

Numerical Modeling Study for the Analysis of Transient Flow Characteristics of Gas, Oil, Water, and Hydrate Flow through a Pipeline

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Abstract—This study presents the development of a four-phase, four-fluid flow pipeline simulator to describe simultaneous flow of gas, oil, water, and hydrate through a pipeline. The model has been equipped with a phase behavior model and hydrate equilibrium model to efficiently estimate thermodynamic and hydrodynamic properties of multi-component mixtures. The governing equations are formulated for describing the physical phenomena of mass, momentum, and heat transfers between the fluids, and the wall. The equations are solved by utilizing the implicit finite-difference method on the staggered-grid system which can properly describe the boundary conditions as well as phase appearance or disappearance. The developed pipeline simulator has been validated against the field data presented by a previous investigator, and their matches are found to be relatively excellent. The model also has been applied to a multi-component, four-phase flow system in order to examine the transient flow characteristics in pipeline. Also, the potential and the location of hydrate formed in the pipeline have been studied by analyzing the flow characteristics. As a result, it was found that a pipeline system flowing gas, oil, water, and hydrate could be optimized by systematically investigating the hydrodynamic variables for the prevention of hydrate formation.

Key words: Four-Phase Flow, Pipeline Model, Phase Behavior, Gas-Condensate, Hydrate

INTRODUCTION

In general, the deposition of solid crystals such as gas hydrates, paraffins, waxes, or asphaltenes in a subsea multi-phase flow pipeline may potentially block the pipe and lead to serious operational problems and other safety concerns such as crushing and breaking of the pipe wall. Since natural gas includes hydrate-forming gases like methane, ethane, propane, butane, carbon dioxide, nitrogen, and hydrogen sulfide, hydrates formation in a long distance subsea natural gas pipeline gives four-phase flow of gas, condensate, water, and hydrate. There are several methods for preventing hydrate formation in pipelines, namely, thermal, chemical, and mechanical methods. These methods require a four-phase, four-fluid model to predict the potential and location of hydrate formation in a pipeline quantitatively.

Several studies on single-phase flow in pipelines have been conducted [Flanigan, 1972; Wylie, 1974; Kwon, 1999; Sung, 1998], whereas there are only a limited number of works on multi-fluid pipeline studies in oil and gas industries. Adewumi and Mucharam [1990] developed a steady-state, gas-condensate model to describe the retrograde condensation process in a long distance pipeline. Kwon et al. [1998] developed an unsteady-state, two-fluid model to analyze transient behaviors of gas-condensate mixture in horizontal and inclined pipe systems.

In the meantime, Tek [1961] presented a correlation for pressure

drop by treating two immiscible liquids as a single phase with averaged mixture properties. Gregory and Forgarasi [1985] confirmed a substantial difference of theoretical results using averaged mixture properties against experimental results. Acikgoz et al. [1992] and Lahey et al. [1992] classified air-oil-water three-phase regimes into ten types from their experiments, and derived a drift flux model to predict volume fractions for three-phase flows. Taitel et al. [1995] developed a prediction method for three-phase stratified flow based on the momentum equation, and Khor et al. [1997] modified the method of Taitel et al. by calculating the shear stresses. The aforementioned three-fluid models are based on a steady-state model, and the volume fractions of each phase are calculated by use of empirical correlation without consideration of mass transfer between the phases. Also, these models are valid only for low velocity conditions in pipelines.

When the gas velocity is high and its void fraction is large in a gas-liquid two phase flowing pipeline, Taitel and Dukler [1976] reveal that a continuous liquid film surrounds a core of gas which contains suspended liquid droplets. This is gas and liquid flows in a thermodynamic point of view, whereas, in hydrodynamic aspect, three-fluid flow of gas, liquid film, and liquid droplets. Saito et al. [1978] developed a steady-state, three-fluid model and they estimated thermo-hydrodynamic characteristics for annular air-water flow with good accuracy. Tso and Sugawara [1990] predicted the axial asymmetric distributions of liquid film in a horizontal annular two-phase flow using a three-fluid model, namely, FIDAS-3DT code. Morooka [1986] and Kang et al. [1999] studied the characteristics of multiphase flow and heat transfer in three-phase fluid-

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ized beds. Bendiksen et al. [1991] applied a dynamic two-phase, two-fluid model, OLGA, on a long distance oil pipeline to analyze steady-state pressure drop, liquid volume fraction, and transitional flowing regime.

Until quite recently, as mentioned above, only a few studies for multi-component, multi-phase transient flow using the multi-fluid model have been conducted. Especially, the development of four-phase, four-fluid model including hydrate formation has not been attempted. Along these lines, in this study, the development of a transient four-fluid model has been attempted to predict transient flowing characteristics of gas, condensate, water, and hydrate mixture in a deepsea natural gas pipeline.

DEVELOPMENT OF FOUR-FLUID HYDRODYNAMIC MODEL

The model consists of three main parts: four-phase flow model in pipeline, phase behavior model, and hydrate equilibrium model. The governing equations were derived under the following assumptions: 1. The overall flow pattern of a four-phase mixture is an annular dispersed flow in cylindrical pipe, as shown in Fig. 1. Condensate oil droplets are uniformly dispersed in continuous gas phase and hydrate droplets are suspended in continuous water phase; 2. Depositions of oil droplet into the water film and entrainment of water droplets and hydrate into the gas core are neglected; 3. Viscous dissipation is neglected; 4. Gravity is the only body force.

1. Governing Equations

The continuity equation for a fluid k can be written as follows:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \frac{1}{A} \frac{\partial}{\partial x}(A \alpha_k \rho_k v_k) = \sum_{j \neq k} m_{kj} \quad (1)$$

$$\alpha_g + \alpha_L + \alpha_w + \alpha_h = 1 \quad (2)$$

where A is cross-sectional area, ρ density, α in-situ volume fraction, v in-situ velocity and m_{kj} mass transfer rate from phase j to k. The subscript k represents gas (g), oil (L), water (w) and hydrate (h), and j implies a phase that is different from phase k.

The momentum equation for phase k can be expressed as follows:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k v_k) + \frac{1}{A} \frac{\partial}{\partial x}(A \alpha_k \rho_k v_k^2) = -\alpha_k \frac{\partial P}{\partial x} - F_k^W - F_k^G - \sum_{j \neq k} (F_{kj}^D + F_{kj}^M) \quad (3)$$

where P denotes pressure and F momentum force. The superscripts W, G, D, and M represent wall friction, gravitational, drag and mass

transfer forces, respectively. Wall friction force is expressed as,

$$F_k^W = \frac{\alpha_k}{\alpha_w + \alpha_h} \frac{1}{2D} \rho_k |v_k| v_k f_k^W \quad (4)$$

where f_k^W is a friction factor. Drag force is as follows:

$$F_{jk}^D = \frac{1}{8} A_{jk}^D \rho_c |v_j - v_k| (v_j - v_k) f_{jk}^D = -F_{kj}^D \quad (5)$$

where A_{jk}^D is the contact area per unit volume between phases j and k and is derived from the annular-mist flow of four fluid model as shown in Fig. 1 [Kwon, 1999]. The subscript C is the continuous phase and f_{jk}^D the interfacial drag coefficient as a function of Reynolds number, flow pattern, equivalent wetted diameter and fluid properties. The interfacial drag coefficients can be calculated by Marble correlation [1969] for gas-to-oil and water-to-hydrate, and Moeck correlation [1970] for others. The average droplet diameter used to predict the interfacial drag coefficients is given by Ulke [1984] for the oil phase and Makogon [1997] for the hydrate phase, respectively. Mass transfer force is the product of mass transfer rate between phases m_{jk} and intrinsic average velocity of the phase losing mass \hat{v}_{jk} .

$$F_{jk}^M = m_{jk} \hat{v}_{jk} = -F_{kj}^M \quad (6)$$

The energy equation for the mixture can be derived with respect to enthalpy and thermodynamic relationships based on the assumption of equal temperature of each phase:

$$\begin{aligned} \sum_k (\alpha_k \rho_k c_{pk}) \frac{\partial T}{\partial t} + \sum_k (\alpha_k \rho_k v_k c_{pk}) \frac{\partial T}{\partial x} &= \sum_k (\alpha_k \rho_k \eta_k c_{pk}) \frac{\partial P}{\partial t} \\ &+ \sum_k (\alpha_k \rho_k v_k \eta_k c_{pk}) \frac{\partial P}{\partial x} + \sum_k \left[\alpha_k \rho_k \frac{\partial}{\partial t} \left(\frac{P}{\rho_k} \right) \right] + \sum_k \left[\alpha_k \rho_k v_k \frac{\partial}{\partial x} \left(\frac{P}{\rho_k} \right) \right] \\ &- \frac{P}{A} \frac{\partial}{\partial x} \sum_k (\alpha_k v_k A) - \sum_k \left[\left(h_k - \frac{P}{\rho_k} \right) m_k \right] + Q_T^W \end{aligned} \quad (7)$$

In Eq. (7), T is temperature, h_k specific enthalpy of phase k. η_k is Joule-Thomson coefficient, c_{pk} is constant-pressure heat capacity for the fluid k. Q_T^W represents overall heat transfer rate to the surroundings and it is a function of average fluid temperature T_{f1} and surroundings T_{f2} , written as,

$$Q_T^W = \frac{4}{D_1} U (T_{f1} - T_{f2}) \quad (8)$$

where D_1 is inside diameter, and U is overall heat-transfer coefficient which is given by

$$\frac{1}{U} = \frac{1}{h_1} + \frac{D_1}{2k} \ln \frac{D_1}{D_2} + \frac{D_1}{h_2 D_2} \quad (9)$$

where D_2 is outside diameter, and k is thermal conductivity of pipe wall. The convective heat transfer coefficients h_1 and h_2 are for mixture and surroundings, respectively, and written by

$$\frac{hD}{k_f} = 0.17 \text{Re}_f^{0.33} \text{Pr}_f^{0.4} \left(\frac{\text{Pr}_f}{\text{Pr}_w} \right)^{0.25} \quad \text{for laminar flow (Re} \leq 2000) \quad (10)$$

$$\frac{hD}{k_f} = 0.023 \text{Re}_f^{0.8} \text{Pr}_f^{0.4} \left(\frac{\text{Pr}_f}{\text{Pr}_w} \right)^{0.25} \quad \text{for turbulent flow (Re} > 2000) \quad (11)$$

where Re and Pr represent Reynolds number and Prandtl number, respectively. The subscripts f and w denote fluid and wall. D is out-

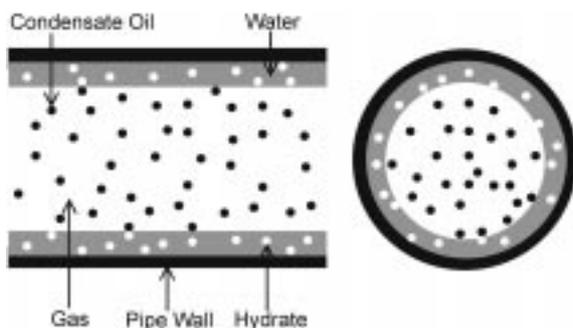


Fig. 1. Annular-mist flow of four fluid model in a round tube.

side or inside diameter of pipe. The symbol h is the convective heat transfer coefficient of either mixture or surroundings.

There are many studies on phase equilibrium [Yoo et al., 1992; Park and Doh, 1997; Lee et al., 2000] and hydrate [Kim et al., 1996; Chun and Lee, 1996; Sung et al., 2000]. Before a pipeline flow model is developed based on the aforementioned governing equations, we have established a phase behavior model to compute physical and thermodynamic properties of the fluid with the aid of the modified Peng-Robinson equation of state. Also, the hydrate equilibrium model has been coded for calculating the hydrate forming condition and its property on the basis of the Munck and Skjold [1988] method which is a modification of the Parrish and Prausnitz [1972] theory.

Now, in the development of the four-phase flow pipeline model, the previously described equations are discretized by using a fully-implicit finite-difference method on the staggered-grid system [Kwon, 1999]. The procedure of the model involves solving for temperature with the energy equation, for pressure with the pressure equation, for partial densities with the continuity equations, and finally, for partial mass flux with the momentum equation.

RESULT AND DISCUSSION

1. Thermodynamic Characteristics of Four-Phase Mixture

In order to analyze the four-phase mixtures in pipe, a gas condensate sample from the North Sea has been used. The composition and properties of the sample data used by Ng et al. [1987] for calculation of hydrate forming conditions are shown in Table 1. Fig. 2 shows the resulting P-T diagram for a four-phase mixture obtained by the phase behavior model and hydrate equilibrium model developed in this work. From this figure, it was found that the regions of gas/water, gas/liquid/water, gas/liquid/water/hydrate, gas/hydrate, and gas/liquid/ice/hydrate can be designed by using the computed dew-point pressure line, freezing point line, and hydrate dissociating pressure line. In the gas/liquid region, gas composition is a function of pressure, temperature, and overall composition of the mixture, and hence, hydrate dissociating pressure is a function of those variables also. However, the incipient hydrate model presented by Parrish and Prausnitz [1972] for finding the hydrate forming condition did not consider the effect of pressure and temperature on gas composition in the gas/liquid region. In this study, the gas composition for estimating the hydrate dissociating pressure in

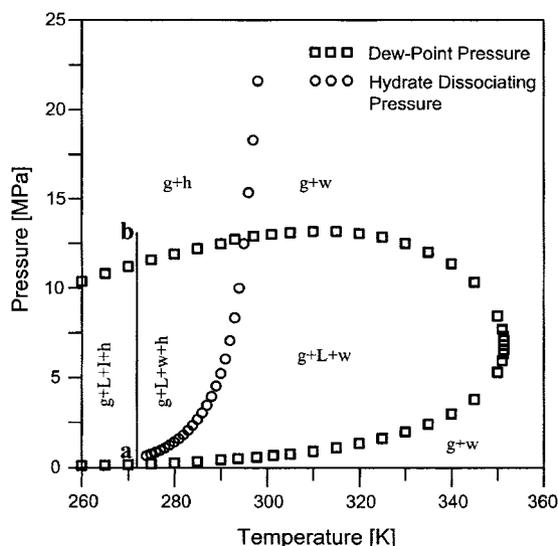


Fig. 2. Phase envelope for hydrate (h), gas (g), oil (L), ice (I) and water (w) in the case of a mixture of hydrate-forming compounds.

the two-phase region is evaluated with multi-phase flash calculation procedure in the phase behavior model. As a result, Fig. 3 shows some discrepancies of the hydrate dissociating pressures obtained by flash (this study) and non-flash (Parrish and Prausnitz) calculations. In this figure, the line **abc** presents the dew-point pressure line; in the single-phase region which is below this line, the results from both models are exactly same, but in two-phase region, there is a maximum difference of 41.7% on the hydrate dissociating pressure against the Parrish and Prausnitz model at a temperature of 285 K.

2. Analysis of Hydrodynamic Characteristics in a Multi-Phase Pipeline

In the validation step, due to the lack of experimental or actual field data for four-phase pipeline flow, the developed model was compared with the measured data for gas condensate pipeline flow in Columbia [Mucharam, 1991]. For this comparison, the pipeline being modeled is 15.53 km long with a diameter of 15.24 cm. At the pipe inlet, pressure and volume fraction of liquid phase are specified as 2.07 MPa and 0.2, respectively. Inlet velocities of gas and liquid are assumed to be 1.981 and 1.966 m/s, and the inlet and sur-

Table 1. Composition of natural gas and its physical properties

Component	Overall composition	Critical temperature °R	Critical pressure psia	Molecular weight lb/lb-mole	Acentric factor
CO ₂	0.0311	584.16	1071.00	44.010	0.2250
N ₂	0.0064	195.76	493.00	28.013	0.0400
C ₁	0.7303	343.37	667.80	16.043	0.0104
C ₂	0.0804	550.09	707.80	30.070	0.0986
C ₃	0.0428	666.01	616.30	44.097	0.1524
i-C ₄	0.0073	734.98	529.10	58.124	0.1848
n-C ₄	0.0150	765.65	550.70	58.124	0.2010
i-C ₅	0.0054	829.10	490.40	72.151	0.2223
n-C ₅	0.0060	845.70	488.60	72.151	0.2539
n-C ₆	0.0753	868.00	419.00	76.200	0.2600

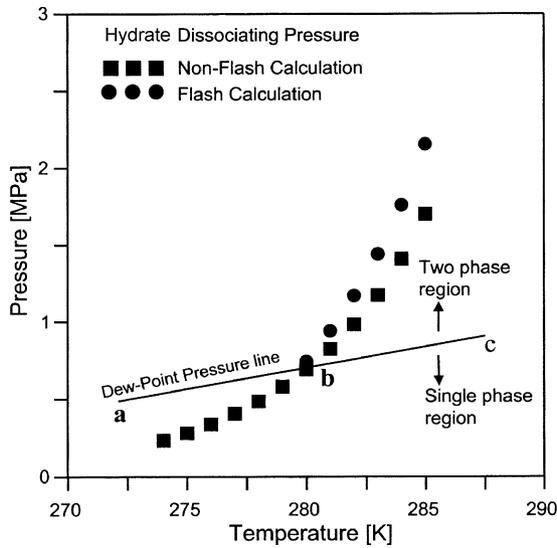


Fig. 3. Comparison of the gas hydrate dissociating pressures obtained by flash and non-flash calculations.

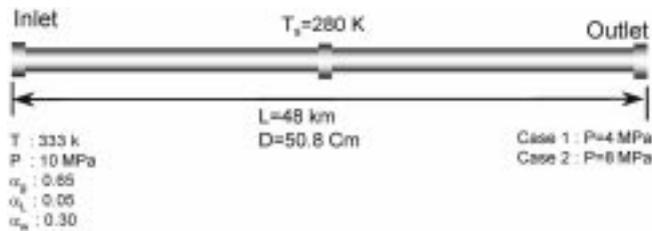


Fig. 4. Pictorial representation of pipeline system of four-phase flow.

rounding temperatures are set at 310.8 and 291.4 K, respectively. The flow pattern of gas-liquid flow is assumed to be a dispersed flow. Under the system, the developed model has been validated with a measured pressure at pipe outlet. From the result, the calculated steady-state pressure of 1.773 Mpa at the outlet was obtained and it agrees well with the measured data of 1.737 MPa.

In order to analyze the transient hydrodynamic characteristics of gas-condensate-water-hydrate mixture, we considered a hypothetical horizontal gas pipeline with 48 km in distance and 50.8 cm in diameter, as shown in Fig. 5. As inlet boundary condition, a temperature of 333 K and pressure of 10 MPa are specified, and the volume fractions of gas, condensate, and water are assumed to be 0.65, 0.05, and 0.30, respectively. In order to analyze the effect of outlet pressure on transient flow characteristics in the pipeline, two different outlet pressures of 4 MPa (Case 1) and 8 MPa (Case 2) are considered with surrounding temperature of 280 K.

Fig. 5 illustrates the simulation results of transient behavior of the temperature at outlet. In Case 1 of lower outlet pressure, the outlet temperature reaches a steady condition at 280.2 K after 2.7 hours, while in Case 2 the constant temperature of 282.3 K appears after 4.5 hours. In this figure, the outlet temperature in Case 1 which yields a larger pressure drop, is lower than Case 2 at initial stage because of the Joule-Thomson cooling effect that gives the difference in temperature according to the pressure at the same enthalpy thermodynamically. But after 3.5 hours, the temperature of case 1

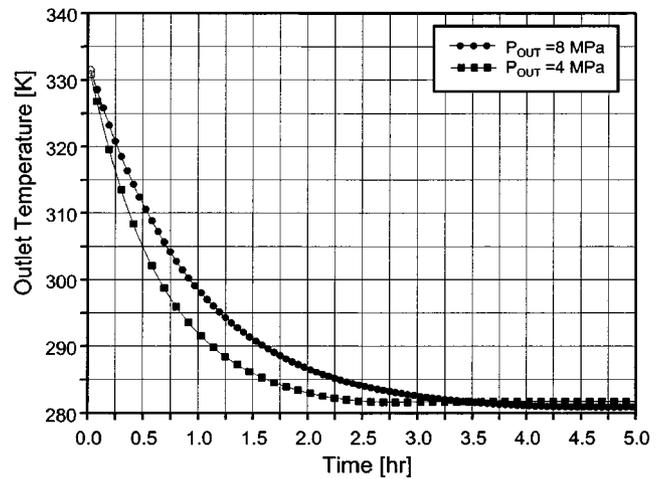


Fig. 5. Transient behavior of temperature at the outlet for different conditions of outlet pressures.

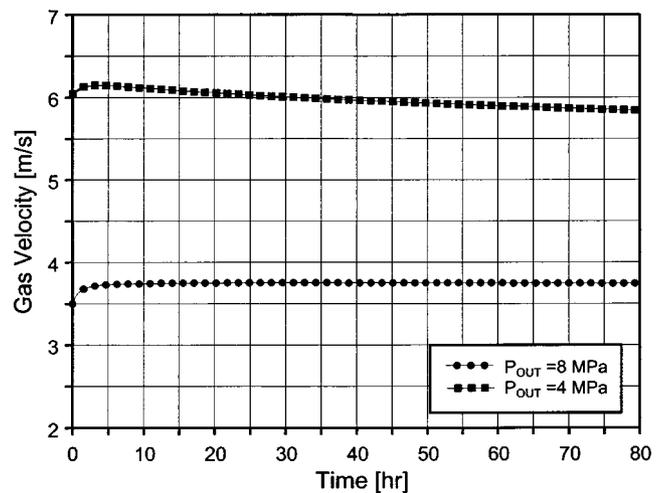


Fig. 6. Transient behavior of gas velocities at the outlet for different conditions of outlet pressures.

becomes a little bit higher than Case 2, because faster velocity (Case 1) results in greater heat convection. Therefore, in the case of predicting the hydrate formation at transient period, the possibility of hydrate formation is greater for Case 1 at the initial stage up to 3.5 hours.

For this system, gas velocity at the outlet with time is presented in Fig. 6. As shown in this figure, the inlet gas velocity is maintained steadily at 3.64 m/s after 2.5 hours in Case 2, whereas it still does not reach steady-state condition even after 80 hours for Case 1. Obviously, this is the reason why the faster flowing fluid takes more time to reach steady state.

In General, hydrates are formed when water and gas meet at high pressures; thus, referring to the results of steady-state pressure distribution as shown in Fig. 7, one can realize that the potential of hydrate formation is higher in Case 2. In the meanwhile, temperature distribution along the pipe, referring to Fig. 8, tends to decrease sharply near the inlet section and approaches to seawater temperature of 280 K. From this figure, the temperature distribution along the pipe in Case 2 is generally lower than Case 1, which means that

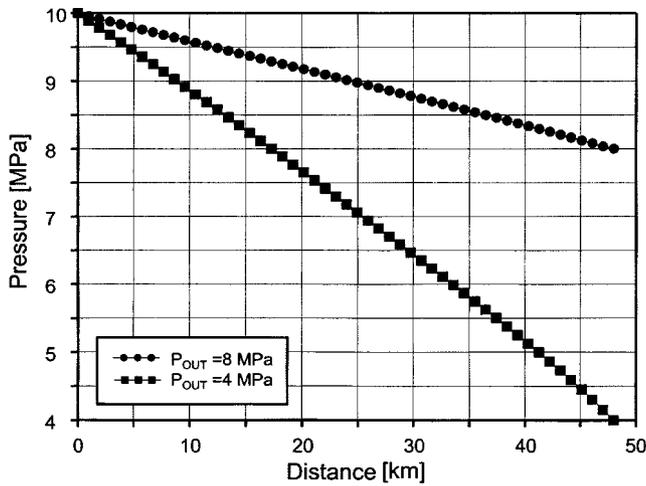


Fig. 7. Distributions of steady-state pressure along the pipeline for different conditions of outlet pressure.

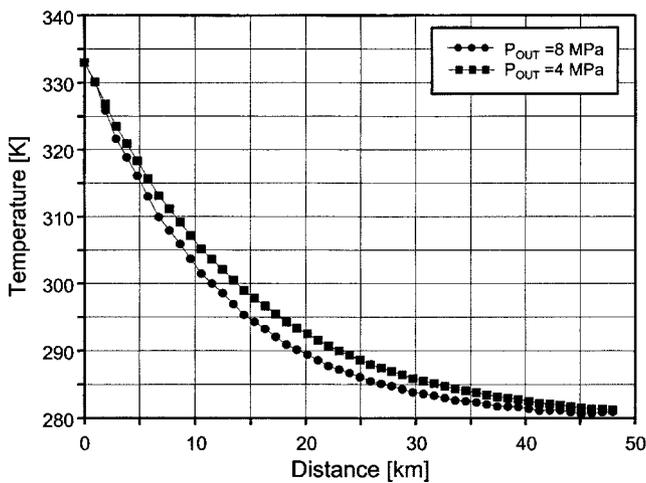


Fig. 8. Distributions of steady-state temperature along the pipeline for different conditions of outlet pressure.

hydrate is possibly well formed in Case 2.

Fig. 9 illustrates the volume fraction of water at steady-state conditions along the pipeline. The water holdups in both cases decrease in going to the outlet portal, which is expected because gas is the most pressure sensitive phase and it expands greatly with the greater pressure drop shown in Fig. 7. Comparing two curves of Cases 1 and 2 in Fig. 9, the volume fraction of water in Case 1 is lower than that of Case 2. Hydrates form only when water molecules exist, which can capture the gas; hence, the amount of water is a great influencing factor for the additional formation of hydrates. This analysis is essential in predicting the risks of hydrates in a multi-phase flow pipeline.

This time, we examined the existence of hydrate and its location along the pipe from the P-T diagram for the sample data used in this study. These results are presented in Fig. 10. The inlet conditions are temperature of 333 K and pressure of 10 MPa. From this system, the estimated outlet temperature in Case 1 is 280.2 K at 4 MPa, and that of Case 2 is 283.3 K at 8 MPa. Therefore one can see that total section of the pipe in both cases exists in a two-phase

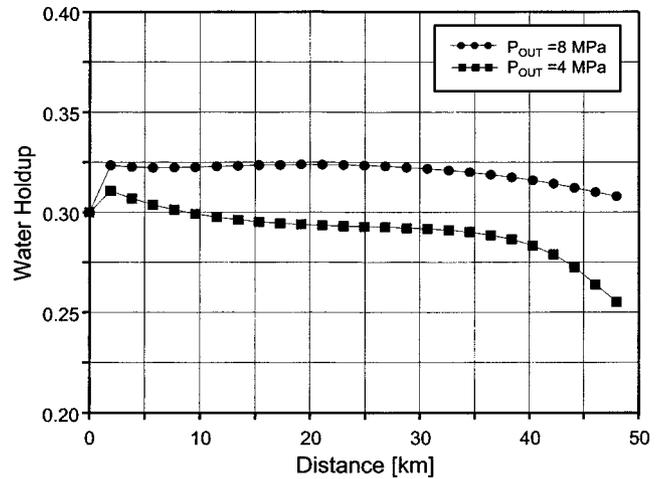


Fig. 9. Distributions of steady-state volume fraction of water hold-up along the pipeline for different conditions of outlet pressure.

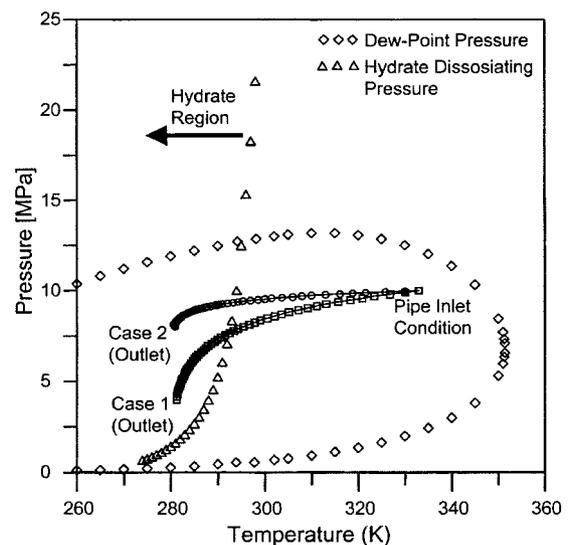


Fig. 10. Phase envelope and pipeline paths predicted by the developed model.

region. In Case 1, we can predict the first appearance of hydrate at 23 km from the inlet, while it can be generated at 16 km in Case 2. This means that Case 2 has the potential to form hydrate in longer distance of pipe, which has a higher risk in hydrate formation.

CONCLUSION

This study presents an unsteady-state, compositional, four-phase, four-fluid pipeline model in order to describe multi-phase flow and to predict hydrate formation in a natural gas pipeline. The validation and application of the developed model has been attempted, and the results of flow characteristics in the pipeline are as follows:

1. The developed model has been validated against the measured field data for gas-condensate flowing system in a pipeline, and the comparison has found to be relatively good match.
2. The modules of the phase behavior model and hydrate equi-

librium model have been utilized for examining the phase behavior of four-phase mixture in pipe. The simulation results are drawn on a P-T diagram which has five different regions separated by dew-point pressure line, freezing point line and hydrate dissociating pressure line.

3. In order to investigate the effect of outlet pressure on transient flow behavior, the gas velocity, water holdup, pressure, and temperature profiles with time as well as distance have been analyzed. From the analysis overall, as outlet pressure is lowered, the system has less potential to form a hydrate.

4. From the analysis of thermodynamic and hydrodynamic results in the P-T diagram, one can find the location of the hydrate formed; also, the flow behavior in the pipeline is more stable from the aspect of hydrate forming condition with the lower outlet pressure.

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