Multiphase Mixture Model to Predict Temperature Drop in Highly Choked Conditions in CO₂ Enhanced Oil Recovery

Lin Teng¹, Datong Zhang¹, Yuxing Li^{*}, Wuchang Wang¹,

Lin Wang², Qihui Hu¹, Xiao Ye¹, Jiang Bian¹, Wenchao Teng¹

1. China University of Petroleum (East China), Qingdao 266555, China

2. China National Petroleum Corporation, Beijing 100000, China

**Corresponding author at Science Hall B320, China University of Petroleum (East China), Qingdao 266555, China*

Tel.: +86 05328399022; fax: +86 053286981822. E-mail address: cuph_co2trans@sina.com (Y. Li).

Abstract

CO₂ enhanced oil recovery (CO₂-EOR) technique is one potential option that **can** not only limit global warming, but also cut the high cost of Carbon dioxide Capture, Storage (CCS). It is well known that **Joule-Thomson cooling (JTC) can occur when multiphase mixtures flow through wellhead chokes**. To predict the temperature drop for multiphase mixtures with high CO₂ content through **choke valves**, a **new** multiphase choked flow model was developed, which was based on the isenthalpic model, gas-liquid solubility equilibrium model and gas-liquid thermal equilibrium model. At the same time, a verification experiment was carried out to study on the flow characteristics in multiphase choked flow. The results also showed that the model predictions were in good agreement with the experiment data and HYSYS simulation results. It was found that choke valve pressure drop, gas components and gas-liquid ratio had impacts on the JTC. The positive contributions to JTC for CH₄, N₂ and H₂ were decreasing gradually and **high mole fraction of CO₂ can enhance JTC**. Based on this study, **low GLR, low pressure drop and high upstream temperature can prevent**

freeze and block of the pipeline downstream.

Keywords:

CCUS; CO₂-EOR; Multiphase choked flow; Mathematical model; Choked experiment

Nomenclature

C velocity, m/s

c_g specific heat at constant pressure, J/(mol·K)

c_w specific heat of water phase, 7.56J/(mol·K)

f fugacity, MPa

GLR gas liquid ratio, mol/mol

H enthalpy, kJ/kg;

H_0 enthalpy of ideal gas, kJ/kg

k_H Henry constant, MPa

M_g molar mass, 44.01kg/kmol

p pressure, MPa

Δp pressure difference between the upstream and downstream, MPa

Q unit quantity of heat, kJ/kg

R universal gas constant, 8.314J/(mol·K)

T temperature, K

T_c critical temperature, K

T_D the initial temperature downstream, K

T_{2g} the initial downstream temperature of gas phase, K

ΔT temperature difference between the upstream and downstream, K

W external work, kJ/kg

x mole fraction of gas at liquid phase

ΔZ difference of elevation, m

Greek letters

ω acentric factor

μ_{JT} Joule-Thomson coefficient, K·MPa⁻¹

γ activity coefficient

ρ density, kg/m³

ρ_c critical density, kmol/m³

Subscripts

aq aqueous phase

c critical parameters

g gas phase

l liquid phase

1 upstream

2 downstream

1 Introduction

Global warming is a great challenge for human beings. Intergovernmental Panel on Climate Change (IPCC) reported that Carbon dioxide Capture, Storage (CCS) can eliminate 20%-40% of global carbon emissions [1]. In order to cut the high cost of CCS, utilization of CO₂ has been a key priority for CCS [2]. CO₂ enhanced oil recovery (CO₂-EOR) technique is one potential option, which has been used for decades and widely accepted as a high-efficient technique to enhance recovery of residual oil in water wet rock [3]. According to the field data, the produced fluid from CO₂-EOR wells is often multiphase mixture which are mainly composed of hydrocarbons (C₁, C₂, C₃ and C₃⁺), water, CO₂ and other gases (such as N₂, H₂). The components of associated gas in Daqing Sartu oil field in China is shown in Table 1.

Due to the strong Joule-Thomson cooling (JTC) effect of CO₂, the high CO₂ content in associated gas is an important characteristic that should be analyzed [4]. When the fluid with high CO₂ content flows through a choke valve, the rapid cooling can cause the temperature downstream of the valve to drop below the freezing point. Thus it can freeze and block the downstream pipeline. As is shown in Fig. 1, massive ice generates downstream the wellhead choked valve and is precipitated onto the ground. Huang et al. found that the temperature of CO₂ dropped below the triple point during releasing high pressure pure CO₂ through a safety valve, which causes periodic blockage of downstream pipe [5-6]. Oldenburg evaluated the Joule-Thomson cooling for injection of CO₂ into a depleted natural gas reservoir using the TOUGH2/EOS7C code [7]. Zhou

et al. presented a method based on the homogeneous equilibrium mixture assumption to simulate the choked flow in pure CO₂ multiphase flow. The temperature of CO₂ multiphase mixture can drop to -50°C. The pressure-temperature variations were discussed during the flow through the nozzle [8]. Zhao and Li [9] presented a choked flow model base on the adiabatic process assumption for calculating temperature drop of an anthropogenic CO₂ pipeline with impurities. The results showed that SO₂ is helpful for increasing the downstream temperatures through the choking device to **prevent frozen hazard**. The models above were used to predict temperature drop of single-phase or multiphase CO₂ during the flow through the nozzle or orifice. However, the temperature drop prediction of the multiphase mixture with high CO₂ content in CO₂-EOR involves **thermophysical properties calculation of multiphase mixture**, heat transfer between liquid and gas and dissolution of gas mixture, which is different from the models above.

In petroleum and natural gas industries, the JTC also exists in the flow through the wellbore, and many works investigated the wellbore temperature profiles. Ramey's model was the first theoretical model to estimate fluid temperature as a function of well depth and production time [10]. However, Ramey's model used the simplifying assumption of single-phase flow. Recently, some researchers have developed more comprehensive and complex numerical model for the prediction of wellbore temperature profiles. Yoshioka et al. presented a model **coupling with** the mass, momentum and energy balances for predicting the temperature profile in horizontal

well. The model can be used to account for Joule-Thomson effects of single phase and multiphase flow [11]. Ouyang and Belanger developed a thermal model for multiphase-fluid flow along a vertical, deviated, or horizontal well. Their model can be applied for both wellbore temperature prediction and for flow profile [12]. In addition some works have been done to predict the temperature and flow profile of multiphase mixture in wellbore. The models often can be derived from mass, momentum, and energy balance equations [13-14]. However comparing to most models for predicting the wellbore temperature profiles, it can be found that they have some limits. Firstly, all these models focused on both flow and temperature profiles, which can make the solution complex. Secondly, the models are applicable to natural gas-oil-water system rather than multiphase mixture with high CO₂ content.

Flow through the capillary tubes in refrigeration industries is also a choked flow [15]. Usually the simulations of choked flow through capillary tubes are assumed as adiabatic two phase flow [16]. Two-phase refrigerant choked flow is often simulated using homogeneous flow, separated flow and drift flux models [17-19]. Some researchers investigated the flow characteristics in two-phase refrigerant choked flow [20-22]. The results indicated that tube diameter, tube length, inlet subcooling and condensing pressure or temperature would affect the pressure drop and the mass flow. Out of these parameters, diameter affects the mass flow rate more significantly than the others. However the models above for multiphase refrigerant choked flow focused on calculating the critical and sub-critical flow rates and pressure drop rather than the

temperature drop.

Recently there are few works **studying on** temperature prediction for multiphase mixture through chokes from the view of thermodynamics principle. One example is the work of Li et al. [23] who develop a theoretical model for predicting the downstream temperature of high pressure high temperature (HPHT) condensate gas flowing through a choke valve. However there are two different points compared with this present work. First, the method in **Li's** work is not suitable for multiphase mixture with high CO₂ content. Second, various effects on temperature drop **were not** investigated in **Li's** paper while they will be focused on **in this present work**. Thus, it is significant to develop a multiphase mixture model to predict temperature drop in highly choked conditions in CO₂ enhanced oil recovery.

In addition, some commercial software (such as the Aspen HYSYS which is a process modeling and simulation tool for the oil and gas industry [24]) can also simulate temperature drop through chokes or orifices. However, they have some common features. **Firstly**, it is complex to describe both multiphase flow and phase equilibrium. Secondly, solving the complex nonlinear equations is computationally time-consuming **and needs more computational memory**. Thus, it is necessary **to develop** a new model to solve this problem.

The objective of the present work is to study on the characteristics of temperature drop when **the multiphase mixture with high CO₂ content flows through choke valves**. Firstly, a simplified model based on thermodynamics process was elucidated to predict

the downstream temperature through chokes. Secondly, we investigated the flow characteristics for multiphase mixture through chokes experimentally and carry out experimental verification of the choked flow model. Then, the results of sensitivity analysis were **presented**, which evaluated the impacts of the various parameters on Joule-Thomson Cooling. Finally, some operational recommendations are presented for **safety management of choked process**.

2 Modelling approach

In multiphase mixture, the vapor phase is **mainly** composed of CO₂, CH₄, N₂ and H₂, and the liquid phase is composed of oil and water. In general, the temperature drop of liquid is negligible when it flows through choke valves. Thus, only gas mixture would be taken into account in isenthalpic choked model, and multiphase mixture would be involved in gas-liquid solubility equilibrium and thermal equilibrium model. Hence the model involves three **sub-models**. Firstly, the isenthalpic model for gas mixtures is presented to calculate the downstream temperature. Secondly, according to gas-liquid solubility equilibrium model, the content of components can be obtained. Finally, the heat exchange between gas and liquid can compute the downstream temperature of multiphase mixtures.

2.1 Isenthalpic model

The pressure and the temperature will decrease when fluid flows through the choke valve. The isenthalpic choke model can be derived from the energy conservation equation. As is shown in Fig. 2, the flow parameters involve pressure, temperature,

velocity, etc. To simplify the model, temperature drop is negligible when liquid flows through choke valves. Thus on the basis of total mass of gas, it can be written as:

$$H_1 + \frac{1}{2}C_1^2 + Q - W = H_2 + \frac{1}{2}C_2^2 + g\Delta Z \quad (1)$$

To establish the isenthalpic model, it is simplified based on the following assumptions:

- (1) The difference in elevation during choked flow is negligible. And this assumption is applicable for horizontal pipes (or small inclination angle pipes). If the difference in elevation cannot be ignored as well as it is positive, then the prediction of choke valve temperature drop may be lower than that based on the assumption (1).
- (2) The velocity of fluid through chokes hardly change, thus the kinetic energy of fluid is ignored. In engineering, the upstream and downstream velocity of the fluid is similar when the multiphase mixture flows through a choke valve in pipeline. However based on the assumption (2), the prediction of temperature drop may be higher than that measured.
- (3) There is no slip between gas and liquid phase. The slip between gas and liquid phase can affect heat change between gas and liquid, and then the prediction of temperature drop may be affected. As shown in Fig. 7, the flow pattern downstream usually is dispersed flow, thus the assumption (3) is reasonable.
- (4) The external work zero, thus the choke flow can be supposed as adiabatic flow. For the pipes with good thermal insulation, the error introduced by the assumption (4)

can be ignored.

- (5) The choked flow is frictionless. The energy change caused by friction heat is much **smaller** than that caused by the Joule-Thomson cooling. Therefore the effect of friction heat on temperature drop can be negligible. And based on the assumption (4), the prediction of temperature drop may be lower than that measured.

Based on these assumptions, Eq. 1 thus reduces to

$$H_1 = H_2 \quad (2)$$

It indicates that the enthalpy across a choke is approximate equal. BWRS EoS is widely used to calculate thermodynamic property of light hydrocarbon and its mixture gas [25]. Thus the enthalpy of mixture gas (such as CO₂, CH₄, N₂ and H₂) can be calculated using BWRS EoS and the isothermal enthalpy difference can be written as [26]

$$\begin{aligned} (H - H_0)M_g = & \left(B_0 RT - 2A_0 - 4\frac{C_0}{T^2} + 5\frac{D_0}{T^3} - 6\frac{E_0}{T^4} \right) \rho + \left(2bRT - 3a - 4\frac{d}{T} \right) \left(\frac{\rho^2}{2} \right) \\ & + \alpha \left(6a + 7\frac{d}{T} \right) \left(\frac{\rho^5}{5} \right) + \frac{c}{\gamma T^2} \left[3 - \left(3 + \gamma \frac{\rho^2}{2} - \gamma^2 \rho^4 \right) \times \exp(-\gamma \rho^2) \right] \end{aligned} \quad (3)$$

Where A_0 , B_0 , C_0 , D_0 , E_0 , a , b , c , d , α and γ are eleven parameters of BWRS EoS. They can be computed in Appendix A. H_0 is the enthalpy of ideal gas at the system temperature, it can be given by [27]

$$H_0 - H_0^0 = A + BT + CT^2 + DT^3 + ET^4 + FT^5 \quad (4)$$

Where H_0^0 is the enthalpy of ideal gas when the temperature is 0 °C.

According to the known quantity p_1 and T_1 , the density of gas upstream of the choke valve ρ_1 is determined by iterative solution of the EoS. Then substituting T_1 and ρ_1 into

Eq. 3~Eq. 4 yields the upstream enthalpy H_1 . We assume the initial temperature of downstream T_D , and then substituting T_D and P_2 into Eq. 3~Eq. 4 to calculates H_2 . Next, iterate on H until Eq. 2 is satisfied. Now T_D is equal to the temperature downstream T_{2g} .

2.2 Gas-liquid solubility equilibrium model

We assume that only carbon dioxide would be soluble in water in consideration of the high solubility of CO_2 compared to other gases. When solubility process reaches equilibrium, the fugacity of CO_2 in gas and liquid phase would be equal as follows:

$$f_{CO_2}^V = f_{CO_2}^{aq} \quad (5)$$

Where $f_{CO_2}^V$ is the fugacity of vapor CO_2 . It can be calculated by BWRS EoS, as is shown in Eq. 6.

$$\begin{aligned} & RT \ln(1000 f_{CO_2}^V) \\ &= RT \ln(\rho RT) + 2 \left(B_0 RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4} \right) \rho + \left(bRT - a - \frac{d}{T} \right) \left(\frac{3\rho^2}{2} \right) \\ &+ \alpha \left(a + \frac{d}{T} \right) \left(\frac{6\rho^5}{5} \right) + \frac{c}{\gamma T^2} \left[1 - \left(1 - \gamma \frac{\rho^2}{2} - \gamma^2 \rho^4 \right) \times \exp(-\gamma \rho^2) \right] \end{aligned} \quad (6)$$

The fugacity of CO_2 in dissolved phase can be written as:

$$f_{CO_2}^{aq} = k_H \gamma_{CO_2}^{aq} x \quad (7)$$

Where K_H is Henry constant of two phase system and it can be described by Carroll's empirical equation [28].

$$\ln k_H = -6.8346 + \frac{1.2817 \times 10^4}{T} - \frac{3.7668 \times 10^6}{T^2} + \frac{2.997 \times 10^8}{T^3} \quad (8)$$

Substituting T_{2g} (the gas temperature downstream obtained in 1.1 section) into Eq. 6 and Eq. 8 calculates $f_{CO_2}^V$ and K_H , respectively. Usually CO_2 mole fraction in the liquid phase tends to 0 ($x \rightarrow 0$), thus $\gamma_{CO_2}^{aq} \rightarrow 1$. Thus substituting Eq. 7 into Eq. 5 yields

$$x = \frac{f_{CO_2}^V}{k_H} \quad (9)$$

2.3 Gas-liquid thermal equilibrium model

In oil and gas production, freeze and block of the pipeline usually happens after a period of time rather than immediately. Thus, it can be considered that the gas-liquid heat exchange reaches equilibrium after the distance from the choke valve. The temperature of gas phase from the wells drops to T_{2g} through a choke valve. However no JTC exists in the process of liquid choke. Therefore the temperature of liquid phase remains T_1 in initial period of choke flow. After that, the temperature of gas and liquid phase tends to equilibrium due to the effect of difference in temperature. We can assume that the heat of dissolution could be ignored because very little amount of CO_2 can dissolve in water. In addition, the mixture in typical CO_2 -EOR conditions could not change phases in choked flow. However if the content of propane and $C3^+$ is really high, we cannot eliminate the possibility of potential phase change. The extreme conditions are out of the scope in this work. Hence when the gas-liquid temperature reaches thermal equilibrium, the equilibrium temperature T_2 can be calculated as following:

$$c_g \left(GLR - \frac{x}{1-x} \right) (T_2 - T_{2g}) = c_l \frac{1}{1-x} (T_1 - T_2) \quad (10)$$

Where c is specific heat capacity. The effect of water vapor in gas phase and carbon dioxide in liquid phase on specific heat capacity is negligible. According to field experience, the effect of oil on choke valve temperature drop is negligible, compared with that of water. And in general the pipeline is frozen by ice instead of oil. Thus, we

assume that the specific heat capacity of liquid is equal to that of water. The specific heat capacity of gas and liquid phase can be written as [29]

$$c_g = 26.75 + 4.2258 \times 10^{-2} T - 1.425 \times 10^{-5} T^2 \quad (11)$$

$$c_l = c_w \quad (12)$$

2.4 Mixing rule

To obtain the mixture parameters of BWRS EoS, the mixture rule in consideration of interaction effect must be used for mixture of different compositions. Usually the mixing rule is developed from both theoretical and experimental studies [30]. The equations of mixing rule are presented in Appendix B.

2.5 Model solution

The density of gas can be computed using BWRS EoS and the numerical method is secant method in this work, as is shown in Eq. 27. Fig. 3 shows that the three **sub-models** (isenthalpic model, solubility equilibrium model, thermal equilibrium model) are solved successively until the temperature downstream of multiphase mixtures is obtained.

$$f(\rho) = \rho RT + \left(B_0 RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4} \right) \rho^2 + \left(bRT - a - \frac{d}{T} \right) \rho^3 + \alpha \left(a + \frac{d}{T} \right) \rho^6 + \frac{c\rho^3}{T^2} (1 + \gamma\rho^2) \exp(-\gamma\rho^2) - p \quad (13)$$

3 Model validation experiments

An experiment was carried out on a high-pressure pipeline loop to validate the numerical predictions and to study flow characteristics in multiphase choked flow.

Experimental setup is designed and established in the laboratory as is shown in Fig. 4. The total length of the pipeline loop is 21.5 m with an internal diameter of 25 mm and the length of test pipe is 1.6 m. The design pressure is 8.0 MPa and the highest permitted pressure is 10 MPa. The material of the pipeline is 316L stainless steel. Objective of the study is to figure out the temperature drop and flow characteristics in choked flow, which is a focus of concern in CO₂-EOR.

Apparatus consists of four subsystem, respectively, gas system, liquid system, mixture system, separation and temperature control system and choke valve and observation system, as is shown in Fig. 4. Gas system consists of gas cylinders, a pressure pan, a gas flow meter and control valves. Liquid system consists of a centrifugal pump, a liquid flow meter and control valves. Mixture system is set to avoid slug flow, which includes a gas-liquid mixer, shear valves. The gas-liquid mixer is based on the principle of venturi tube, which can make gas and liquid mix well. Separation and temperature control system consists of a gas-liquid separator and a thermostat controlled heater, which is designed to separate gas and liquid and control the temperature of fluid. Thermostat controlled heater is fitted at the bottom of the separator. Choke valve and observation system is the test section in this setup, which consists of a choke valve, a high-pressure transparent tube and pressure and temperature measurement system. The pressure sensors and thermocouples are inserted into the upstream and downstream pipeline of the choke valve for measuring the pressure and the temperature along the test section. All data is recorded by National

Instruments data acquisition system, which mainly consists of sensors, a data acquisition card and a computer, etc. The key instruments are pressure sensors/transmitters, temperature sensors/transmitters and gas/liquid flow meters, as is shown in Table 2.

4 Results and discussions

4.1 Experimental results of multiphase mixtures through chokes

Fig. 5 shows the flow parameters profile upstream and downstream through a choke valve in experimental condition 1. It can be seen from Fig. 5 that the temperature downstream would drop rapidly once the choke valve is opened. At the same time, the pressure upstream fluctuates slightly and then remains steady; the pressure downstream remains nearby 0.60 MPa because of the function of the choke valve on setting back pressure. As is shown in partial enlarged detail view A of Fig. 5, the choke valve temperature drop will maximize when the pressure drop remains steady. The minimum temperature after the choke valve can be stable for 200 seconds, which indicates that the temperature drop is caused by the JTC excluding other interruptions. At the experimental ending stage, the pressure upstream drops gradually and meanwhile the temperature downstream increases gradually as the fluid upstream is blown down.

Fig. 6 illustrates flow parameters profile upstream and downstream at different choke pressure in experimental condition 2. The result presents that three “pressure platforms” are 3.2/2.0/1.3 MPa, respectively. The temperature downstream drops rapidly to bottom and then it increases gradually as the pressure upstream changes from

pressure platform 1 to pressure platform 3. At the ending stage, there is an inflection point of the pressure and temperature. The experimental results show that temperature drop corresponds to pressure drop. It indicates that the temperature downstream should be a constant value at given pressure drop when the temperature upstream remains invariant, which contributes to predict choke valve temperature drop.

4.2 Flow visualization upstream and downstream of the choke valve

Fig. 7 displays the visualization flow upstream and downstream of the choke valve. The high pressure glass tube is used to visualize the flow in the pipeline. Flow is visualized by High Speed Camera System. The left-hand side panels show that the two phase flow upstream usually is stratified wave flow while the right-hand side panels show that the flow pattern downstream usually is dispersed flow. Thus, it is justified for the assumption of homogeneous flow model involved in downstream gas-liquid thermal equilibrium model for prediction of choke temperature drop.

4.3 Model validation

The verification of the model is carried out by comparing with experimental data and HYSYS, as is shown in Table 3. The range of upstream pressure is about 2-6MPa, which corresponds with field data from Daqing Sartu oil field.

Fig.8 (a) illustrates the deviation analysis of the model and HYSYS simulation results compared with experimental data. The results show that the predicted temperature drop of the model and HYSYS is approximate. The majority of relative error of the predicted temperature drop compared with experimental data is between

-10% and +50% and maximum relative error can reach 100%. To validate the predictions of the model, we also compute relative errors of temperature between the model and HYSYS, as is shown in Fig.8 (b). We can see that the majority of relative error is controlled within 10% and a very few is between -20% and -30%. It indicates the deviation is acceptable for engineering application.

4.4 The effect of choke valve pressure drop on temperature drop

To examine the effect of choke valve pressure drop on the temperature drop, pressure drop was varied from 1 MPa to 5 MPa. Fig. 9 displays the effect of choke valve pressure drop on the temperature drop for different components of gas. In simulation, the content of other gas components except CO₂ is 20 mol% and *GLR* is 24 mol/mol. It is observed that the predication of temperature drop demonstrated by both the model and HYSYS results is increasing in a linear fashion as choke valve pressure drop increases. Thus we can write the Joule-Thomson coefficient μ_{JT} for two phase choked flow as

$$\mu_{JT} = \lim_{\Delta p \rightarrow 0} \left(\frac{\Delta T}{\Delta p} \right)_{H-System} = \left(\frac{\partial T}{\partial p} \right)_{H-System} \quad (14)$$

Where H-System is that the two phase flow system is in isenthalpic choking process. When other parameters such as gas components and *GLR* are the given values, μ_{JT} is also determined. At this point, there is a linear relationship between pressure drop and temperature drop.

4.5 The effect of gas components on temperature drop

Other gas components except CO₂ are defined as “impurity”. Fig. 10 presents the

effect of gas components on the temperature drop when Δp is 3MPa and GLR is 19 mol/mol. Fig. 10 shows high mole fraction of CO_2 can enhance JTC. Hence it is more dangerous for oil and gas wells with high content of CO_2 because of lower temperature downstream. Fig. 10 also demonstrates that impurity such as CH_4 , N_2 and H_2 would affect JTC, and the positive contributions to JTC for CH_4 , N_2 and H_2 are decreasing gradually compared with Fig. 9. The rate of temperature drop is increasing with the increase of CO_2 mole fraction, which is more obvious for the gas components that suppress JTC. It can be explained that with the increase of CO_2 content, combined effects of different gases on JTC are different. For example, hydrogen can suppress JTC, but the suppression would decrease with the increase of CO_2 content. And higher CO_2 content can make JTC stronger. The two positive contributions to JTC can make the rate of temperature drop increase. In addition, it can be seen that the model simulation results are closed to HYSYS results at high content of CO_2 in Fig. 10.

4.6 The effect of GLR on temperature drop

To study the effect GLR on the temperature drop, GLR was varied from 10 to 3000 mol/mol. Fig. 11 shows the effect of gas-liquid ratio on choke valve temperature drop at constant pressure drop of 3.5 MPa. And then gas phase is composed of 85% CO_2 , 5% CH_4 , 5% N_2 and 5% H_2 . It can be seen that JTC of two phase choked flow is greatly sensitive to GLR . When GLR is below 20 mol/mol, the temperature drop is increasing rapidly with the increase of GLR . It can be explained that GLR has a great impact on temperature drop because of the wide difference of JTC for gas and liquid. The liquid

content is decreasing with the increase of GLR. And when the liquid content is very low, it can be considered as choke flow of “pure gases”. Thus the temperature changes little at high GLR, as shown in Fig. 11. It indicates that **it is a bigger hazard for the oil and gas wells with high GLR.**

5 Conclusions

A mathematical model has been developed to predict the temperature downstream for high pressure gas-liquid mixture in choked flow and a verification experiment **were carried out** to study the flow characteristics in multiphase choked flow. The proposed model has some advantages, such as definite physical meaning, high computational efficiency. And it can predict temperature drop in highly choked conditions in CO₂-EOR, which can benefit the production safety.

- (1) The model based on isenthalpic model, solubility equilibrium model and gas-liquid thermal equilibrium model can predict the temperature downstream for high pressure gas-liquid mixture in choked flow.
- (2) The experimental results presented the variation of pressure and temperature in choked flow and the Joule-Thomson coefficient μ_{JT} for two phase choked flow is defined.
- (3) The model predictions have been validated by the experimental results and HYSYS simulations. And the results show that JTC of two phase choked flow was greatly sensitive to choke valve pressure drop, gas components and *GLR*. The predicted temperature drop is increasing in a linear fashion as pressure drop increased. The

positive contributions to JTC for CH₄, N₂ and H₂ are decreasing gradually and **high mole fraction of CO₂ can enhance JTC.**

- (4) The operational recommendations for multiphase choked flow can be drawn **that low GLR, low choke valve pressure drop and high upstream temperature can prevent freeze and block of the pipeline downstream.**

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Appendix A.

$$\rho_c B_0 = A_1 + B_1 \omega \quad (\text{A.1})$$

$$\frac{\rho_c A_0}{RT_c} = A_2 + B_2 \omega \quad (\text{A.2})$$

$$\frac{\rho_c C_0}{RT_c^3} = A_3 + B_3 \omega \quad (\text{A.3})$$

$$\rho_c^2 \gamma = A_4 + B_4 \omega \quad (\text{A.4})$$

$$\rho_c^2 b = A_5 + B_5 \omega \quad (\text{A.5})$$

$$\frac{\rho_c^2 a}{RT_c} = A_6 + B_6 \omega \quad (\text{A.6})$$

$$\rho_c^3 \alpha = A_7 + B_7 \omega \quad (\text{A.7})$$

$$\frac{\rho_c^2 c}{RT_c^3} = A_8 + B_8 \omega \quad (\text{A.8})$$

$$\frac{\rho_c D_0}{RT_c^4} = A_9 + B_9 \omega \quad (\text{A.9})$$

$$\frac{\rho_c^2 d}{RT_c^2} = A_{10} + B_{10} \omega \quad (\text{A.10})$$

$$\frac{\rho_c E_0}{RT_c^5} = A_{11} + B_{11} \omega \exp(-3.8 \omega) \quad (\text{A.11})$$

Appendix B.

$$B_0 = \sum_{i=1}^n x_i B_{0i} \quad (\text{B.1})$$

$$A_0 = \sum_{i=1}^n x_i x_j A_{0i}^{1/2} A_{0j}^{1/2} (1 - k_{ij}) \quad (\text{B.2})$$

$$C_0 = \sum_{i=1}^n x_i x_j C_{0i}^{1/2} C_{0j}^{1/2} (1 - k_{ij})^3 \quad (\text{B.3})$$

In Eq. (B.1) to Eq. (B.2), n is the total number of components and i and j are indices for the components. where x_i and x_j are the mole fractions of the component. A_{0i} , C_{0i} , and so forth are the pure component parameters which can be expressed as the functions of component acentric factor ω_i , critical temperature T_{ci} , and critical density ρ_{ci} . Where k_{ij} is the binary interaction parameter of i-j components. Nishiumi et al. [31]

and Starling and Han [26] give the value of k_{ij} different components.

Tables & Figures

Fig. 1. Field blow down process of oil well for CO₂-EOR

Fig. 2. Diagram of multiphase choked flow

Fig. 3. Flowchart for predicting temperature downstream of multiphase mixtures through chokes

Fig. 4. Schematic of the experimental setup

Experimental condition 1: pure CO₂, $GLR=1156 \text{ m}^3/\text{t}$, $p_1=2.35 \text{ MPa}$, $T_1=18.61 \text{ }^\circ\text{C}$, $p_2=0.60 \text{ MPa}$

Fig. 5. Flow parameters profile upstream and downstream in experimental condition 1

Experimental condition 2: $n(\text{CO}_2):n(\text{N}_2)=3:1$, $GLR=1639 \text{ m}^3/\text{t}$, $p_1=4.12 \text{ MPa}$, $T_1=20.27 \text{ }^\circ\text{C}$, $p_2=0.60 \text{ MPa}$

Fig. 6. Flow parameters profile upstream and downstream in experimental condition 2

(a) $n(\text{CO}_2):n(\text{N}_2) = 4:1$, $\text{GLR}=56 \text{ m}^3/\text{t}$, $\Delta p = 3.70 \text{ MPa}$

(b) $n(\text{CO}_2):n(\text{N}_2) = 3:1$, $\text{GLR}=280 \text{ m}^3/\text{t}$, $\Delta p = 1.20 \text{ MPa}$

(c) $n(\text{CO}_2):n(\text{N}_2) = 2:1$, $\text{GLR}=912 \text{ m}^3/\text{t}$, $\Delta p = 3.52 \text{ MPa}$

Fig. 7. Visualization of flow in choked flow

Fig. 8. Relative errors analysis of predicted temperature

Fig. 9. The effect of choke pressure drop on the predicted temperature downstream

Fig. 10. The effect of gas components on the predicted temperature downstream

Fig. 11. The effect of *GLR* on the predicted temperature downstream

Table 1. The components of associated gas in Daqing Sartu oil field

Components	Mole fraction (mol%)
Methane	10.22
Ethane	1.29
Propane	0.77
Iso-butane	0.06
n-butane	0.23
Iso-pentane	0.02
n-pentane	0.06
Hexane and C ₆ ⁺	0.03
Carbon dioxide	87.07
Nitrogen	0.25

Table 2. Experimental instrumentation and measurement accuracy

Instrument	Range	Measurement accuracy (%)
Pressure sensors	0-13kPa	0.075
temperature sensors	PT100	0.1
turbine flow meter	0-10m ³ /h	1
vortex gas meter	0-70m ³ /h	0.75

Table 3. The comparison of downstream temperature between predictions and experimental data

No.	Components			GLR	p_1	T_1	p_2	$T_2(^{\circ}C)$		
	CO ₂	CH ₄	N ₂	(m ³ /t)	(MPa)	($^{\circ}C$)	(MPa)	Measured	HYSYS	Model
1	1.00	0.00	0.00	infinity	2.31	22.87	0.61	2.69	2.17	1.96
2	0.50	0.50	0.00	infinity	2.64	18.73	0.61	5.12	4.87	3.30
3	0.50	0.00	0.50	infinity	2.10	24.21	0.61	16.26	14.46	15.16
4	0.00	0.00	1.00	infinity	3.66	19.54	0.60	14.01	11.81	12.78
5	1.00	0.00	0.00	303	2.50	18.82	0.61	15.94	15.99	16.26
6	0.50	0.50	0.00	769	3.81	25.65	0.61	21.52	19.89	20.54
7	1.00	0.00	0.00	1785	2.28	19.55	0.61	11.26	10.59	10.92
8	1.00	0.00	0.00	556	5.14	18.51	0.59	6.14	5.55	5.09
9	0.50	0.00	0.50	204	4.74	20.66	0.60	3.74	9.01	9.49
10	0.67	0.00	0.33	1695	5.77	21.06	0.61	4.45	3.93	3.98
11	0.75	0.00	0.25	1389	4.72	17.76	0.60	5.12	3.77	3.82
12	0.80	0.00	0.20	1515	4.90	18.13	0.60	1.42	1.30	1.37
13	0.00	1.00	0.00	2941	2.60	18.18	0.59	14.86	12.10	11.94
14	0.80	0.20	0.00	1315	4.91	18.19	0.60	0.72	1.35	1.47
15	0.80	0.00	0.20	1471	2.85	16.05	0.58	7.03	7.54	7.89
16	0.25	0.60	0.15	568	5.26	24.13	0.61	21.68	19.77	20.15