

Mathematical Modeling of the Gas Hydrate Formation in a 90° Elbow Utilizing CFD Technique

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Gas hydrate considered as one of the major issues in gas transmission industry forming an ice-like substance by water molecules under certain temperature and pressure conditions. This may cause obstruction of the pipeline and other operating equipment while reducing the throughput of production line ultimately leading to the general pipeline plugging. The goal of this study was to develop a dynamic mathematical model of a gas hydrate production in gas transport pipeline in order to identify the potential areas being prone to collect hydrate, as well as appropriate management for time and zone of inhibitor injection eliminating hydrates. For this purpose, a 90° elbow modelled in 3D and appropriate points to form hydrate determined. Results revealed that at the beginning (i.e.; at the inlet of the geometry and on the inner walls of the elbow) due to the favorable low temperatures and high pressures, methane hydrate formed and increased over time until it blocked the flow path. To validate results of the developed model, since there existed no experimental data for hydrate formation in a 90° elbow; at first; hydrate formation in a 3D pipeline modelled utilizing the kinetics and user defined function (UDF) available for other configurations in the open literature. Then obtained theoretical results of the current work checked against existing pipeline's experimental data of the open literature. The average resulting error was about 8.2 %. One considered this outcome very satisfying.

1. Introduction

Gas hydrate formed under pressure-driven formation of crystalline water around cages occupied by gas molecules, for example methane, at temperatures below 10 °C. Naturally, such conditions found in permafrost and deep at bottom of water tanks. The formation of gas hydrate through the pipelines considered mostly along with petroleum products. Hydrates transported by the flows as solids particles dissipating energy during collisions with the pipe walls as well as each other. This phenomenon significantly increased the pumping costs while formed plugs. Therefore, the presence of these materials considered very harmful. Figure 1 depicted a real pipeline through which gas hydrate formed.

Balakin et al. (2016) investigated the density and deposition of gas hydrates inside industrial tubes using a combination of computational fluid dynamics and modeling with Population Balance Method (CFD-PBM). The resulting model was capable of predicting the agglomeration and deposition of hydrate particles in turbulent oil-dominated flows. Omidi et al. (2016) modeled and simulated thermal decomposition of the hydrates around the vertical pipelines produced gas from subocean sediments. As such, in layers of sediments, the volume of the gas and hydrate analyzed and the related pressure determined. They understudied the effect of the gas flow in the vertical pipelines while porosity of the sediment layers and volume of the hydrate investigated. Results revealed that the raising of the gas velocity in the pipelines enhanced the hydrate decomposition. Naseer et al. (2011) modelled the production of hydrate inside a pipeline-transported gas by CFD-Software. They found out that, some parts of the pipeline with a positive gradient considered the best place for accumulating water and forming gas hydrate. Lorenzo et al. (2018) presented a preliminary sloughing model to determine the effective shear strength of the hydrate deposits considered a key property to predict hydrate detachment and accumulation in gas-dominated pipelines. Musakaev et al. (2018) proposed a mathematical model for decomposition of gas hydrate under a negative (i.e.; below 0°C) initial reservoir temperature. This model took

into account the methane hydrate decomposition in a porous medium with both the frontal surface and extended zone of phase transitions. Saeedi-Dehghani et al. (2016) investigated the Thermodynamic modelling of the gas hydrate production in the presence of some chemical inhibitors like methanol, Ethanol, and Mono Ethylene glycol. Their model could predict the equilibrium temperature of the methane hydrate production. In a different research, Inkong et al. (2016) studied the effects of mixed MES (Methyl Ester Sulfonate) and SDS (Sodium Dodecyl Sulphate) hydrate promoters on formation and dissociation of gas hydrate kinetics. Their work aimed at facilitating the rate of hydrate formation towards improving its storage capacity for transportation. They revealed all concentrations of mixed surfactants enhanced the methane formation rate compared to pure water. Nonetheless, this did not significantly affect the rate of methane recovery. In another study, three phase (liquid-vapour-hydrate) equilibrium for some gas mixture containing methane with various compositions investigated by Lee et al. (2013). Results of their work illustrated that existing of large cavity occupying molecules (e.g., ethylene) increased non-linearly of the equilibrium curves.

In the present study, a 3D CFD model containing three phases (gas-vapour-hydrate) developed to determine the position and time of gas hydrate formation in a gas transfer pipeline including a 90° elbows. Obtained results could help predicting the location and time for injection of hydrate inhibitors to prevent the pipeline plugging.



Figure 1: Gas hydrate in a gas pipeline

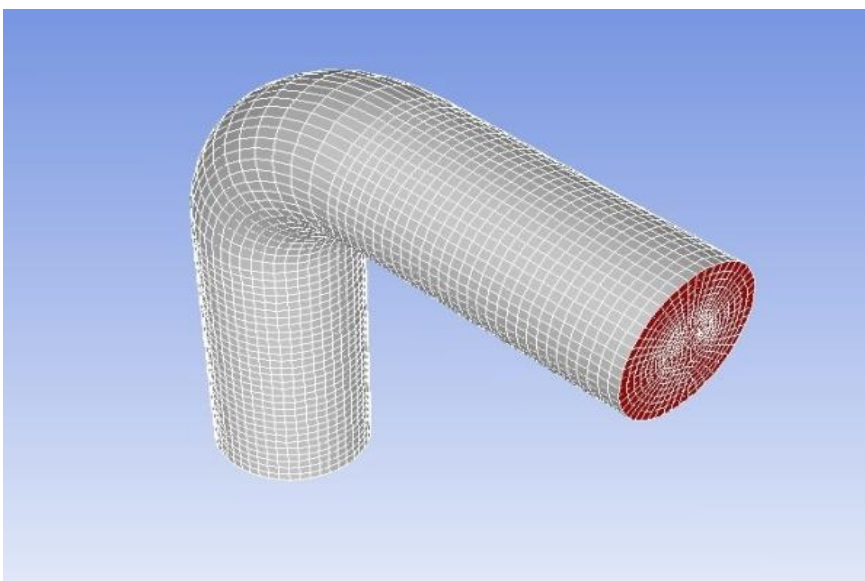


Figure 2: Scheme of a 90° elbow

2. The modeling of gas hydrate

In this study, a 90° elbow modelled in the context of a three-phase flow. The mesh characterization of the model illustrated in Table 1. A schematic of this elbow presented in Figure 2.

Table 1: Characterization of model's mesh

Method	No. of elements	Size function	Relevance Center	Transition
Automatic	36,260	Proximity and Curvature	Fine	Slow

3. Utilized equations

In order to predict the hydrate formation phenomena, one needed to solve equations of continuity, momentum and energy balances simultaneously. These equations provided below.

3.1 The continuity equation

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = 0 \quad (1)$$

Where ρ_m and \vec{v}_m are volume fraction averaged mixture density and mass averaged velocity, respectively.

3.2 The momentum equations

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = \nabla P + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m^T)] + \rho_m \vec{g} + \\ \vec{F} + \nabla \cdot \left(\sum_{k=1}^n \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k} \right) \end{aligned} \quad (2)$$

Where μ_m is volume fraction averaged mixture viscosity and $\vec{v}_{dr,k}$ is the drift velocity of individual phases.

3.3 The energy balance equations

$$\frac{\partial}{\partial t} \sum_{k=1}^n (\alpha_k \rho_k E_k) + \nabla \cdot \sum_{k=1}^n (\alpha_k \vec{v}_k (\rho_k E_k + P)) = \nabla \cdot [k_{eff} \nabla T] + S_E \quad (3)$$

Where E_k was the energy of phase k , α_k known as the volume fraction of phase k , P was its pressure, K_{eff} taken as the effective thermal conductivity, T was the temperature, and S_E represented an energy source.

As long as operating conditions for hydrate formation hold, one assumed that the gas hydrate formation followed the Naseer et al. (2011) equation provided:

$$M_{hydrate} = (\rho_{water} * \alpha_{water}) \oplus (\rho_{gas} * \alpha_{gas}) \quad (4)$$

A mixture of 80% methane gas and 20% water vapour (by volume) utilizing velocity-inlet condition entered into the pipe. Initialization method used was the standard with no slip shear condition and stationary wall motion. The saturated temperature determined with existing experimental data related to every inlet pressure through the following equation (Naseer et al., 2011):

$$T^{sat} = 16.335 * \ln P \oplus 167.08 \quad (5)$$

However, as the process was unsteady, computations repeated in every 10 seconds duration with the Pressure-outlet condition for the exiting flowing mixture. In the present model, PISO (Pressure Implicit Split Operator) method used to couple the velocity and pressure of the system. The K- ϵ -RNG (Re Normalization Group) Viscous model with Standard Wall Functions and Implicit body force also utilized for solving the aforementioned equations. Summary of solution method for model's equations provided in Table 2.

Table 2: Model Solution Methods

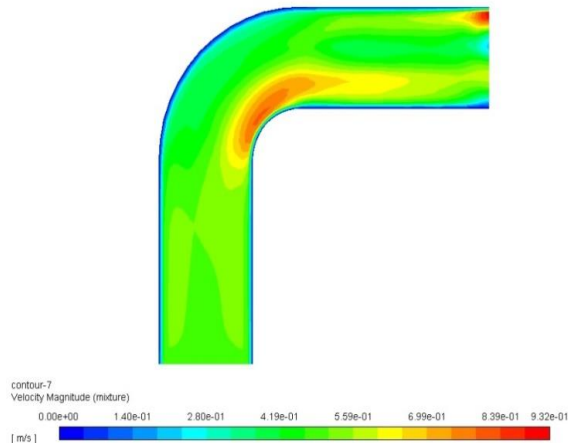
P-V coupling	Gradient	pressure	energy	momentum
PISO	Least Square cell based	PRESTO	First order upwind	First order upwind

Eventually, to increase the accuracy of the computations for discretization as well as the momentum equations in terms of the volume fractions, the first-order up winding incorporated. The operating parameters used for this model presented in Table 3.

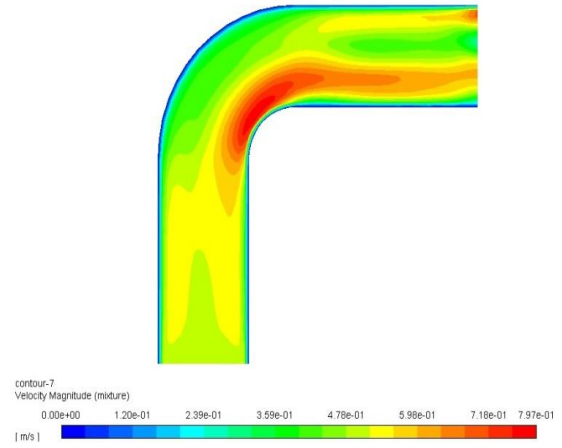
Table 3: Operating parameters of the model

Pipe diameter	Gas inlet temperature	Operating pressure	Inlet velocity	Volume fraction of water vapor in the feed
0.25m	315K	6.3Mpa	2m/s	0.2

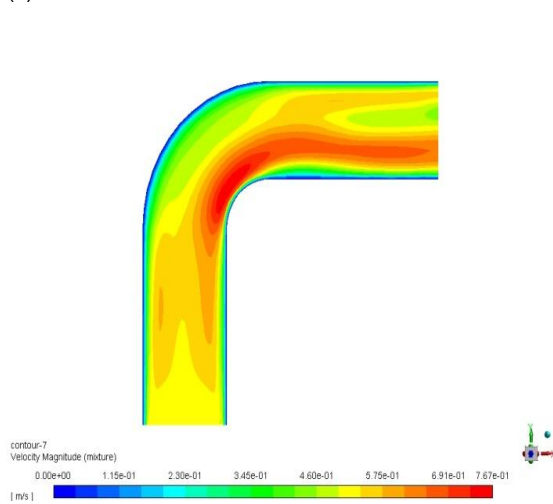
(a)



(b)



(c)



(d)

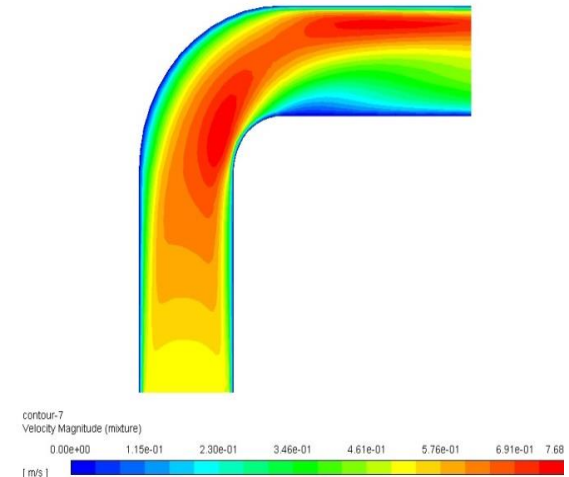


Figure 3: The velocity contours of three phases flow in a 90° elbow understudied (a) t=10s, (b) t=100s, (c) t=1000s and (d) t= 3000s

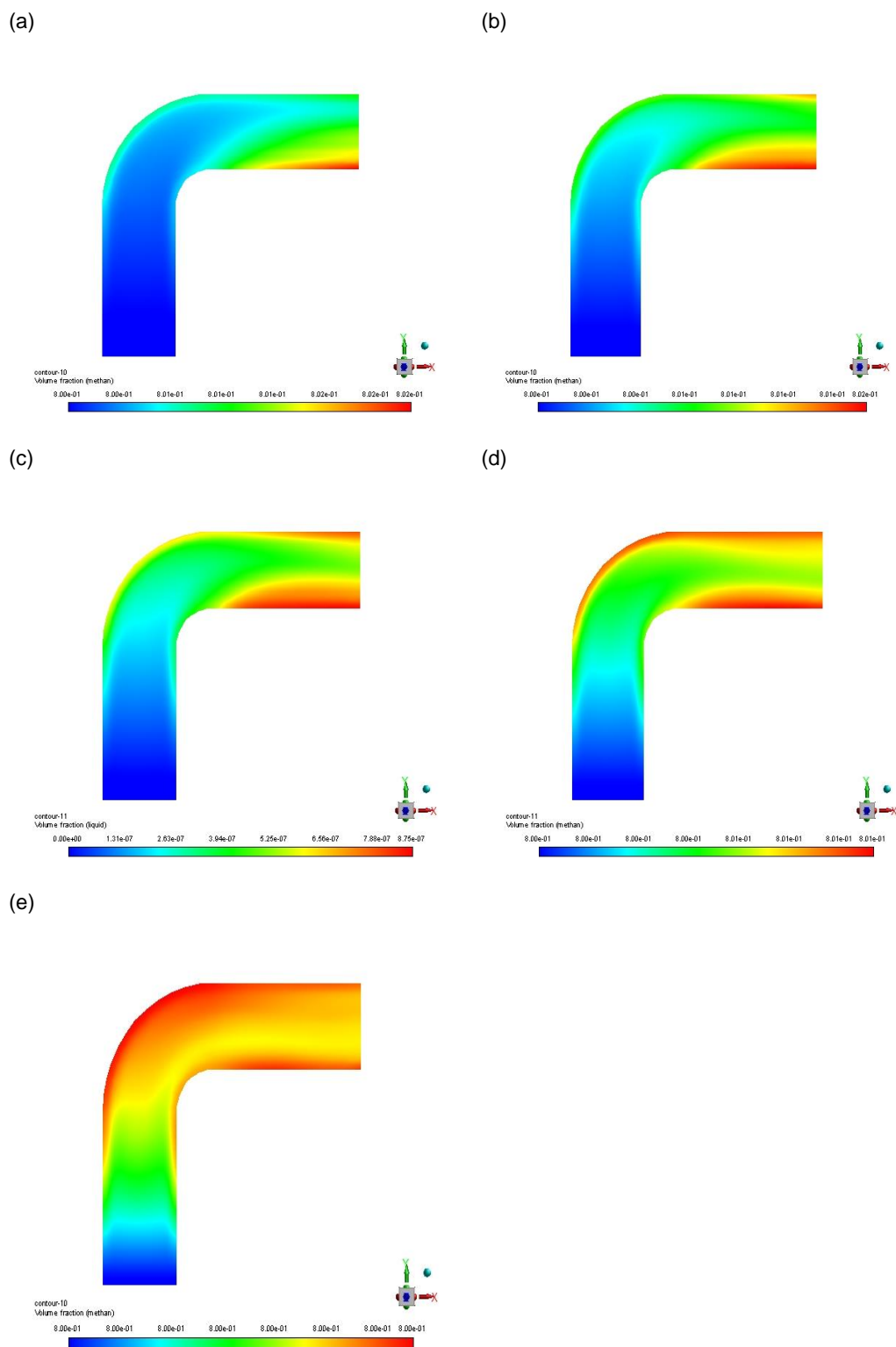


Figure 4: Formation of methane hydrate as time elapsed in terms of the methane volume fraction (a) $t=10$ s, (b) $t=50$ s, (c) $t=100$ s, (d) $t=1,000$ s and (e) $t=5,000$ s

4. Results and discussion

The stream velocity for the three-phase flow systems considered as a function of the flowing route and the amount of formed gas hydrates (Figure 3). Moreover, formation of the hydrates in gaseous regions further enhanced with corresponding high fluid velocities. This attributed to the reduced cross sectional area (due to the hydrate formation) imposed upon the flowing fluid. In other words, the gas hydrate formed at the inlet of the geometry, at the bottom of the pipe and in some parts of the elbow, the velocity increase seemed logical. At the beginning (i.e.; at the inlet of the geometry and on the inner walls of the elbow) due to the favorable low temperatures and high pressures, the methane hydrate formed and increased over time until it blocked the flow path. In the present work, through the computational fluid dynamics the formation of methane hydrate predicted inside a pipeline (Figure 4). This meant one was able to identify the location and amount of the hydrate formed. This information helped to prevent hydrate formation through injecting of inhibitors at a right spot. Furthermore, this model rendered proper operating conditions in order to slow down or stop forming of gas hydrate.

5. Conclusions

One of the most important problems in the gas pipeline transportation considered hydrate formation causing excess line pressure drop ultimately leading to the pipeline plugging. The main goal of the present research was to develop a dynamic model capable of predicting the time and location of gas hydrate formation in a 90° elbow utilizing the CFD technique. In this model, gas hydrate formation predicted utilizing Piecewise-linear mechanism at 0.01sec time intervals. For this purpose, a typical system comprising three phases of methane, liquid water and gas hydrate considered and consequent equations solved through application of an appropriate mixing rule model. Moreover, the PISO method used to solve simultaneously the energy and momentum balance equations. The K- ϵ -RNG model along with Standard Wall Functions used to determine gas turbulence. Ultimately, a first-order up-winding method utilized to discretize the momentum balance equations. Results of this research directly applied to determine amounts and locations of hydrate inhibitor injection needed to prevent problems due to such natural gas transportation through pipelines.

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