Journal of Petroleum Science and Engineering 101 (2013) 28–34

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Predicting temperature distribution in the waxy oil-gas pipe flow

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ARTICLE INFO

Article history:
Received 8 November 2011
Accepted 28 October 2012
Available online 19 November 2012

Keywords:
oil–gas two phase flow
thermodynamic model
waxy oil
temperature simulation
multiphase pipeline
waxy oil

ABSTRACT

In the simulation of waxy oil–gas pipeline multiphase flow, the physical parameters and rheological properties of the multiphase fluid are the sensitivity functions of the temperature. The precise temperature distribution of multiphase fluid is the foundation of predicting the pressure distribution accurately, wax deposition rate, optimized design and operating analysis of waxy oil and gas pipeline, and so on. Based on the energy equation of oil–gas flow in pipeline, the explicit temperature drop formula (ETDF) for oil–gas steady state calculation is derived from the energy conservation analysis in micro-element. This new energy equation has considered many factors, such as heat transfer with the surroundings along the line, Joule–Thomson effect and impact of terrain undulation to potential energy. So it is an overall form of energy equation, which could reflect the actual fact of multiphase pipeline accurately. Elimination of temperature iteration loop and integration of the explicit temperature equation, instead of enthalpy energy equation, into the conjugated hydraulic and thermal computation have been found to improve the efficiency of algorithm. The calculation program of temperature drops of waxy oil–gas flow in pipelines is compiled on the basis of the ETDF employing modification of the specific heat of the waxy oil. This model is carried out with a practical waxy oil–gas two phase flow pipeline, and the temperature results are compared with OLGA. It is shown that this model has simulated the temperature distribution very well.

1. Introduction

The flow characteristic of multiphase fluid is closely related to physical properties such as density, viscosity of every phase fluid and the physical properties of waxy oil and nature gas change with the pressure and temperature in actual applications, the pressure and temperature are both known. So the flow characteristic and heat transfer characteristics are mutual intertexture and influence (Aziz et al., 1972).

By predicting the temperature of the waxy oil–gas multiphase fluid can reach the following aims: (1) the phase transformation and the flow process of waxy oil–gas fluid are mutual correlation; (2) the inner wall temperature distribution of the pipeline can obtain until the temperature of the multiphase fluid calculated, further more estimate the wax deposition occur or not; (3) accurate calculation on the temperature of the fluid is the prerequisite of prediction of wax deposition rate (Gong et al., 2011). The calculation of the temperature of the fluid holds the important position in the process calculation of the waxy oil–gas multiphase flow pipeline. Therefore, it is necessary for doing some research on the temperatures of waxy oil–gas flow, which is crucial to security and economical operation of the pipeline system.

As the fluid flows in pipeline, the heat is constantly transferred to the surroundings and temperature of the fluid and enthalpy value is changed. The temperature drop calculation for single flow usually calculated by the Sukhoi model that only takes heat transfer with the surroundings and friction work between fluid and inner wall into account. That for oil–gas flow differs from that for single-phase liquid or gas in that not only the oil–gas mixture transfers heat to the surroundings through wall, but the quality and heat exchanges between gas and liquid should also be considered. The calculation should take into consideration the Joule–Thomson effect caused by gas cubic expansion, due to gas and temperature rise as a result of heat generated by friction in liquid flow, due to oil (Bendiksen et al., 1991). The effect of the latent heat due to wax crystal precipitation to the temperature of fluid is still needed to be considered in waxy oil–gas multiphase flow pipeline. So the accurate prediction of the temperature distribution of oil–gas flow is very complicated. The models calculating temperature drop in oil–gas two phase flow pipeline used by the scholars and business software often only consider the wall heat transfer and energy conversion caused by elevation changes (de Hemptinne and Behar, 2006). Although an accurate prediction of the temperature distribution of oil–gas flow is very complicated, the temperature of the mixed fluid can be calculated

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http://dx.doi.org/10.1016/j.petrol.2012.10.003

Nomenclature

u	internal energy of per unit mass (J kg^{-1})
v	fluid velocity (m s^{-1})
g	gravity acceleration (m s^{-2})
z	altitude (m)
ρ	density (kg m^{-3})
α	cross-sectional void fraction
h	enthalpy of unit mass (J kg^{-1})
q	heat of oil–gas fluid transfer with the surroundings (J s^{-1})
U	overall heat transfer coefficient (W(m^2 K)$^{-1}$)
D_O	outer diameter (m)
t	time (s)
T	temperature (K)
x	pipe length of one section (m)
W	mass flow (kg s^{-1})
A	cross section area of the pile (m^2)
θ	angle contained by the infinitesimal section and horizontal (rad)
ϕ	mass quality (%)
c_p	specific heat at constant pressure (J(K kg)$^{-1}$)
μ_J	coefficient of Joule–Thomson effect (K Pa^{-1})
P	pressure (Pa)
β	volume expansion coefficient of liquid (K^{-1})
Δx	pipe length of one section (m)
ς	specific volume (m^3/kg)
d_4^{20}	relative density of the crude oil at 20 °C to density of the water at 4 °C
$\overline{T}$	mean temperature in pipe (K)
ψ	latent heat generated by wax precipitation (J kg^{-1})
w	wax precipitation (%)

using the energy equation, that is, enthalpy equation combining with continuity equation and equation of momentum (Gould, 1979).

Akashah (1980), Alves et al. (1992), Cawkwell and Charles (1985), Dulchovnaya and Adewumi (2000), Gregory and Aziz (1978), and Moshfeghian et al. (2002) proposed the interaction algorithm of momentum equation, energy equation and phase behavior model (PR EOS or SRK EOS) based on the correlative expressions to calculate the pressure and temperature of the oil–gas two phase flow, respectively. The algorithm contains two-lever iterative: enthalpy and pressure calculation. Alves discussed the possibility of enthalpy equation replaced by the unified Coulter–Bardon formulate[8] to iterative compute the temperature. However, Akashah, Cawkwell, and Moshfeghian used not right energy equation and the calculation of the enthalpy of multiphase fluid proposed by Gregory is remain consider.

Gregory proposed a simple relationship between enthalpy of oil–gas mixture and liquid holdup, only to find that the effect of liquid holdup on enthalpy of the mixture is insignificant. According to the previous derivation, it is inappropriate to calculate enthalpy of the mixture on the basis of liquid holdup. Instead, it should be calculated by use of mass liquid holdup of the cross section.

In his method, Cawkwell added the change of the latent heat of phase to the calculation of enthalpy increment in the energy equation, but methods for calculating latent heat of phase change are not stated. In fact, there is no need to additionally compute the latent heat of phase change, for the fact that the phase change between gas and liquid is a gradual process and is included in enthalpy difference between the two phases.

Alves proposed a model that applies to calculating the temperature drop of single phase fluid and oil–gas fluids with a full range of contained angles and unified Coulter–Bardon (1979), formula and Ramey (1985) formula. They neglected mass transfer between gas and liquid but they took into account pressure gradient, slope of the pipeline, acceleration energy loss, and Joule–Thomson effect in the temperature calculation and they applied a new method to adjust the specific heat capacity and the Joule–Thomson effect coefficient. This model is widely used to calculate temperatures of pipe fluids and is accurate true for both compositional model and black-oil model.

Dukhovnaya suggested a novel approach in calculating the temperature of oil–gas flow. In their model, the energy equation of oil–gas mixed fluid does not include the kinetic energy term and the potential energy term. One of the main disadvantages of their model is that it neglects the difference between the internal energy and the enthalpy.

Moshfeghian used the energy equation that their model does not contain potential energy term to calculate the temperature of mixed fluid in undulant pipelines. In practice, gas has a high density under high pressure conditions, so the effect of the undulation, or of the potential energy, on the temperature drop of mixed fluid should not be ignored. The liquid holdup in oil–gas pipes effects significantly the temperature drop computation, and is dependent on the pipeline inclination. For declined pipes, the liquid holdup is relatively low and the temperature drop of oil–gas mixed fluid increases, while for upward pipes, the liquid holdup is high and temperature drop decreases.

Gabriela et al. (2005) and Khuzhayorov and Burnashev (2001) propose to use a method deviating from the calculating temperature drop of the oil–gas flow in an horizontal pipe, to directly calculate the temperature drop of a two-phases flow in an undulant pipe, by replacing mass gas content with section gas content to calculate specific heat of mixed fluid. They guess that they would obtain a higher precision on the calculating temperature of the mixed fluid in comparison with the former method. However, based on the former derivation, slipping between gas and liquid has little influence on the enthalpy of the mixed fluid if the kinetic energy is neglected. Therefore, calculate the temperature drop in an undulant pipe, using section gas content in place of mass gas content for the determination of the specific heat to be apparently not well-founded. The feasibility of utilizing the temperature drop formula, with no consideration of the potential energy, to calculate the temperature drop of oil–gas flow in an undulant pipe is questionable. Furthermore, the temperature drop formula considering the Joule–Thomson effect of the gas and the heat generated by friction of the liquid is non-uniform in theory. As the Joule–Thomson effect coefficient of the oil is below 0 °C and as the gas temperature is over 0 °C within a certain range, the oil is heated and the gas is cooled due to friction. The friction-generated heat for the oil and the Joule–Thomson effect of the gas can be uniformly expressed by the Joule–Thomson effect of the mixed fluid.

Manabe (2011) proposed a comprehensive heat transfer model for oil–gas pipe flow. The overall performance was well with experimental data. However the hydrodynamic model and the heat transfer formulations for stratified and slug flows need to be improved.

In the simulation of thermodynamics in multiphase flow, the convergence of equations is crucial and most scholars focus lies in how to improve the stability of the solution of equations. The heat transfer characteristics in the energy equation proposed by Chen et al. (1995) is represented by only one variable. And even the