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Monitoring liquid Dropout for Investigating Liquid Loading in Gas Wells

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ABSTRACT: *This paper presents a dynamic simulation approach to monitoring liquid dropout in gas wells for investigating liquid loading of a fluid flowing in mist flow regime. It involves incorporating an event location property into an ODE solver that runs a dynamic mist flow model. The dynamic mist flow model was developed by coupling thermodynamic and hydrodynamic models as well as constitutive equations using Matlab programs that incorporate the Peng-Robinson equation of state and the convex hull algorithm. The event location property is integrated in such a way that at arbitrary positions in the wellbore, the event parameter informs the solver in the ODE file to return appropriate event function information. This is so because during flow, phase and compositional changes occur at different segments of the wellbore that would trigger the Event location property. In this instance, it returns temperature, pressure and composition at specific depths. Phase change is being monitored by changes in the color as the phase proportions vary. Using appropriate color coding, the liquid and vapor phases are monitored along the wellbore, and the amount of condensable liquid is being tracked by the changes in the color of the fluid composition at a given temperature and pressure. Hence, at specific depths in the wellbore, the composition of the fluid is determined which gives a clue of the amount of liquid dropout. The calculated phase compositions were validated using data obtained from commercial software, NIST RefProp and the results show good agreement. This procedure can provide substantial benefits in adequately investigating how liquids dropout during flow in gas wells.*
KEYWORDS *Liquid loading, mist flow, liquid dropout, event location, Peng-Robinson EOS, Convex hull, gas well.*

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I. INTRODUCTION

Investigating the onset of liquid dropout is one of the most controversial aspects of investigating liquid loading in gas wells. This controversy is made worse by the occurrence of flow regimes whose sequence of occurrence has not been conclusively established in multiphase flow studies. This is because the occurrence of flow regimes is strongly influenced by fluid properties, the geometry of the wellbore and prevailing downhole conditions which varies significantly from well to well producing the same or different reservoirs. Hence, several researchers had developed models for predicting critical flow rate based on the extent their lens of vision can see through with very reasonable assumptions. However, these assumptions are the reasons why most of these models, though adjudged outstanding, have failed and rendered most gas assets less promising to exploit. Some renown critical rate predicting models often used in the oil industry are Turner [1] and Coleman [2].

These models have inherent shortcomings such as: using drag coefficients for solid spheres rather than oscillating liquiddrops, use of the critical Weber number established for droplets falling in air and not for conditions that exist in gas wells and ignoring flow regimes. Moreover, these models also assumed isothermal flow; which wrongly depicts the actual flow ingas wells which are known to be significantly associated with cooling as the fluid flows from the wellbore to the wellhead. These assumptions have led to several modifications of the pioneer models. However, most of these modifications seem not to holistically address the shortcomings of the pioneer models, hence this paper. In this work, instead of looking at a droplet, the entire well stream flowing under steady-state is considered. Hence, phase and compositional changes are being monitored using an event location property that is integrated into an ODE solver that models mist flow. The following sections highlights the procedure used for achieving this.

II. METHOD

The method used involves first modeling a mist flow of a two-phase gas-liquid mixture and then, incorporating an event location property to the mist flow model to monitor phase changes in the wellbore. The following subsections describe the procedure used.

(a) Modeling Mist Flow

The modeling of mist flow involves coupling a thermodynamic model with a hydrodynamic model along with appropriate constitutive equations that describes the behavior of a gas stream flowing in a pipe. The thermodynamic model was developed using the Peng-Robinson equation of state and the convex hull method while the hydrodynamic model consists of solving the conservation equations (mass, momentum and energy equations) for the gas and liquid phases as they travel simultaneously along a pipe [3]. The convex hull is a mathematical method, and algorithmic implementations of this method are available in many sources including Matlab. The convex-hull was used to perform the flash calculations from which the initial input values where obtained for the numerical simulation [4].

The mist flow model was developed for a two-component two-phase flow using seven variables. These variables include: temperature, pressure, velocity, the molar volume of the liquid phase V_{liq}; the molar volume of the vapor phase V_{vap}; the mass fraction of component 1 in the liquid phase x_1 and the mass fraction of component 1 in the vaporphase y_1[5]. The determination of the values of these variables as phase change occurs requires solving seven ordinary differential equations. Detailed description of the mist flow model can be obtained from the works of Joseph and Peter [5]. However, for the purpose of clarity, the governing seven ordinary differential equations used for the development of the mist flow model are reproduced thus[5]:

• The Peng-Robinson equation of state solved for each phase [6];

$$Z^3 - (1 - B)Z^2 + (A - 3B^2 - 2B)Z - (AB - B^2 - B^3) = 0 \quad (1)$$

where:

$$Z = \frac{PV}{RT}, \quad (2)$$

$$A = \frac{aP}{R^2T^2}, \quad (3)$$

and

$$B = \frac{bP}{RT}, \quad (4)$$

For a mixture of N components, Peng and Robinson [6] defined parameters a and b with conventional mixing rules and an empirically determined binary interaction coefficient δ_{ij}, as:

$$a = \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j a_{ij}, \quad (5)$$

where x_i and x_j are the mole fractions of component i and j in the mixture,

$$a_{ij} = (1 - \delta_{ij})a_i^{\frac{1}{2}}a_j^{\frac{1}{2}}, \quad (6)$$

$$a_i = a_c\sqrt{\left(1 + (0.37464 + 1.5422\omega - 0.26992\omega^2)\right)\left(1 - \sqrt{T_r}\right)}, \quad (7)$$

Where:

$$a_c = 0.45724\frac{R^2T_c^2}{P_c}, \quad (8)$$

And

$$b = \sum_{i=1}^{N} x_i b_i, \quad (9)$$

$$b_i = 0.07780\frac{RT_c}{P_c} \quad (10)$$

- One mass flow rate equation for component 1 in the mixture, expressed as a product of the density of component 1 and the mixture velocity:

$$\rho_1 v = v\frac{M_1}{\left(V_{vap}\, y_1 f_{mg} + V_{liq}\, x_1 f_{ml}\right)}. \quad (11)$$

Here, ρ 1 is the density of component 1 in the mixture, f mg is the mass fraction of the mixture in the vapor phase, $f_{ml} = 1 - f_{mg}$, is the mass fraction of the mixture in the liquid phase and M_1 is the mass of component 1 inthe mixture. The value of f mg is obtained from convex hull while the mass of component 1 in the mixture M_1, is determined using $M_1 = y_1 m_1 f_{mg} + x_1 m_1 f_{ml}$; where m_1 is the molecular mass of component 1 which can obtainedfrom standard natural gas tables. Equation 11 was differentiated with respect to the seven variables to obtain the mass flow rate equation required to constitute the matrix.

- One momentum equation for the mixture, expressed as a function of the mixture density [7]:

$$\frac{d\sigma}{dz} + \rho_m g = \rho v \frac{dv}{dz}, \quad (12)$$

where σ is the stress (tension taken as positive), g is the acceleration due to gravity. The density of the mixture was determined using

$$\rho_m = \frac{M_m}{\left(V_{liq} f_{ml} + V_{vap} f_{mg}\right)}, \quad (13)$$

where M_m is the mass of the mixture. The mass of the mixture M_m, is determined using the expression:

$$M_m = M_1 + M_2 \quad (14)$$

where M_1 and M_2 are the mass of components 1 and 2 in the mixture. Like M_1 , the value of M_2 is determined using $M_2 = y_2 m_2 fmg + x_2 m_2 f_{ml}$, where m_2 is the molecular mass of component 2. The values of both M_1 and M_2vary as the mass fraction changes during flow.

- The fugacity coefficient equation solved for each phase

$$ln\left(\frac{f_k^l}{x_k^l}\right) = \frac{b_k}{b}(Z^l - 1) - ln(Z^l - B) - \frac{A}{2\sqrt{2B}}\left(\frac{2\sum_{i=1}^{N} x_i a_{ik}}{a} - \frac{b_k}{b}\right) ln\left(\frac{Z^l + 2.414B}{Z^l - 0.414B}\right) \quad (15a)$$

$$ln\left(\frac{f_k^v}{x_k^v}\right) = \frac{b_k}{b}(Z^v - 1) - ln(Z^v - B) - \frac{A}{2\sqrt{2B}}\left(\frac{2\sum_{i=1}^{N} x_i a_{ik}}{a} - \frac{b_k}{b}\right) ln\left(\frac{Z^v + 2.414B}{Z^v - 0.414B}\right) \quad (15b)$$

• and one combined energy equation for the vapor and liquid phases [9]

$$\frac{d}{dz}\left[\rho_g v\left(H_g + \frac{v^2}{2} + gz\right)\right] + \frac{d}{dz}\left[\rho_l v\left(H_l + \frac{v^2}{2} + gz\right)\right] = 0 \quad (16)$$

here, ρ is density, v is velocity, g is acceleration due to gravity, z is the depth (vertical distance) and H is the specific enthalpy. Subscripts g and l represent the vapor and liquid phases. The specific enthalpy for each phase was determined using Equation 23 from the Peng-Robinson paper [6].

$$H - H^* = RT(Z - 1) + \left(\frac{1}{2\sqrt{2b}}\right)\left(T\frac{da}{dT} - a\right)\left(\frac{Z + 2.414B}{Z - 2.414B}\right) \quad (17)$$

where H^* is the specific enthalpy of an ideal gas at temperature T and pressure p. In this work, the specific enthalpy of the ideal gas H^* , was calculated using the correlation of Fouad and Lloyd [10]:

$$H^* = BT + CT\left(\frac{D}{T}\right) coth\left(\frac{D}{T}\right) - ET\left(\frac{F}{T}\right) tanh\left(\frac{F}{T}\right) + A \quad (18)$$

Here A, B, C, D, E, and F are constants which can be obtained from tables. TheFouad and Lloyd correlation is used because of its accuracy and simplicity in application.

(b) Monitoring Liquid Dropout

Having modeled mist flow, a mechanism was developed to track the behavior of the phases. The mist flow model was used to carry out this investigation, in order to track the onset of condensation, which has been the major controversy existing among critical velocity prediction models.

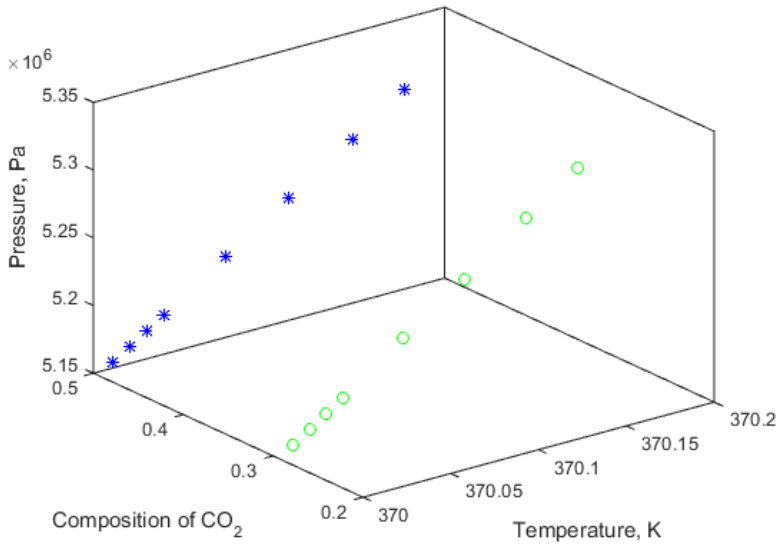

Figure 1: A plot showing the quality of the vapor with variations in temperature and pressure: the blue curve is rich in CO_2 (represents the vapor phase) and the green circle curve is lean in CO_2 (represents the liquid phase)

To monitor liquid dropout and phase change as the carbon-dioxide-isobutane mixture travels up the wellbore to thewellhead, an Event Location Property was integrated with the ODE solver of the Mist flow model using the 'event' function in Matlab. With the event function, the ODE solver returns appropriate information about different events suchas when the entire mixture becomes completely liquid, completely vapor or when it becomes a mixture of liquid and vapor at certain proportions. The statement for the event integrated with the ODE solver takes the form [11]:

[T,Y,TE,YE,IE] = solver('F',tspan,y0,options),

where (T,Y) is the vector of the 'event' function and represents the value of the first argument which can be of any length, TE is a column vector of times at which events occur, rows of YE are solutions corresponding to times in TE and the indices in vector IE specify which event occurred at times in TE. The ode15s solver was used to handle any form of stiffness that may be encountered.

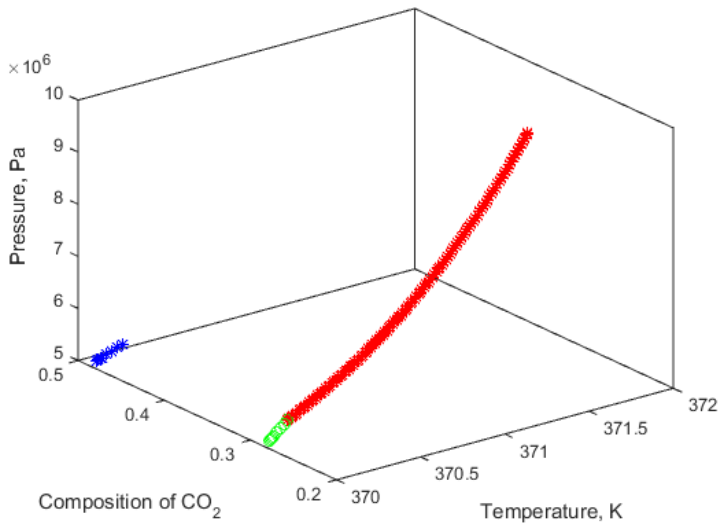

Figure 2: Profiles for identifying phase change as temperature and pressure changes: The red curve is triggered using the function 'event' when most of the vapor has become liquid following condensation.

In this program, an arbitrary position in the wellbore was chosen at a pressure of 5.165MPa and convex hull was used to get the initial values. The use of convex hull algorithm for calculating vapor-liquid equilibria is established by Joseph et al [4]. The program has two sections. First, it integrates down the wellbore, where the

pressure increases and the quality of the vapor was monitored. This produces Figure 1. The blue asterisk curve is rich in component 1 (being CO_2) and represents the vapor phase while the green circle curve is lean in component 1 and represents the liquid phase.

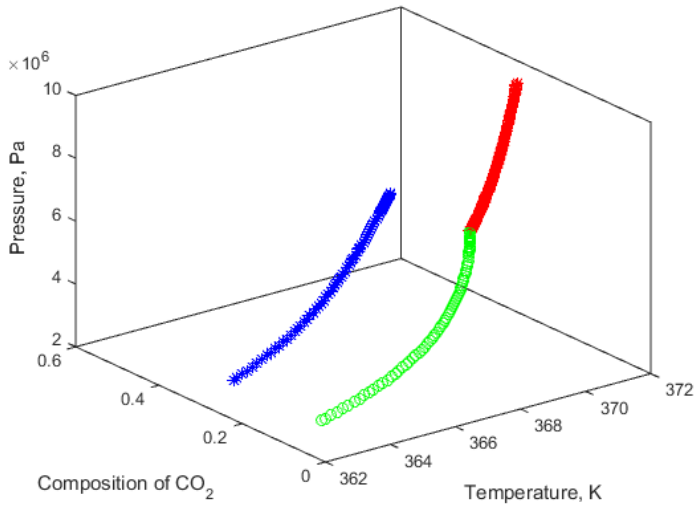

Figure 3: Plots showing regions in the well having liquid rich vapor phase (blue), pure liquid phase (red) and vapor rich liquid phase (green) of CO_2.

III. RESULTS AND DISCUSSIONS

An event is triggered when all the vapor has become liquid, signified by the change of the line color to red on the P − x − T (pressure, composition and temperature) diagram in Figure 2. At this instance, the program is switched to a single phase liquid (program) and integrates (−z) for a further 1000 meters when that section stops.

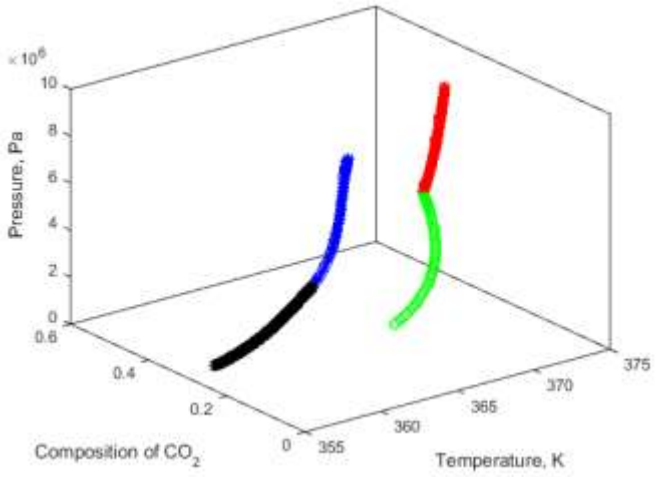

Figure 4: Plots showing regions in the well having pure vapor phase (black), liquid rich vapor phase (blue), pure liquid (red) and vapor rich liquid (green) of CO_2

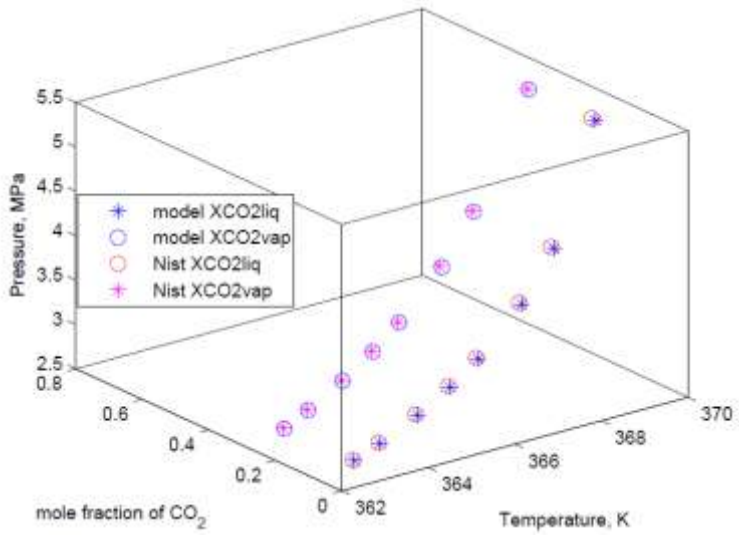

Figure 5: Pressure-temperature-composition plots: comparing model results obtained with the 'event' function with results from NIST RefProp simulator

Once this section of the program has run, the program resets the pressure to 5.165 MPa and proceeds with the initial values and integrates the variables (pressure, temperature and the quality of a phase) up the well. Each event monitors X_{vap} $(1 - X_{vap})$, which will be zero if $X_{vap} = 0$ (i.e no vapor and all liquid) or if $(1 - X_{vap}) = 0$ (i.e all vapor and no liquid). This is shown in Figure 3.

Continuing the integration up the wellbore, where there are no more liquids, the program is switched to a single phase algorithm and plots the output in black (single phase gas). Once this section is completed, the ODE solver is set to run from the bottom of the wellbore at zero depth to the top as shown in Figure 4.

Figure 4 shows the results of the final section of the program showing the fluid compositions at different conditions. With this model, the composition at a given depth can be determined for a given temperature and pressure. Hence, the amount of liquid in the gas stream that can trigger liquid condensation can be determined to monitor and predict when liquid loading occurs at a given depth where the temperature and pressure is known.

IV. CONCLUSION

This work presents a new procedure for monitoring liquid accumulation in gas wells. In this procedure, an event location property was integrated with an ODE solver that models mist flow in gas wells. The model is developed in such a way that at different arbitrary positions in the wellbore, the ODE solver returns appropriate event information and tracks different events as they occur during flow from wellbore to wellhead. Typical information obtained include: temperature, pressure and composition at different depths. With appropriate color coding, the composition is monitored when phase changes occur to determine the extent of liquid dropout in the wellbore. The model results were validated with data obtained from commercial software, NIST RefProp, and the results show good agreement. This procedure is believed to provide substantial benefits in investigating the phenomena of liquid loading in gas wells.

Nomenclature

Symbol	Units	Description
a	$m^6Pa\ mol^{-2}$	Peng-Robinson EOS attractive parameter formixture eq9
A	-	Peng-Robinson EOS parameter eq7
A	Joules	Helmholtz Energy
B	-	Peng-Robinson EOS parameter eq 8
b	m^3mol^{-1}	Peng-Robinson co-volume parameter for the i^{th}component eq3
bm	m^3mol^{-1}	Peng-Robinson co-volume parameter for mixture eq11
f	Pa	fugacity
G	Joules	Gibbs Energy
H	Joules mol^{-1}	enthalpy
M	kg	mass
m	kg	molecular mass
n	-	number of moles
P	Pa	pressure

R	$m^3PaK^{-1}mol^{-1}$	Gas Constant
T	K	temperature
V	m^3mol^{-1}	molar volume
x	-	mole fraction
Z	-	gas deviation factor
Greek symbols		
ω	-	acentric factor
μ	Joules mol^{-1}	chemical potential
Superscripts		
v		vapor phase
l		liquid phase
∗		reference state
Subscripts		
i,j,k		component index
m		mixture
c		critical property

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