Pigging simulation for horizontal gas-condensate pipelines with low-liquid loading

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Abstract

Liquid condensation in natural gas transmission pipelines commonly occurs due to the thermodynamic and hydrodynamic imperatives. Condensation subjects the gas pipeline to two phase transport, which dramatically affects their delivery ability and operational modality and the associated peripheral facilities. It is therefore imperative for the pigging simulation in gas-condensate flowlines to be taken into consideration in their design. Periodic pigging helps keep the pipeline free of liquid, reducing the overall pressure drop, and thereby increasing the pipeline flow efficiency. A new simplified pigging model has been developed for predicting the pigging operation in gas-condensate horizontal pipelines with low liquid-loading, which couples the phase behavior model with the hydro-thermodynamic model. The comparison of the calculating results with those of the two-phase transient computational code OLGA (with a dynamic, one-dimensional, extended two-fluid model), indicates the new pigging model has a good precision and high speed in calculation. The model also contains the capability of pig-tracking and slug-length-increasing model, which can be suitable for engineering design.

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Keywords: Natural gas-condensate; Pigging simulation; Low-liquid loading; Compositional hydrodynamic model; Phase behavior model; Two-phase flow; Pipeline

1. Introduction

With the rapid development of offshore and desert gas/condensate field, pre-treatment of natural gas at the wellhead to remove the heavies is not generally an option because of the hostile environment. The pro-duced gas must, therefore, be transported by seabed or underground pipelines, over substantial distances. Liquid condensation in natural gas transmission pipelines commonly occurs due to the thermodynamic and hydrodynamic imperatives. Condensation subjects the gas pipeline to two-phase transport, and the presence of condensation in gas pipelines dramatically affects their delivery ability and operational modality and the associated peripheral facilities. It is therefore imperative for the pigging simulation in gas-condensate
flowlines to be taken into consideration during their design.

Pigging operation is a common practice in the petroleum and natural gas industry. Periodic pigging helps keep the pipeline free of liquid, reducing the overall pressure drop, and thereby increasing the pipeline flow efficiency. Sphering was originally introduced to increase gas flow efficiency. However, there are only a few published studies on the hydrodynamics of the phenomena. Xu et al. (2003) has given a review on the pigging simulation models in multiphase pipelines.

McDonald and Baker (1964) were probably the first investigators to present a study on pigging of gas–liquid pipelines, and they presented that the sphering could increase transportation efficiency by 30% to 70%. However, attempting to model the pigging phenomena, they assumed that a successive steady-state approach could be used, that is, the standard steady-state two-phase empirical correlations for both liquid holdup and pressure drop could be used within each timestep, which caused much calculation error. Barua (1982) attempted to improve the McDonald and Baker (1964) pigging model, and removed some limiting assumptions of the original model, and proposed a procedure to model the liquid slug acceleration during its delivery into the separator/slug catcher. However, the main assumption of a successive steady-state condition was not removed.

Kohda et al. (1988) proposed the first pigging model base on full two-phase transient flow formulation. Their model includes the drift flux transient code, which is based on the Scoggins’ (1977) study, and a pigging model. The pigging model is composed of correlations for pressure drop across the pig, slug holdup, pigging efficiency, pig velocity model, and a gas and liquid mass flow boundary condition applied to the slug front. The resulting set of equations was solved numerically by a finite difference method, using two coordinate systems, one fixed and the other adaptive. No further detail was given on how the difference equations were coupled and solved simultaneously. However, the experimental data compared relatively well with the predicted values for the numerical simulator. Note that the Kohda et al. (1988) model still uses flow-pattern-independent steady-state holdup and pressure drop correlation to account the slip between phases. Empirical correlations are known to be restricted when applied beyond the range of parameters covered by the experimental data used to develop them.

Minami and Shoham (1991) developed a pigging model and coupled it with the Taitel et al. (1989) simplified transient model assuming quasi-steady state gas flow. An Eulerian–Lagrangean approach using a fixed and moving co-ordinate system is used. Minami and Shoham (1991) used mechanistic models for predicting flow pattern, the slippage between phases and the pressure drop, and he performed an extensive experimental program showing this simplified approach is physically sound.

Meanwhile, other pigging models, such as TACITE (Pauchon and Dhulesia, 1994), Lima (1998), Petra (Larsen et al., 1997), have no difference in essence from the Minami and Shoham (1991) model, and slug/pig tracking and boundary conditions have just been improved.

In China, the research to the pigging simulation starts relatively late, and only a few scientific research institutions (China University of Petroleum, Xi’an Jiaotong University, etc.), have carried out the pertinent research. Liang (1997) developed a simplified pigging model for predicting the dynamics of pigging operation. And Li and Feng (2004) conducted pigging experiments in an air–water two-phase flow loop. And Petroleum University (Beijing) has done some valuable work on gas-condensate pipelines.

2. Pigging model development

Gas-condensate flow with low liquid loading is a multiphase flow phenomenon commonly encountered in raw gas transportation. Fig. 1(a) is the schematic description of the liquid holdup in horizontal gas-condensate pipelines. The pipeline is divided into two sections, that is, gas section (Ao) with no condensate near the input for the higher pressure and temperature, and two-phase flow section (Bo) with condensate for lower pressure and temperature. According to the characteristic of the low-liquid loading, the physical model used in the development of the pigging model is given in Fig. 1(b). A similar physical pigging model had been used by Kohda et al. (1988) and Minami and Shoham (1991). The pipeline is also divided three sections. Just ahead of the pig is the liquid slug section (B). The region to the left of the pig is the upstream single-
phase gas flow section (A). To the right of the liquid slug is the downstream transient two-phase flow section (C). However, Kohda et al. (1988) and Minami and Shoham (1991) models cannot be used for non-isothermal two-phase pipeflow systems with phase changes and mass transfer.

3. Pigging simulation

3.1. Compositional hydrodynamic model

Prediction of temperature and mass transfer is extremely important for multicomponent or compositional flow, such as gas condensate systems. Compositions of such complex systems are not constant, but vary significantly along the pipeline as a function of pressure, and especially temperature. Thus, the black oil model is inadequate to handle compositional systems, which should be treated by vapor–liquid equilibrium flash calculation at each pressure and temperature. Accurate prediction of both pressure and temperature is thus essential.

This paper presents a compositional hydrodynamic model that describes the hydrodynamic behavior of gas/gas condensate flow in pipelines, in which gas is condensing/vaporizing at some section of the pipeline. One of the most difficult features of this system is that the condensing/vaporizing section must be identified. This problem is resolved by coupling of a phase-behavior model to the basic hydrodynamic equations.

The phase behavior model incorporates the Peng–Robinson two-parameter EOS (Peng and Robinson, 1976) for the thermodynamic calculation of physical properties of both phases at the given temperature, pressure and composition. This approach is quite reliable and relatively fast in process calculations involving light hydrocarbon systems, such as gas-condensate system, which can be used to determine the numbers of phases in pipe, to estimate the densities, enthalpies, specific heat capacities of gas and liquid, the flow parameters such as liquid and gas viscosities and the surface tension.

Meanwhile, the onset of condensation means that two phases coexist in the pipeline, with continuous mass and momentum transfer between phases. This coexistence creates an additional complication because the mass transfer rate depends on the system’s temperature, pressure and composition. The mass transfer rate cannot be determined in advance; it must be evaluated simultaneously with the solution of the hydrodynamic equations, which is necessary to satisfy the conservation of mass, momentum and energy. For calculating pressure and temperature profiles in pipe flow, these conservation equations lead to two independent equations: the pressure gradient and enthalpy balance equations (Fig. 2).

3.1.1. Momentum equation

The pressure gradient equation is developed by combining the momentum and mass balance equations for one dimensional flow in a pipe, which includes friction loss, elevation and acceleration pressure gradient.

\[
\left( \frac{dP}{dx} \right)_{\text{Total}} = \left( \frac{dP}{dx} \right)_{\text{Friction}} + \left( \frac{dP}{dx} \right)_{\text{Elevation}} + \left( \frac{dP}{dx} \right)_{\text{Acceleration}}
\]

(1)

3.1.2. Energy equation

As fluids flow through a pipe, they continuously exchange heat with the surroundings. The temperature profile in flowing fluids is affected by heat transfer,
elevation changes, velocity changes and expansion effect. Temperature change resulting from expansion is referred to as the Joule–Thomson effect, which can cause the temperature to drop below the surrounding temperature. Taking into account all these effects in two-phase flow, the enthalpy balance on a segment of pipe may be written as follows,

\[
\left(\frac{dH}{dx}\right)_{\text{Total}} = \left(\frac{dH}{dx}\right)_{\text{Exchange}} + \left(\frac{dH}{dx}\right)_{\text{Elevation}} + \left(\frac{dH}{dx}\right)_{\text{Kinetic}}
\]

For quasi-steady-state flow,

\[
\frac{dH}{dx} = -\frac{dQ}{dx} - \frac{dv}{dx}g - \frac{dZ}{dx}.
\]

Then, the enthalpy at the segment outlet can be written as following

\[
H_K = H_{K-1} - g\Delta Z - \frac{\nu_{sg}\Delta P}{P_K} - \frac{K\pi D\Delta L(T_{av} - T_{\text{env}})}{M}
\]

The mixture enthalpy at the pipe segment outlet \((H_K)\) is the function of pressure \((P_K)\) and temperature \((T_K)\). However \(P_K\) and \(T_K\) are unknowns. \(P_K\) can be calculated from the hydrodynamic model, while the model parameters are function of \(P_K\) and \(T_K\), which can be calculated by the phase behavior model. So it is necessary to couple the hydrodynamic model and phase behavior model, the hypothesis pressure and temperature are needed before the iterative calculation. In one pipe segment, with two-phase properties gained by the phase behavior model, liquid holdup can be predicted by the empirical correlations, such as BB (Beggs and Brill, 1973), Eaton (Eaton, 1967), MB (Mukherjee and Brill, 1983) models. MB model is exactly used in this study.

With coupling the hydrodynamic model with phase behavior model (that is, the compositional hydrodynamic model), pressure, temperature, liquid holdup along the pipeline can be predicted.

3.2. Gas section (A) calculation

Given the input pressure, temperature, flow rate, composition, total thermal conductivity (pipe wall thermal conductivity and soil thermal conductivity), wall roughness, the single-phase gas flow hydrodynamic model can be used to predicted the pig velocity and the pressure near the back of the pig, which are the boundary condition of the slug zone calculation.

The mass and momentum is described by the equations of compressible gas dynamics as follows,

\[
\frac{\partial \rho_g}{\partial t} + \frac{\partial (\rho_g v_g)}{\partial x} = 0
\]

\[
\frac{\partial (\rho_g v_g^2 + P)}{\partial x} = -f \rho_g v_g |v_g| + \rho_g g \sin \theta.
\]

The local friction factor \(f\) is calculated by an empirical correlation. The pressure and the gas density are related by gas EOS,

\[
\frac{P}{\rho_g} = \frac{zRT}{M_g}
\]

where, \(z\) and \(M_g\) are the gas compressibility factor and molecular weight, respectively.

3.3. Slug section (B) calculation

3.3.1. Control volume (CV)

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This process caused a liquid slug to accumulate in front of the pig as it progresses along the line. For modeling the pigging phenomena, mass and momentum conservation equations are applied. An expanding CV and a fixed coordinate system are chosen as shown in Fig. 1(b).

### 3.3.2. Mass balance equation

A general mass balance equation for a moving and expanding control volume is given by

\[
\frac{d}{dt} \int_{V(t)} \rho dV + \int_{A(t)} \rho (\mathbf{v} - \mathbf{w}) \cdot d\mathbf{A} = 0. \tag{8}
\]

There is no liquid slippage behind the pig. In each timestep \( \Delta t \), the liquid holdup and density do not change with time. Under the above assumptions, Eq. (8) can be rewritten as following

\[
E_{ls} \frac{dL_s}{dt} + (v_L - v_i)E_L = 0. \tag{9}
\]

Meanwhile, the time rate of change of the length of the liquid slug (B) is given by

\[
\frac{dL_s}{dt} = v_t - v_p. \tag{10}
\]

Substituting Eq. (10) into Eq. (9), we can derive an expression for translational velocity \( v_t \),

\[
v_t = \frac{E_{ls}v_p - E_Lv_L}{E_{ls} - E_L} \tag{11}
\]

where, the slug holdup is usually taken as a function of \( v_s \) as in the Gregory et al. (1978) correlation,

\[
E_{ls} = \frac{1}{1 - (v_s/8.66)^{1.39}} \tag{12}
\]

### 3.3.3. Momentum balance equation

A general momentum balance equation expressed by the Eq. (13) is also applied to the CV shown in Fig. 1(b). Since the momentum equation is a vector equation, only the \( x \) component of the momentum equation is considered. And \( \mathbf{F}^e \) is the external force exerted by the surroundings on the CV.

\[
\frac{d}{dt} \int_{V(t)} \rho \mathbf{v} dV + \int_{A(t)} \rho (\mathbf{v} - \mathbf{w}) \cdot d\mathbf{A} = \mathbf{F}^e. \tag{13}
\]

Assuming that the liquid density, slug velocity, and the slug holdup do not change within one timestep, and the liquid slipping past the pig is zero, the momentum accumulation term and the momentum flux across the surface enclosing the CV, that is, the left hand side of Eq. (13) are rewritten

\[
\frac{d}{dt} \int_{V(t)} \rho \mathbf{v} dV + \int_{A(t)} \rho (\mathbf{v} - \mathbf{w}) \cdot d\mathbf{A} = \rho_L v_s E_{ls}A \frac{dL_s}{dt} + \rho_L v_L (v_L - v_i)E_LA. \tag{14}
\]

The net external force \( \mathbf{F}^e \) is given by

\[
\mathbf{F}^e = (P_p - P_f)A - g \int_{x_p}^{x_v} \rho_s A \sin \theta dx - \tau_s \pi DL_s \tag{15}
\]

where, \( \tau_s \) is the shear stress between the slug and the pipe wall. For one horizontal pipeline, substituting

<table>
<thead>
<tr>
<th>Component</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>nC4</th>
<th>nC5</th>
<th>C6</th>
<th>CO2</th>
<th>N2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>mol %</td>
<td>88.73</td>
<td>7.1</td>
<td>1.31</td>
<td>0.29</td>
<td>0.34</td>
<td>0.17</td>
<td>0.10</td>
<td>0.22</td>
<td>0.14</td>
<td>0.09</td>
<td>1.51</td>
</tr>
</tbody>
</table>
Eqs. (14), (15) into Eq. (13), the momentum balance equation can be expressed by

\[
P_F = P_p - \frac{4 \tau_s L_s}{D} - \rho_L (v_s - v_L) E_{ls} \frac{E_L (v_p - v_L)}{E_{ls} - E_L}
\]

where, \( E_L, v_L \) can be described the liquid holdup and velocity between B and C, respectively.

3.4. Slug delivery calculation

As the slug front reaches the pipeline outlet and the liquid is producing into the slug catcher, the slug delivery would be taken place and the pig is accelerated (Fig. 3). The purpose of the slug delivery calculation is to estimate the time of slug delivery. The basic assumptions involved in the slug delivery calculation are shown as following,

(1) The outlet pressure is constant;
(2) The slug is homogeneous gas–liquid two-phase mixture;
(3) The mass flow rate of gas behind the sphere is constant.

4. Numerical solution

The time step \( \Delta t \) is assumed as constant, \( \Delta t = \text{const.} \). In each timestep, the change of the slug length \( \Delta x \) can...
be given by $\Delta x = (v_t - v_p) \Delta t$. At the next timestep $(k+1)$, the new coordinate at the pig position is given by $x^k_{p+1} = x^k_p + v^k_p \Delta t$, where $v^k_p$ is the pig velocity of the new timestep, which is assumed to be equal to the gas velocity closely behind the pig. The new slug length is $L^k_{S+1} = L^k_S + \Delta x$, and the new $x$ coordinate at the slug front is determined from $x^k_F = L^k_S + x^k_p$.

5. Pigging analysis

One horizontal gas-condensate pipeline in Tarim gas field in western China is used to test the proposed pigging model. It represents a typical gas-condensate pipeline, and fluid composition and pipeline data are given in Tables 1 and 2. And the phase envelope is shown in Fig. 4.

Since there is no pigging data of gas-condensate pipelines in practice, the famous transient flow simulation software OLGA is used to test against the proposed model. With higher precision, OLGA, a dynamic, one-dimensional, extended two-fluid model has been jointly developed by IFE and SINTEF (Bendiksen et al., 1991), with higher precision, which has been widely used in oversea oil and gas fields.

From the Figs. 5, 6 and 7, it can be concluded that the hydrodynamic and thermodynamic calculation results are quite close to that of OLGA. Meanwhile, the simplified pigging model developed has good precision in prediction of the pigging operation as shown in Table 3. And the quasi-steady state approach has been used in the simulation, which could save much more time in simulation than OLGA, and the newly developed model can be used in practice. The pig tracking and simulation of slug length was also shown in Figs. 8 and 9.

6. Conclusion

Pigging simulation study has already been carried out from the 1950s (McDonald and Baker, 1964). However, in China, much more work needs to be done. The proposed pigging model couples the phase behavior model, hydrodynamic model (momentum and energy equation), which is able to simulate the pigging operation of gas-condensate pipelines with low liquid loading, which can also be used to other gas–liquid two-phase pipelines. Since there are much phase behavior changes (condensation, retro-condensation) during the normal running and pigging operation, some boundary conditions have been simplified and assumptions have been used. Meanwhile,
the transient pigging model under the unsteady operations, (such as terrain, shutdown, restart, wax deposition), would also need to pay more attention.

Nomenclature

\begin{align*}
A & \quad \text{Pipe cross area (m}^2) \\
D & \quad \text{Pipe diameter (cm)} \\
E_L & \quad \text{Liquid holdup} \\
E_{Ls} & \quad \text{Slug holdup} \\
T_{\text{env}} & \quad \text{Surrounding temperature (K)} \\
\dot{v} & \quad \text{Fluid velocity (m/s)} \\
V & \quad \text{CV volume, m}^3 \\
f & \quad \text{Wall friction factor} \\
\nu_g & \quad \text{Gas velocity (m/s)} \\
F & \quad \text{External force on the CV (N)} \\
H & \quad \text{Fluid enthalpy} \\
L & \quad \text{Slug length (m)} \\
M_g & \quad \text{Gas molecular weight (kg/mol)} \\
P & \quad \text{Gas pressure in EOS (Pa)} \\
P_F & \quad \text{Pressure at the slug front (Pa)} \\
P_P & \quad \text{Pressure at the pig position (Pa)} \\
Q & \quad \text{Heat loss through the wall (J)} \\
R & \quad 8.314472 \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1} \text{ mol}^{-1} \\
t & \quad \text{Time (s)} \\
T & \quad \text{Gas temperature in EOS (K)} \\
T_{\text{av}} & \quad \text{Average temperature in one section (K)} \\
\tau & \quad \text{Shear stress} \\
\theta & \quad \text{Pipeline inclination (rad)} \\
\Delta P & \quad \text{Pressure drop of one segment (Pa)} \\
\Delta Z & \quad \text{Elevation of one segment (m)} \\
\dot{v}_L & \quad \text{Liquid velocity (m/s)} \\
\dot{v}_P & \quad \text{Pig velocity (m/s)} \\
\dot{v}_S & \quad \text{Slug velocity (m/s)} \\
\dot{v}_{sg} & \quad \text{Gas superficial velocity (m/s)} \\
\dot{v}_t & \quad \text{Transitional velocity at slug front (m/s)} \\
\dot{w} & \quad \text{Velocity of the CV (m/s)} \\
x & \quad \text{X coordinate} \\
x_F & \quad \text{X coordinate at slug front, m} \\
x_p & \quad \text{X coordinate at the pig, m} \\
z & \quad \text{Gas compressibility factor} \\
Z & \quad \text{Pipe elevation (m)} \\
\text{s} & \quad \text{Liquid slug} \\
p & \quad \text{Pig} \\
F & \quad \text{Slug front}
\end{align*}

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