



Full Length Article

Numerical evaluation of phase behavior properties for gas condensate under non-equilibrium conditions

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ABSTRACT

It is generally known that for a gas reservoir if its pressure changes or flow rate is smaller than the phase transition or mass transfer rate, non-equilibrium effect may arise. Commonly, this situation is ignored when the approaches based on the local equilibrium assumption were applied. Previously there are only a few works focused on this subject and now it attracts more and more attentions now. In this work, a mathematical model was formulated to simulate the gas-related properties of Constant Composition Expansion (CCE) tests under non-equilibrium conditions. In this method, the condensed liquid or condensate is assumed to form a continuous film when brought into contact with gas condensate that was depressurized incrementally at a constant temperature. The whole process is controlled by interphase mass transfer and is completed when abandonment pressure or thermodynamic equilibrium is reached. The elapsed time to reach the final state is determined by the pressure dropping rate and the pressure difference between the initial and final states. The results obtained using the current method match satisfactory with the experimental data. The results demonstrate that the larger the pressure drop rate, the lower the retrograde condensate saturation, and the stronger degree of non-equilibrium effect. It proved that a higher pressure dropping rate can not only alleviate the retrograde condensate phenomenon but also improve the recovery of gas condensate.

1. Introduction

Gas condensate reservoirs, many of them with industrial exploitation value play a significant role in natural gas industries. For retrograde condensate, the stratum pressure of the reservoir usually decreases below the dew point pressure during the production process. The condensed oil will not flow and therefore a region of high saturation will build up near the wellbore unless its saturation exceeds a threshold value. It makes the phase behavior of such system (gas and condensate) quite complex and difficult to be simulated, and the more crucial issue is that it will cause the condensate blockage problem and reduce the recovery of both gas and oil phases [1].

In contrast to the conventional natural gas reservoirs, numerous studies were focused on condensate oil which may cause lots of formation problems. In these studies, some of them derived a simulation model that considers the radius of condensate blockage as a function of time [2]; some findings demonstrated that condensate blockage would reduce well deliverability [3,4]; a few studies introduced the first gas rate equation to describe the condensate blockage [5]; some other studies focused on Equation of State (EoS) compositional simulation

[6–8]. All of the above studies concentrated on the macroscopic well deliverability and they in fact alleviated the effect of condensate blockage on gas production to some extent. However, how to attenuate the condensate blockage and explore and develop gas condensate reservoirs economically and effectively are still critical issues. In this work, our attention is focused on the better understanding of the mechanisms of condensate of gas condensate reservoir.

A.X [9] pointed out that when the pressure of the condensate gas reservoir decreased below the dew point pressure with a constant rate, it was difficult for both gas phase and condensate liquid phase to reach thermodynamic equilibrium at high speed gas flow rate. This phenomenon was henceforth denoted as a non-equilibrium effect, namely that when the pressure or temperature change rate is large enough to supersede the phase transition rate (mass or heat transfer), non-equilibrium effect will arise. Based on this rationale, it was observed that the amount of condensate liquid gradually decreased with increasing pressure dropping rate. And a correlation was proposed to describe the relationship between the condensate liquid and pressure dropping rate under the non-equilibrium conditions.

At present, it is generally believed that the non-equilibrium effect

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Nomenclature	
L	liquid phase
V	gas phase
x_i	mole fraction of component i in bulk liquid phase
y_i	mole fraction of component i in bulk gas phase
n	number of components
x_i^I	interfacial mole fraction of component i on the liquid phase side
y_i^I	Interfacial mole fraction of component i on the gas phase side
S_V^0	initial mole amount of gas phase,%
S_L^0	initial mole amount of liquid phase,%
N_i	mole flux of component i , mol/(m ² ·s)
\bar{N}_i	total molar flux, mol/(m ² ·s)
(F)	vector of Independent equations
P_i^V	mass transfer rate equations of component i in the gas phase
P_i^L	mass transfer rate equations of component i in the liquid phase
J_i^V	molar diffusion flux of component i in gas phase, m/s
J_i^L	molar diffusion flux of component i in liquid phase, m/s
C_i^V	total mole density of gas phase, mol/m ³
C_i^L	total mole density of liquid phase, mol/m ³
D	matrix of effective diffusion coefficient, m ² /s
B	A square matrix
Γ	matrix of thermodynamic factor
P_d	dew point pressure, MPa
T	simulated temperature, K
V_l	measured volume of condensed liquid, m ³
V_t	measured total volume of the system, m ³
\bar{D}	matrix of Max-Well diffusion coefficient, m ² /s
δ_{ij}	Kronecker delta function
γ_i	activity coefficients of component i
k	matrix of finite flux mass transfer coefficient, m/s
k	mass transfer coefficient, m/s
l	thickness of the film, m
Ξ	matrix of correction factor
Φ	matrix of Mass transfer rate factor
Θ	matrix of thermodynamic correction factor
Q_i^I	interfacial equilibrium equation of component i
K_i	equilibrium factor of component i
P_{si}	saturation vapor pressure of component i , MPa
P	system pressure, MPa
I	unit matrix
(χ)	vector solution variables
Δt	Time step, hour
A	Effective area of continuous film, m ²
N_i^j	mole amount of component i at time step j , mol
$N_{positive(i)}^j$	positive mole amount of component i at time step j , mol
$N_{negative(i)}^j$	negative mole amount of component i at time step j , mol
$N_{L(i)}^j$	mole amount of component i in the liquid phase at time step j , mol
$N_{V(i)}^j$	mole amount of component i in the gas phase at time step j , mol
(J)	matrix of Jacobi
(E_f)	vector of deviation parameter

has a significant effect on gas condensate within the reservoir and it needs to be taken into account to accurately model this process. At this moment, only a few works were proposed in the literature to model non-equilibrium effect on gas related properties of gas condensate, especially with the assistance of theoretical research.

On one hand, experimental studies indicated that the produced gas and oil are in non-equilibrium state for both ‘condensing’ and ‘vaporizing’ gas drives [10] and there is a precipitation lag when a constant pressure dropping rate is maintained below the dew point pressure [11–14]. In the process of depressurization, portions of the formed condensate liquid moved along with the gas phase until they are deposited. This non-equilibrium phenomenon leads to a higher content of liquid condensate in the gas phase compared with those at equilibrium state situation [15,16]. Other researches also confirmed that the ultimate condensed liquid recovery had approximately increased from 36.15 wt% to 42.55 wt% due to the inadequate contact between the gas and liquid phases [17]. Results show that the higher the pressure dropping rate, the more serious of the non-equilibrium effect, the more condensate fluid produced with gas, the lower amount of the retrograde condensate remained in the formation, and the greater deviate degree from the equilibrium state [18].

On the other hand, theoretical research [19] stated that for the non-equilibrium state of a two-phase mixture, mass transfer took place at the interface. The above process could be expressed by using an efficiency factor which was an exponential function of the contact time and the mass transfer coefficient. Later on, a new K -factor for a system at non-equilibrium has been proposed [20]. It stated that these equilibrium and non-equilibrium K -factors could be related by a variable so called the degree of non-equilibrium of the system (E). And a semi-empirical equation was proposed to obtain the value of E based on the fact that the mass transfer rate not only depends on the equilibrium K -factor and the contact time but also is inversely proportional to the effective mobility ratio of the two phases. Following that, several studies were focused on the mass transfer rate [21–23]. They introduced a coefficient C which is a function of reservoir characteristics and

dynamic flow parameters, and then a new mass transfer rate named normalized component mass transfer rate was obtained. All of these correlations are used in the compositional flow equations.

Actually, as gas condensate flows from formation to the wellbore, due to the drastic pressure declining rates, the gas velocity increases and reaches a maximum near the wellbore. When the gas velocity is extremely low, the system has enough time to reach equilibrium; however as velocity increases, the system has no sufficient time to reach equilibrium thus it shifts to a non-equilibrium state. The situation described above has been studied experimentally in most of the aforementioned works, and the process was unpredictable by using a commercial compositional simulator since they are all based on the local equilibrium assumption. Consequently, the non-equilibrium mechanism for gas condensate reservoirs is still obscure and the required gas related properties are also insufficient at different pressure stages since the whole experimental process is at a non-equilibrium state. It is

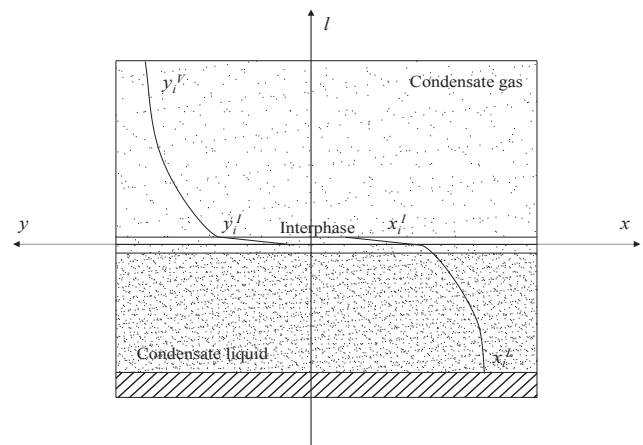


Fig. 1. The schematic of interphase mass transfer.

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