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Comparison and analysis of drainage measures for draining accumulated water condensed from wet CBM and transported in surface gathering pipeline network

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ABSTRACT

When compared with conventional gas field development, the coalbed methane (CBM) production process has its unique features that the produced natural gas contains saturated vapor and the gathering system is characterized as two-phase flow and liquid drainage. This paper aims to compare the drainage measures for draining liquid that condenses from wet CBM and transported in surficial gathering pipeline network. The unsteady non-fully developed flow of wet CBM in dendritic gathering and transmission pipeline network was simulated and analyzed. Phase change of water vapor was presented during the low-liquid loading flow and heat transfer process. The mass flow rate in pipeline network was supposed to increase continuously due to the aggregation and accumulation of liquid. The pressure at some adjacent nodes was validated by experimental data in situ. Three measurements for draining liquid are proposed, which include pigging, installing devices and cooling fluid at pipe inlet. It is concluded that the optimal strategy is combining the pigging method with installing several drainage devices rather than only pigging or the combination of pigging and cooling. Additionally, the presented model is a worthy way to optimize the pigging cycle to ensure the high efficient operation for the pipeline. Therefore, this paper provides a safe and economic method for the flow assurance of wet CBM fields.

1. Introduction

1.1. Background

Compared with conventional gas field development, the wet CBM production process has its unique features that the produced natural gas contains saturated water and the production system is characterized as liquid drainage and gas recovery (Liu et al., 2017; Wang and Zhu, 2017). With the increase of pipeline transporting distance, the drops of temperature and pressure gradually result in the precipitation of condensed water (Schouten et al., 2005; Vincent and Adewumi, 1990). Some negative impacts may occur if the condensed water is not drained in time (Mansoori et al., 2009; Shah, 1981; Ullmann and Brauner, 2006; Wang et al., 2015; Wróblewski and Dykas, 2016). For example, (1) The flow in the pipeline would convert into gas-liquid flow, which increases the friction loss and even triggers slug flow in the pipeline; (2) The area of flowing cross section would be diminished, leading to reduction of transporting efficiency; (3) Driven by gas flow, the condensed water will be pushed forward and form a tide, increasing the difficulty of operation safety; (4) The condensed water may be frozen once upon the temperature is below 0 °C and it may influence the operation of the pipeline; (5) The content of water will directly impose effect on the subsequent production facilities such as influencing the processing capacity of the separator. Hence, it is essential to analyze and compare the available drainage measures for draining accumulated liquid which condenses from wet CBM and is transported in gathering pipeline network after the prediction of the location of condensed water and its corresponding volume. The result could provide guidance for pressure control, drainage equipment selection and draining plans (Deng and Gong, 2006; Eaton et al., 1967; Li et al., 2016).

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Nomenclature

A	The cross sectional area of pipeline (m^2)
$c_{P,mix}$	Specific heat capacity at constant pressure of the mixture (kJ/(kg·K))
$c_{P,G}$	Specific heat capacity at constant pressure of the gas phase (kJ/(kg·K))
d	Inner diameter of the pipeline (m)
$dr_{j,k}$	The thickness of water film in segment j within time k (m^3)
$D_{j,k}$	Effective inner diameter in segment j within time k (m)
$D_{throttle}$	The throttling effect coefficient (°C/MPa)
Fr	Froude number (–)
g	The gravity acceleration (m^2/s)
G_G	Mass flow rate of gas phase with vapor (kg/s)
G_L	Mass flow rate of liquid phase (kg/s)
ΔG	Change of mass flow rate because of phase change (kg/s)
H_L	Liquid hold up of the cross section (–)
i_h	Hydraulic gradient (m/m)
K	Integral coefficient of heat transfer ($W/(m^2 \cdot K)$)
K^{carr}	Gas carrying coefficient of liquid membrane (–)
K^{grav}	Gravity coefficient of liquid membrane (–)
K_{f1}, K_{f2}	Coefficient determined by operating conditions and pigging data. (–)
l	The length of the pipe segment (m)
L_i	The length of the pipeline I (m)
N_{Lw}	Liquid apparent velocity index (–)
m	Total Mass flow rate of the mixture at node (kg/s)
M	Total Mass flow rate of the mixture in pipeline (kg/s)
$\overline{P}$	The average absolute pressure of the fluid in pipe (Pa)
p_0	Saturated vapor pressure of water, (Pa)
P	The pressure of wet CBM in pipeline (MPa)
$Q_{i,j,k}$	Total flow rate in pipeline i segment j within time step k (m^3/s)
$Q_{G,i,j,k}$	Wet CBM flow rate containing saturated vapor in pipeline i segment j within time step k (m^3/s)
R_L	Volumetric liquid holdup (–)
R_m	Universal gas constant, R_m = 8314J/(kmol·K)
S_i	The admittance coefficient of i pipeline (–)
tk	The time at k time step (s)
T	Temperature of wet CBM in pipeline (°C)
T_{cp}	Average temperature (K)
T_0	Ambient temperature (°C)
v	Flow velocity of gas-liquid mixture (m/s)
v_{sg}	Superficial velocity of gas phase (m/s)
V	The volume of moisture, (m^3)
$V_{I,J,K}$	Total volume of condensed water in the pipeline system (m^3)
$V_{i,j,k}$	The volume of condensed water in pipeline i segment j at time t_k (m^3)
ΔV_k	The volume of newly increased condensed water during time step k (m^3)
W_a	Absolute humidity of coalbed gas, (kg/m^3)
W^{H_2O}	The saturated water content in the gas phase (g/m^3)
x	Mass fraction of gas phase (–)
y	Mass fraction of liquid phase (–)

Greek symbols

α_i	The variables for i pipeline regarding pipe diameter, length and flow rate (Pa·s/kg)
θ	Inclination of the pipeline segment (–)
λ	Hydraulic friction coefficient (–)
μ_w	Molecular weight of water (–)
μ_g	Molecular weight of dry coalbed methane (–)
ϕ	Relative humidity of coal bed gas (–)
ρ_G, ρ_L, ρ_{mix}	Density of gas phase, liquid phase, and the mixture (kg/m^3)
ρ_a	Density of dry gas (kg/m^3)

Subscripts

i, j	the number of pipeline and pipe segment
in	pipeline inlet
initial	pipeline initial state
k	the number of time
mix	mixture fluid
n	the number of node in network topology
out	pipeline outlet
G	gas phase with vapor
I	maximum of i
J	maximum of j
K	maximum of k
L	liquid phase
N	maximum of n

1.2. Related work

Researches on the above-mentioned problems were mainly carried out in four aspects including hydraulic and thermal calculation in pipeline network, phase change of flow in pipeline, liquid accumulation in pipeline, and analysis and simulation of drainage measures.

1.2.1. Two-phase flow in single pipeline with phase change and liquid accumulation

Heat transfer is a substantial and fundamental problem in the two-phase flow process with phase change phenomenon. Many cases were discussed in previous studies, such as the prediction on the solid phase of wax, hydrate, asphalt, and scale in pipeline. Other cases about heat transfer and phase change existed in the process of deep-water oil and gas development (Deng and Gong, 2006; Duan et al., 2014, 2015; Newton and Behnia, 2000, 2001; Li et al., 2016) as well as some flow assurance problems like pipeline shutdown and restart (Akansu, 2006; Hu and Zhang, 2007; Zhang et al., 2012; Wang et al., 2015). Some scholars carried out related research on heat transfer of two-phase flow based on the method combining experiment and theory together (Shah, 1981; Vincent and Adewumi, 1990; Schouten et al., 2005; Zaghloul, 2006; Zhang and Sarica, 2011; Wróblewski and Dykas, 2016). They assumed that the phase change in the gas-liquid mixed transportation process belongs to P-T flash evaporation and tried to introduce phase equilibrium theory to the two-phase flow and heat transfer model to describe changes of gas and liquid components in flow process. (Beggs and Brill, 1973; Berthelsen and Ytrehus, 2005; Deng and Gong, 2006; Mansoori et al., 2009; Chena et al., 2012; Fontoura et al., 2013; Minami, 1991; He, 2017; Liu et al., 2017; Wang and Zhu, 2017). The 2D (two-dimensional) or 3D (three-dimensional) mathematical model, which is performed by virtue of CFD (computational fluid dynamics) theory, can also be employed to reveal the varying gas-liquid interfacial location and the secondary flow near the wall (Berthelsen and Ytrehus, 2004; He et al., 2017). However, the 2D or 3D model, is hard to simulate the transient process of long-distance pipeline fast and accurately when considering the coupling relationship of flow, heat transfer and mass transfer. Thus, some scholars made related simplifications on the mass transfer process (Eaton et al., 1967), especially in the commercial software OLGA, which is one of the commonly used transient simulation software of one-dimensional multiphase flow. This software is based on two-fluid model and the extended two-fluid model (Revellin et al., 2009; Ullmann and Brauner, 2006). Its basic equations include