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Nsidibe Sunday. Studying the Effect of Turbulence Models on Flow Pattern and Pressure Drop for a Two-Phase Hydrocarbon Flow in Horizontal Pipelines using Openfoam. AIP Conference Proceedings of ICNAAM 2021, Sep 2021, Rhodes, Greece. hal-03869310

HAL Id: hal-03869310

<https://hal.science/hal-03869310>

Submitted on 24 Nov 2022

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Studying the Effect of Turbulence Models on Flow Pattern and Pressure Drop for a Two-Phase Hydrocarbon Flow in Horizontal Pipelines using Openfoam

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Abstract. As hydrocarbon search approaches next frontiers in a hostile subsea surrounding. Hydrocarbon multiphase transportation is now mainstream with a robust system being designed integrating very reliable flow assurance techniques. Two-phase flow in pipes finds application in many industrial activities especially, in the energy sector. Therefore, the need to model systems that correctly predict flow patterns and pressure drop is very important during the design and planning of a fluid transport system. This study aims to examine a two-phase oil and gas flow in a horizontal pipeline to probe the impact of different turbulence models on the flow behavior and pressure drop. A transient 3D CFD simulation was carried out on a half-pipe using OpenFOAM source code based on the Volume of Fluid (VOF) method. InterFoam, a two-phase solver that resolves Reynolds- Averaged Navier-Stokes (RANS) equations was first modified to implement three turbulence models (standard k-epsilon, low Re k-epsilon, and SST k-omega) and is employed to identify flow patterns. Generated numerical results of pressure drop were compared for different superficial gas and oil velocities with the results of the mechanistic model developed by Petalas and Aziz. Results are further discussed in the context of the accuracy of the required turbulence models on flow patterns prediction.

INTRODUCTION

Hydrocarbon two-phase flow is commonly encountered in the petroleum, chemical, and nuclear industries, especially in the combustion systems, power generation, and oil and gas transport networks [1], [2]. The study of flow effects on qualities like flow patterns, pressure drop, and flow rates have long been of engineering interest [3]. So, the demand for quantitative information about fluid flow is important for pipeline design, safety, and optimization [3], [4]. Pipelines design demands a lot of precise estimation of pressure drop to guarantee hydrocarbon does not drift during transport from its working limits thereby causing injury to personnel, equipment, or plant [1], [2]. Thus, the sizing of multiphase lines needs distinct or extra measures as those applied to single-phase lines [2], [5]. Flow assurance is very important for two-phase fluids transportation and called for evaluation on both transient and steady-state conditions that initiate likely issues that could emerge in the system [2], [6], due to perturbations that give rise to changes in flow regime down the system [2], [6].

OpenFOAM has recently gained a firm grip as a substitute simulation tool to conventional commercial software. Although interFoam solver in OpenFOAM has shown good accuracy with existing validations, it has hitherto been limited to certain users and its usage to a broad scope of multiphase flow applications is yet to be entrenched [1], [7]. Also, not many attempts have been made to utilize different turbulence models for two-phase flow applications in order to obtain the right choice of a turbulence model.

In line with this, the paper seeks to further validated the 3D numerical simulations results using interFoam by studying the effect of the different turbulence models on flow patterns and pressure drop for different ranges of oil and gas flow combinations and to also describe the accuracy of the turbulence models for two-phase oil and gas flow patterns. The work is advantageous in selecting better turbulence models for flow patterns predictions and pressure distribution in hydrocarbon two-phase flow. The intention is to reduce uncertainties and associated risks with the business and then establish the foundation for a sustainable reference network.

NUMERICAL FRAMEWORK

The open-source C++ CFD software OpenFOAM v.4.0 was utilized to simulate different two-phase flow cases, based on the Finite Volume Method (FVM) executed in the considered system of equations. Different turbulence models were implemented for all simulations, they are the Standard k- ϵ model [8], low-Re k- ϵ model [9], and SST k- ω model [10]. The low Re k-epsilon turbulence model supporting the low y^+ approach was used for the grid-sensitive studies because it allows for accurate near-wall treatment with an automatic switch from a wall function to low-Reynolds number formulation by grid spacing [11].

For a two-phase incompressible, isothermal, and immiscible turbulent flow using the interFoam solver based on the VOF approach, the equations for each phase are seen below [12]–[14]:

Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \quad (1)$$

Momentum conservation equation

$$\frac{\partial \rho U}{\partial t} + \nabla \cdot (\rho U U) = \nabla p + \nabla \cdot [\mu_{eff} (\nabla U + \nabla U^T)] + (\rho g) + F_s \quad (2)$$

Volume of Fluid equation

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha U) + \nabla \cdot (1 - \alpha) \alpha U_r = 0 \quad (3)$$

where: U is the velocity field, P is the pressure, ρ is the density, t is the time, g is the acceleration due to gravity, μ_{eff} is the effective dynamic viscosity which is the summation of the molecular and turbulent viscosity ($\mu + \mu_t$), U_r is the relative velocity between phases, α is the fluid volume fraction, and F_s is the surface tension force.

A three-dimensional half pipe geometry was constructed with a diameter and pipe length of 0.08 m and 5 m respectively and mesh consisting of 144000 hexahedral elements as seen in Figure 1. The geometry and the structured grids were both created by the blockMesh utility in OpenFOAM.

VALIDATION

For the validation of the numerical simulation results, the mechanistic model of Petalas and Aziz [15] was used for comparison with the corresponding flow patterns and pressure drops. Figure 2 shows the flow pattern map of Petalas and Aziz's mechanistic model for the hydrocarbon system at 0° inclination (horizontal).

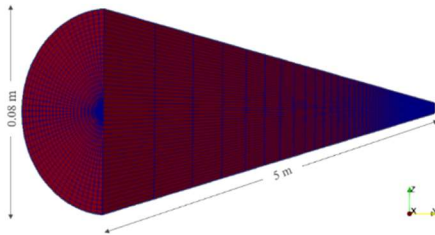


Figure 1. Mesh topology in the cross-section of a half-pipe

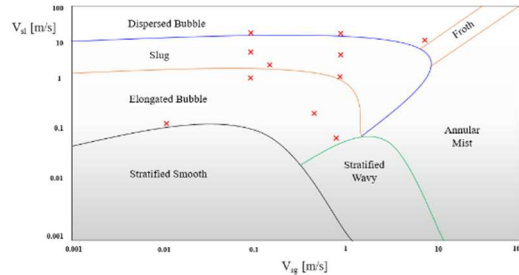


Figure 2. Petalas and Aziz flow pattern map for hydrocarbon horizontal system with simulation points

RESULTS AND DISCUSSIONS

1. Effect of turbulence models on flow patterns

The general flow patterns visualized using three different turbulence models are presented and compared with the Petalas and Aziz model as shown in Table 1. Figure 3 gives a graphical flow pattern with the volume fraction of oil described as α . The red color indicates the liquid (oil) phase ($\alpha = 1$), the blue color signifies the gas phase ($\alpha = 0$), while $\alpha = 0.5$ represents the interface between both phases. In summary, the different models evaluated the

hydrocarbon flow regime with different accuracy. The low Re $k-\epsilon$ and the $k-\omega$ SST turbulence models are the most reliable models because it provides a good agreement with the mechanistic model results.

2. Effect of turbulence models on the pressure gradient and error comparison

The pressure gradient at different superficial gas and oil velocities was compared using different turbulence models (Table 2). It is observed that the turbulence models estimated pressure drop with different accuracy as seen in Fig. 4 a & b.

Table 1. Comparison of Turbulence Models on the Flow Pattern.

Case	V_{sl}	V_{sg}	Petalas-Aziz Model	Krumrick 3D Model	Present work $k-\epsilon$	Present work Low Re $k-\epsilon$	Present work $k-\omega$ SST
1	0.09	0.01	EB	SS	SS	EB	EB
2	0.9	0.1	EB	SS	EB	EB	EB
3	0.15	0.7	EB	SW	EB	EB	EB
4	0.05	0.9	EB	-	SW	EB	EB
5	5	0.1	SL	DB	DB	SL	SL
6	1.8	0.2	SL	SW	SL	SL	SL
7	1	1	SL	SW	SW	SL	SL
8	5	1	SL	SL	SL	SL	SL
9	10	0.1	DB	-	DB	DB	DB
10	10	1	DB	F	SL	DB	DB
11	10	10	DB	F	F	DB	DB

Table 2. Effect of Turbulence Models on Pressure Gradient [Pa/m].

Case	Petalas-Aziz Model	Krumrick 3D Model	Present work $k-\epsilon$	Present work Low Re $k-\epsilon$	Present work $k-\omega$ SST
1	16	18	17.82	16.68	16.25
2	238	381	380	231	235
3	105	92	93	104	104.49
4	68	-	121	65.74	68.93
5	3956	3163	3170	3893	3941
6	751	1490	1524	738	749
7	543	1188	1193	544	542.43
8	4639	3770	3755	4612	4628
9	13406	-	8233	13254	13398
10	14530	16560	16505	14187	14519
11	26237	36864	36379	26047	26220

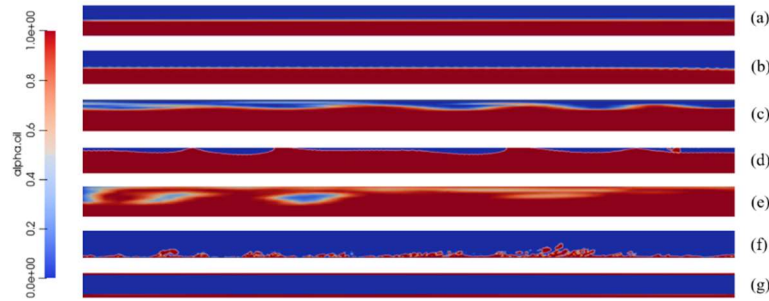


Figure 3. Two-phase flow pattern visualization for (a) stratified smooth, (b) stratified wavy, (c) elongated bubble, (d) slug, (e) dispersed bubble, (f) froth, and (g) annular mist flow.

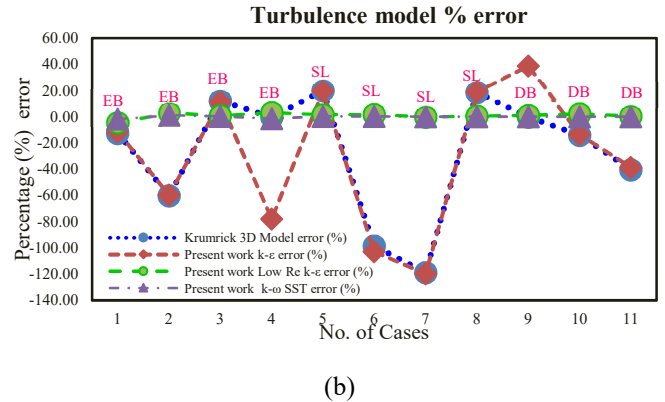
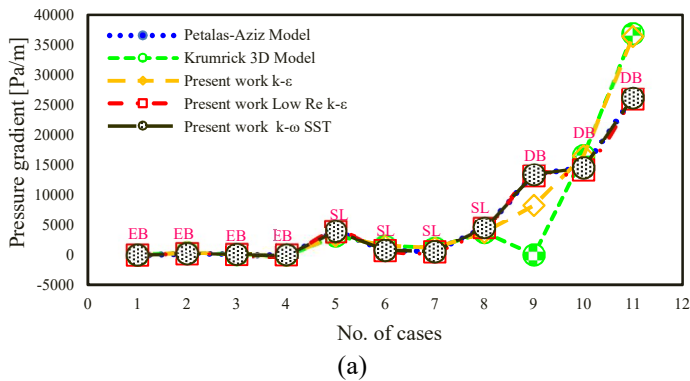


Figure 4. Turbulence model comparison on the pressure gradient.

For the dispersed bubble flows, the standard $k-\epsilon$ turbulence model tends to overpredict and underpredict the pressure drops while the low Re $k-\epsilon$ and the $k-\omega$ SST models show good agreement. The low Re $k-\epsilon$ and the $k-\omega$ SST models for slug flow exhibit better accordance with the mechanistic model with a good linear performance, while a strong discrepancy occurred with the standard $k-\epsilon$ model with errors due to its poor performance. The best agreement

with the mechanistic model is discovered with the low Re k - ϵ and the k - ω SST models for elongated bubble flow, the standard k - ϵ model produces poor results. In conclusion, the low Re k - ϵ and the k - ω SST turbulence models give the best agreement for resolving pressure drop.

CONCLUSION

Hydrocarbon two-phase flow simulations in a horizontal pipeline were run using OpenFOAM. The different turbulence models have been compared for the prediction of flow patterns and pressure distribution. The model's performance was analyzed and validated with the Petalas and Aziz mechanistic model. The predictions of the flow pattern using low Re k - ϵ and the k - ω SST turbulence models showed excellent agreement with the mechanistic model. The standard k - ϵ model didn't give a good flow pattern prediction in the viscous sub-layer region of the pipe. The following important conclusions were put together from this study;

- Simulation results reveal that all flow regimes can occur for two-phase horizontal pipeline flow and the flow regime is also strongly dependent on fluid flow rates
- The pressure gradient is more accurately predicted with a higher superficial liquid velocity than gas velocity.
- The low Re k - ϵ and the k - ω SST give the best agreement to the mechanistic model and is suitable to describe the hydrocarbon flow.

ACKNOWLEDGMENTS

The authors express heartfelt appreciation to the Petroleum Technology Development Fund (PTDF) for funding the Ph.D. thesis at PRISME Laboratory INSA Centre Val de Loire, Bourges- France.

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