.

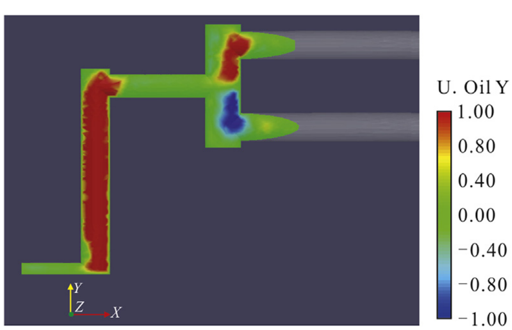

Fig. 6. Y component of oil velocity.

Increasing the distance between the splitter section and the inlet header, the flow returns symmetric (Fig. 7(b)), but however the separation section continues to be not sufficient to absorb the slug volume, as shown in Fig. 7(a).

Another possible solution is to increase the distance between the fingers, changing the flow distribution inside the inlet header, in order to restore the symmetry. Simply by changing the base model, it is possible to study different slug catcher configurations, aimed to ensure the correct operation of the equipment with a certain level of detail.

This shown that the CFD approach is very flexible. In fact, allows the engineers to study the best design solutions according to correct operation of the equipment, construction requirements and capital expenditure.

4.1.2. Hydrodynamic slug case

Fig. 8 and Fig. 9 refer to the same timestep 1.248 h (see Fig. 2) when the incoming liquid volume into the fingers is maximum, due to the passage of three slugs.

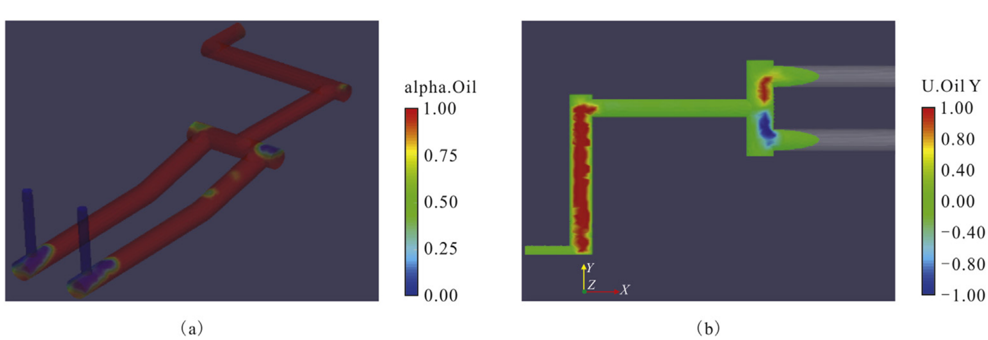

Fig. 7. Increased distance between splitter and inlet header: (a) Oil volume fraction for slug catcher 8 finger, D = 28”. (b) Y component of oil velocity.

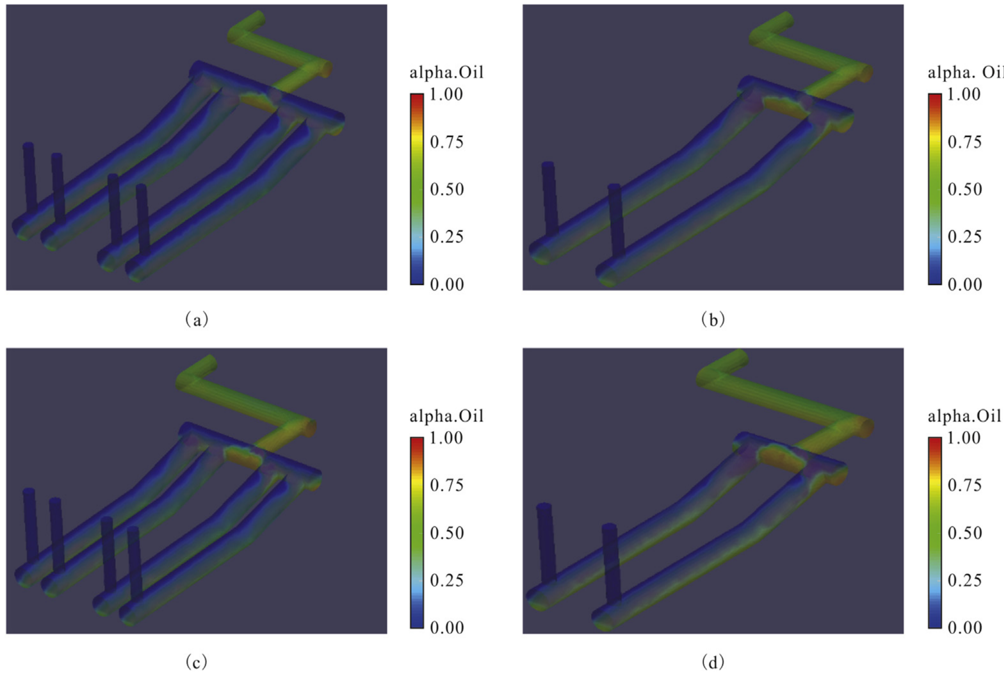

Fig. 8. (a) Oil volume fraction for slug catcher 8 finger, D = 28". (b) Oil volume fraction for slug catcher 4 finger, D = 28". (c) Oil volume fraction for slug catcher 8 finger, D = 24". (d) Oil volume fraction for slug catcher 4 finger, D = 24″.

4.2. Liquid carry over

An excessive reduction of finger diameter causes an increase of phase velocities. This can lead to liquid being carried over into gas risers and consequently to the gas outlet section. This has to be taken deeply care in order to avoid damage on the equipment downstream for gas treatment.

OpenFOAM® provides functionalities that can be executed during a simulation to obtain a derived data, for example a force coefficient during a simple flow calculation. To study the liquid volume fraction carried over into the gas risers, it has been used the function *fieldValue*. This function allows to calculate the average of an arbitrary field across a patch. In this case it was extracted the $\alpha_{oil,v}$ average value across the gas outlet section (patch outlet_g, see

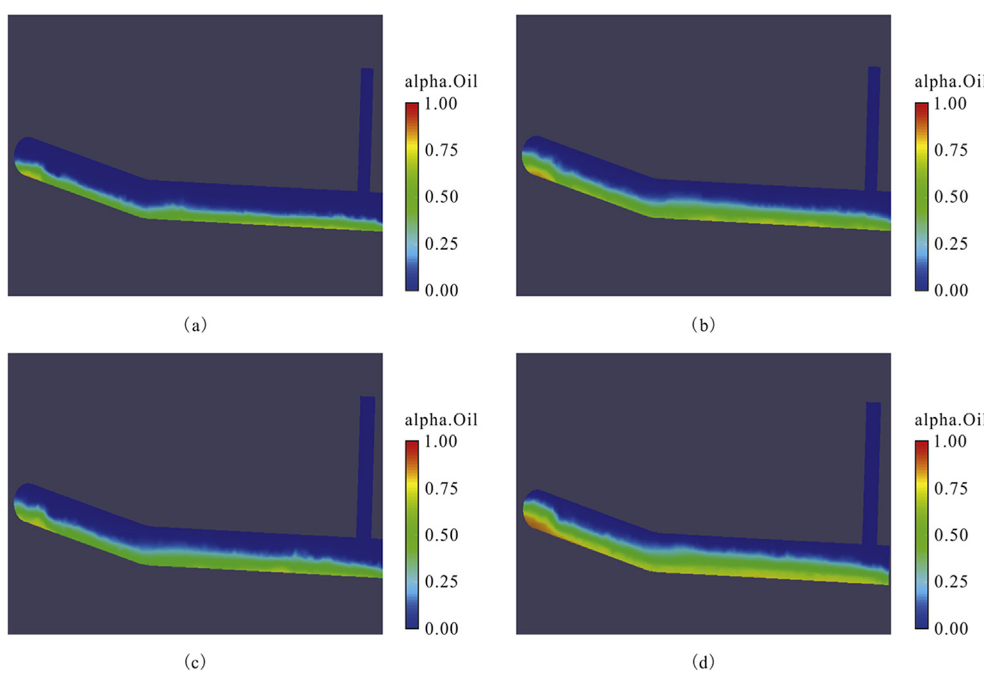

Fig. 9. Finger section: (a) Oil volume fraction for slug catcher 8 finger, D = 28". (b) Oil volume fraction for slug catcher 4 finger, D = 28". (c) Oil volume fraction for slug catcher 8 finger, D = 24". (d) Oil volume fraction for slug catcher 4 finger, D = 24″.

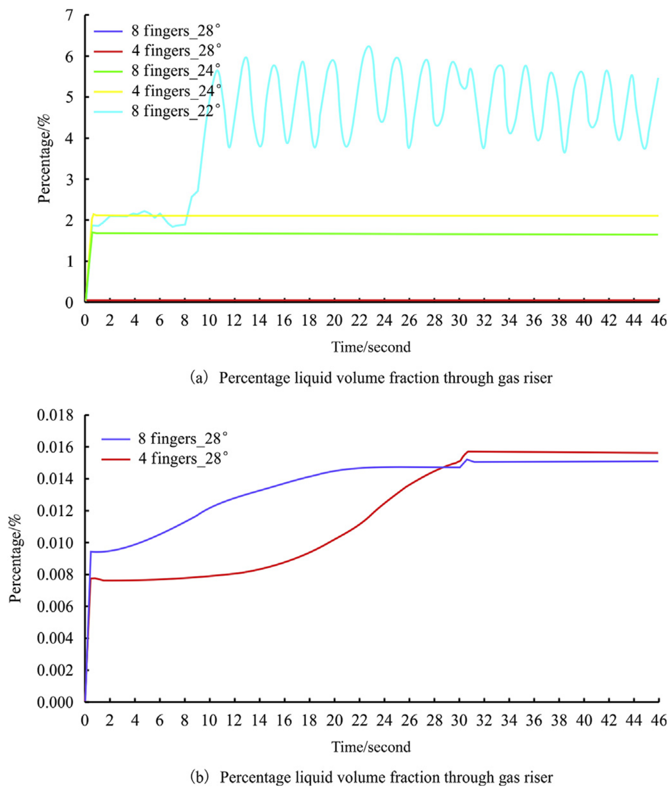

Fig. 10. Percentage liquid volume fraction through gas riser: a) All analysed case. b) Zoom on 28″ fingers cases, not visible in a).

Fig. 3).

Fig. 10 reports the $\alpha_{oil,v}$ trends for different slug catcher configuration, in a specific time interval during the pigging case. Through these graphs, it is possible to evaluate the oil volume fraction in the gas section. In order to provide a proper design of slug catcher, it is possible to study the optimal position for gas risers, to minimize the liquid carry-over fraction.

From Fig. 10 it is possible to note that the solution with finger diameter 22″ is not applicable, due to high quantity of oil particle carried over into gas section. Furthermore, the results highlight a fluctuation of liquid volume fraction due to the increasing of gas velocity, being the effect of a stratified-wavy flow in separation section.

The graphs reported in Fig. 10 shows the same trend already highlighted by Bos in Ref. [2], for the uniform carry over figures. However, these authors did not arrive to stress the sizing up to the arising of the very interesting wavy figure, clearly due to a high disturbed flow in separation section.

5. Conclusions

The model developed in this work allows to:

(1) represent the evolution of fluid dynamics inside the slug catcher for different intake flow conditions;
(2) obtain a “tailor made” design of the slug catcher, based on the actual project data, supporting and improving the current approach with empirical and analytical methods;
(3) study several solutions for the reduction of slug catcher overall dimensions, which is profitable in terms of capital expenditure and installation flexibility.

The reduction of slug catcher overall dimensions is profitable in terms of capital expenditure reduction and installation flexibility. These aspects are of great importance especially in the gathering of offshore production fields, where this kind of equipment is deployed subsea and the total weight of each item may impact on the size and capacity of required laying vessels.

The results of these analyses seem to simulate correctly the physics of the problem, for example the asymmetric behaviour of the flow when the length between the main splitter and the inlet header is reduced (Fig. 6). However this work is only the beginning and in the nearfuture we are going to validate the model through the comparison versus analytical methods and available experimental data.

Appendix A

A mesh sensitivity on the analysed domain has been performed. It has been studied three different levels of mesh refinement for the case 8 fingers with diameter 28”. The finer grid is made of 66999 cells, the medium grid of 31970 cells and the coarser of 16195 cells. For all grids, the refinement ratio is the same.

The mesh sensitivity has been performed only for the case with 8 fingers with diameter 28″ during the pigging case. Fig. A.1. shows the percentage liquid volume fraction at fingers outlet for different mesh refinement.

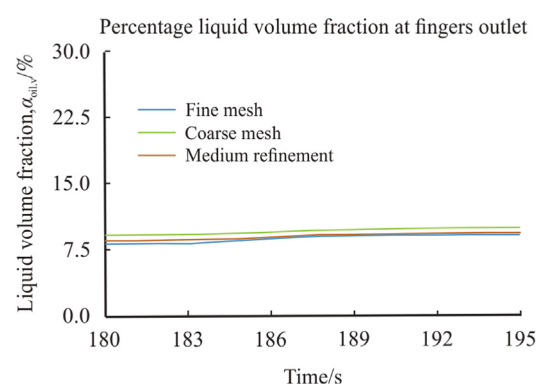

Fig. A.1. Percentage liquid volume fraction at fingers outlet.

Fig. A.1. shows a substantial overlap between the finer mesh and the grid with a medium refinement. Little differences are highlighted for the coarser grid. The order of convergence of the grid has been calculated as follow:

$$p = \ln\left(\frac{\int_0^T (\alpha_{oil,fine} - \alpha_{oil,medium})dt}{\int_0^T (\alpha_{oil,medium} - \alpha_{oil,coarse})dt}\right) \Big/ \ln\sqrt{2}$$

The resulting order of convergence is 1.52. Considering that the theoretical value for the order of convergence is 2, this is a good result. However, for sake of accuracy, the finest mesh has been chosen.

References

[1] F.M. Bos, H.J. Bos, CFD Analysis of the Header of a Finger-Type Slug Catcher, Dynaflow Research Group, 2010.
[2] F.M. Bos, H.J. Bos, CFD Analysis of the Two-phase Flow in the Finger of a Slug Catcher, Dynaflow Research Group, 2010.
[3] OpenFOAM User guide; http://www.openfoam.com.
[4] H. Rusche, Computational Fluid Dynamics of Disperded Two-phase Flows at High Phase Fraction, PhD thesis, Imperial College of London, 2002.