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Research Article

A NEW TIME-DEPENDENT MODEL FOR CONTROLLING THE GAS INJECTION PRESSURE IN CONTINUOUS GAS LIFT

Mohammad Reza MAHDIANI[1], Ehsan KHAMEHCHI*[2], Amir Abolfazl SURATGAR[3]

[1]*Department of Petroleum Engineering, Amirkabir University of Technology (Tehran Polytechnic), Hafez Avenue, Tehran, IRAN;* ORCID: 0000-0001-9252-8475
[2]*Department of Petroleum Engineering, Amirkabir University of Technology (Tehran Polytechnic), Hafez Avenue, Tehran, IRAN;* ORCID: 0000-0002-3907-6104
[3]*Department of Electrical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Hafez Avenue, Tehran, IRAN*

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ABSTRACT

There are a number of models for gas lift in the literature, but most of them suffer from large scale simplifications and, hence, unacceptable errors. Those simplifications include ignoring the temperature profile, assuming ideal gas, and neglecting the time- delay between applications of the gas injection pressure on the surface and sensing its effect at point of injection. In this study, all mentioned deficiencies are overcome and a new model is developed for predicting the pressure profile in the annulus and at the injection point. Then using sensitivity analysis, the applicability and accuracy of this model are discussed and compared with earlier models. Results show that the new model yields accurate results and hence serves as an excellent tool for control problems. In addition as by accurate estimation of pressure at the injection point, flow instability can be predicted and prevented, this model can be of great help to prohibit the problem of flow instability.
Keywords: Gas lift, real gas, lag time, PDE model, real-time, mathematical model.

1. INTRODUCTION

Gas lift is one of the most common methods for increasing oil production. Natural gas (or in some cases CO_2 [1]) is injected from the annulus, at the injection point, it enters the tubing, dissolves in tubing fluid and hence decreases the head pressure and helps the oil to be delivered to the surface at the greater production rates[2]–[7]. The injection pressure which is applied to the gas depends on the type of the gas [8]. There are two distinct methods for controlling the process: first using sensors and intelligent systems and second the modeling. Spontaneous control of the gas lift allows the production to stay on its optimum point during the gas injection process [9]–[15]. Modeling the gas lift, on the other hand, is a challenging problem of the gas lift operation. The modeling of gas lift consists of three integrated parts: modeling of the gas flow in the annulus, the multiphase (gas and oil) flow in tubing and the reservoir flow. There are a large

* Corresponding Author: e-mail: khamehchi@aut.ac.ir, tel: +982164545154

number of research works on m odeling the reservoir inflow [16]–[18], and the multiphase flow in wells [19]–[21]. In addition, some considering some marginal incidents such as asphaltene perception [22] and flow through valves and constrictions [23], [24]. However, there is no comprehensive model on the gas flow modeling in the annulus. Even in studies such as gas lift optimization [25]–[28] the employed lift gas models are of decades old, and overly simplistic. Therefore, even in control studies of gas lifts [29], [30], time lag between applying surface injection pressure and sensing it at the injection point is ignored.

In 1975, Galss [31] presented a simple model for gas lift. In which the gas rate is computed by employing the gas formation volume factor. Later in 1984, Coltharp [32] studied the intelligent systems in gas lifts which were limited to surface facilities without a mathematical model employment. In 1999, Denney [33] spoke about the downhole sensors which were very good and accurate but not applicable in many cases due to economic reasons. In 2004, Ayatollahi [34] presented a model for gas lift, which only focused on two-phase flow in tubing and he did not consider any special cases about the gas flow in the annulus; neither the compressibility factor changes in tubing nor the time involvement. In the same year, Bloemen [35] considered the time factor in modeling but just in the two-phase flow of tubing, not in the gas flow. In 2006, Camponogara [36] studied the gas allocation optimization by dynamic programming and used GOP modeling. Again in 2007, Ray [37] studied the gas lift in an optimization problem He used a nonlinear algorithm for modeling and genetic algorithm for optimization. In 2009, Jahanshahi [38] involved the time for gas lift modeling but just in two phase flow in tubing not in gas flow in the annulus, in fact, his work was a repetition of the Bloemen [35] work, but in another field. In 2010, Camponogara [39] studied the gas lift in an automation process but he preferred to used sensors instead of mathematical modeling. As mentioned earlier, sensors may act accurately but using them is presently expensive and not applicable in many cases. In 2013, Guerrero [40] studied gas lift modeling including the multiphase flow, reservoir performance and the stability of the flow but he did not change the gas lift modeling. Afterward, in 2015 Jung [41] and [42] studied the gas lift optimization but they did not represent anything novel compared to the previous studies in gas flow modeling. In 2016, Shao [43], [44] presented two analytic models for gas lifts. However, in both of them he assumed ideal gas behavior and ignored the time lag between applying pressure and observing its effect on the injection point. Also, in the same year, Rocha-Valadez [45] presented a model but again he ignored the temperature profile in the annulus and time lag and considered an average compressibility factor. In addition, some other researchers [46] in this year used some software such as PROSPER. It should be mentioned that this kind of software also uses the models that other researcher have developed and had a lot of simplification which decreases accuracy.

In 2017 Khamehchi et al [12] discussed about different modeling of fluid flow, and their strength and weakness of them in a gas lifted well. Also in this year Pedersen [47], reviewed the different ways of modeling the fluid flow, he concentrated on slug flow regime. In 2018, Farahani et al. developed a gas lift model for the deviated wells, they involved some parameters of deviated well to make their model accurate. In 2019 Mahdiani et al [48] in a gas lift control problem, modified the simplified model by considering the temperature profile. Also in this year Yudin [49] tried to develop a model for controlling the gas lifted wells, but he didn’t focus in increasing the accuracy of the model of fluid flow. In summary, many of the previous studies suffer from large simplifications, and none of them consider the time delay of the flow, that is when the injection pressure changes, its effect will take some time to be sensed in the injection point.

Nowadays creating a new model for well for finding the best plan of injection and production is very important. Especially in cases such as control problems which are based on the previous steps. In these problems, small errors can accumulate and cause a huge error and unrealistic results. If the gas be assumed as ideal gas or the temperature profile be ignored or the delay between the gas injection and its effect at injection point does not be considered, an error in injection and production estimation arises, next step of optimum injection and production uses the data of the previous step and the error of this step is added to the error of next step and this continues. Finally the total estimation of production and revenue has a big error, in addition, this error can lead the system to unstable flow in which cause damages to downhole and surface facilities.

In this work, we present an accurate model of pressure profile in the tubing. The results of the novel model have been compared with those of the previous models and a sensitivity analysis showed that the flow conditions which aggravates differences between our model and previous models. Performing a mass balance, yielded a novel equation for estimating the time delay between applying an injection pressure and measuring its effect on the injection point. Such an equation is necessary for modeling the gas lift in a control problem.

2. METHODOLOGY

First the model for the injection gas needs to be developed all models assume that initially, the lift gas is injected through the annulus and at the injection point and it enters the tubing. For comparison purposes, we first present the simple model developed by earlier researchers assuming a constant compressibility factor all over the annulus. In addition, the simple model accounts for no acceleration and friction and assumes a constant temperature all over the annulus length. Based on the above assumption equations of the gas properties and annulus flow pressure equation is given by Eq.1:

Please remove all equations 1 through 6 and provide a reference where these developments can be found.

$$P = P_0 e^{\frac{Mgh}{z_{av}RT_{av}}} \tag{1}$$

Where, P_0 is the reference pressure.

In this study, a temperature profile has been assumed in the well and gas is not ideal any longer. However, like previous works friction and acceleration are ignored once more.

2.1.1. Novel modeling of the gas flow in annulus

First, the temperature profile in the well will be developed. We assume that there exist two distinct and constant temperature profiles above and below the injection points. Thus, the temperature at any depth is given by:

$$T = T_{surface} + \alpha_1 * \ H\left(D_{inj} - h\right) * h + \ \alpha_2 * H\left(h - D_{inj}\right) * h \tag{2}$$

In which:

α_1	Temperature gradient above injection point
α_2	Temperature gradient below the injection point
h_0	Surface
h	Depth from surface
H	Heaviside step function
D_{inj}	Injection depth
$T_{surface}$	Surface Temperature

In the above equation, H stands for the Heaviside step function. H(x) is zero for all negative “x” and it is unit for all positive “x”. For x = 0 it is equal to “1/2”.

For Heaviside equation there is:

$$H(-x) = 1 - H(x) \tag{3}$$

Thus, from (2) and (3) it concluded:

$$T = T_{surface} + \left(1 - H\left(h - D_{inj}\right)\right) * \alpha_1 * h + \alpha_2 * H\left(h - D_{inj}\right) * h \tag{4}$$

$$T = T_{surface} + \alpha_1 * h - H\left(h - D_{inj}\right) * \alpha_1 * h + \alpha_2 * H\left(h - D_{inj}\right) * h \tag{5}$$

$$T = T_{surface} + (\alpha_2 - \alpha_1) * h * H\left(h - D_{inj}\right) \tag{6}$$

For calculating the gas compressibility factor, the Beggs and Brill correlation will be employed given by Eq.:

$$z = 1.39\left(\frac{T}{T_{pc}} - 0.92\right)^{0.5} - 0.36\frac{T}{T_{pc}} - 0.1 + \frac{\left(1 - 1.39\left(\frac{T}{T_{pc}} - 0.92\right)^{0.5} - 0.36\frac{T}{T_{pc}} - 0.1\right)}{e^{\left(0.62 - 0.23\frac{T}{T_{pc}}\right)*\left(\frac{P}{P_{pc}}\right) + \left(\frac{0.066}{\frac{T}{T_{pc}} - 0.86} - 0.37\right)\left(\frac{P}{P_{pc}}\right)^2 + \frac{0.32\left(\frac{P}{P_{pc}}\right)^6}{10^{9*\left(\frac{T}{T_{pc}} - 1\right)}}}} + \left(0.132 - 0.32\log\left(\frac{T}{T_{pc}}\right)\right)\left(\frac{P}{P_{pc}}\right)^{10^{\left(0.3106 - 0.49\left(\frac{T}{T_{pc}}\right) + 0.1824\left(\frac{T}{T_{pc}}\right)^2\right)}} \tag{7}$$

In equation (7), z is explicitly a function of pressure and temperature and supposing a fixed composition of injection gas during the life of the gas lift, P_{pc} and T_{pc} will be constant.

The second step in this section is the development of the pressure model for the flow of lift gas in the annulus. In general, the pressure gradient is composed of three components: head pressure (because of the fluid's weight), friction and acceleration.

Gas is injected from the surface, thus for downward flow, the pressure gradient is positive. Consider the hydrostatic pressure equation in a fluid column:

$$P = \rho g h \tag{8}$$

Differentiating Eq. (8) with respect to height:

$$\frac{dP}{dh} = g * \left(\frac{\partial \rho}{\partial h} h + \rho\right) \tag{9}$$

Using real gas law to express density in terms of pressure, temperature and gas compressibility factor we can arrive at Eq (10).

$$\rho = \frac{PM}{zRT} \tag{10}$$

M is constant. R is the universal gas constant, thus:

$$\rho = \frac{M}{R}\left(\frac{P}{zT}\right) \tag{11}$$

$$\frac{d\rho}{dh} = \frac{M}{R}\left(\frac{P}{z}\frac{\partial}{\partial h}\left(\frac{1}{T}\right) + \frac{P}{T}\frac{\partial}{\partial h}\left(\frac{1}{z}\right) + \frac{1}{zT}\frac{\partial P}{\partial h}\right) \tag{12}$$

$$\frac{dP}{dh} = g * \left(\frac{M}{R}\left(\frac{P}{z}\frac{\partial}{\partial h}\left(\frac{1}{T}\right) + \frac{P}{T}\frac{\partial}{\partial h}\left(\frac{1}{z}\right) + \frac{1}{zT}\frac{\partial P}{\partial h}\right) * h + \rho\right) \tag{13}$$

In other words:

$$\frac{dP}{dh}=\frac{M}{R}*g*h*\frac{P}{z}\frac{\partial}{\partial h}\left(\frac{1}{T}\right)+\frac{M}{R}*g*h*\frac{P}{T}\frac{\partial}{\partial h}\left(\frac{1}{z}\right)+\frac{M}{R}*g**\frac{1}{zT}\frac{\partial P}{\partial h}+\rho*g \tag{14}$$

Using Eq.8 we can write the following expression appearing in Eq (14):

$$\frac{\partial}{\partial h}\left(\frac{1}{T}\right)=\frac{\partial}{\partial h}\left(\frac{1}{\left(T_{surface}+\alpha_1\left(H\left(D_{inj}-h\right)\right)h+\alpha_2\left(H\left(h-D_{inj}\right)\right)h\right)}\right) \tag{15}$$

Carrying out the differentiation with respect to h in Eq. (15) one can obtain:

$$\frac{\partial}{\partial h}\left(\frac{1}{T}\right)=\frac{\alpha_1*(-1)*\delta\left(D_{inj}-h\right)*h+\alpha_1*H\left(D_{inj}-h\right)+\alpha_2*\delta\left(h-D_{inj}\right)*h+\alpha_2*H\left(h-D_{inj}\right)}{\left(T_{surface}+\alpha_1\left(H\left(D_{inj}-h\right)\right)h+\alpha_2\left(H\left(h-D_{inj}\right)\right)h\right)^2} \tag{16}$$

Where $\delta(x)$ is the Dirac Delta Function and it has the following property:

$$\delta(-x)=\delta(x) \tag{17}$$

Using Eq. (9), we can write:

$$\frac{d}{dh}\left(\frac{1}{z}\right)=\frac{d}{dh}\left(A+\frac{1-A}{e^B}+C*\left(\frac{P}{P_{pc}}\right)^D\right) \tag{18}$$

Carrying out the differentiation with respect to z in Eq. (18), we obtain:

$$\frac{d}{dh}\left(\frac{1}{z}\right)=\frac{dA}{dh}+\frac{-\frac{dA}{dh}e^B+\frac{dB}{dh}e^B(1-A)}{e^{2B}}+\frac{dC}{dh}\left(\frac{P}{P_{pc}}\right)^D+C*\frac{dD}{dh}\left(\frac{P}{P_{pc}}\right)^D \tag{19}$$

We can write the following expressions:

$$\frac{dT}{dh}=-\alpha_1*\delta\left(D_{inj}-h\right)+\alpha_2(\delta\left(h-D_{inj}\right) \tag{20}$$

$$\frac{dA}{dT}=\frac{1.39}{T_{pc}}*\frac{1}{2\sqrt{\frac{T}{T_{pc}}-0.92}}-\frac{0.36}{T_{pc}} \tag{21}$$

$$\frac{dB}{dT}=-\frac{0.23}{T_{pc}}\frac{P}{P_{pc}}+\frac{\frac{0.066}{T_{pc}}}{\left(\frac{T}{T_{pc}}-0.86\right)^2}\left(\frac{P}{P_{pc}}\right)^2+\frac{0.32\left(\frac{P}{P_{pc}}\right)^6*\frac{9}{T_{pc}}*10^{9*\left(\frac{T}{T_{pc}}-1\right)}}{10^{18*\left(\frac{T}{T_{pc}}-1\right)}} \tag{22}$$

$$\frac{dC}{dT} = -0.32 * \frac{\frac{1}{T_{pc}} \ln\left(\frac{T}{T_{pc}}\right)}{\ln 10} \tag{23}$$

$$\frac{dD}{dT} = \frac{dF}{dT} 10^{F} = -\frac{0.49}{T_P} + \frac{2*0.1824}{T_{pc}}\left(\frac{T}{T_{pc}}\right) * 10^{0.3106-0.49\left(\frac{T}{T_{pc}}\right)+0.1824\left(\frac{T}{T_{pc}}\right)^2} \tag{24}$$

Substituting equations (20) to (24) in equations Eq. (19) to yields:

$$\frac{dA}{dh} = \left(\frac{1.39}{T_{pc}} * \frac{1}{2\sqrt{\frac{T}{T_{pc}} - 0.92}} - \frac{0.36}{T_{pc}} \right) * T \tag{25}$$

$$\frac{dB}{dh} = \left(-\frac{0.23}{T_{pc}} \frac{P}{P_{pc}} + \frac{\frac{0.066}{T_{pc}}}{\left(\frac{T}{T_{pc}} - 0.86\right)^2} \left(\frac{P}{P_{pc}}\right)^2 + \frac{0.32\left(\frac{P}{P_{pc}}\right)^6 * \frac{9}{T_{pc}} * 10^{9*\left(\frac{T}{T_{pc}}-1\right)}}{10^{18*\left(\frac{T}{T_{pc}}-1\right)}} \right) * T \tag{26}$$

$$\frac{dC}{dh} = \left(-0.32 * \frac{\frac{1}{T_{pc}} \ln\left(\frac{T}{T_{pc}}\right)}{\ln 10} \right) * T \tag{27}$$

$$\frac{dD}{dh} = \left(-\frac{0.49}{T_P} + \frac{2*0.1824}{T_{pc}}\left(\frac{T}{T_{pc}}\right) * 10^{0.3106-0.49\left(\frac{T}{T_{pc}}\right)+0.1824\left(\frac{T}{T_{pc}}\right)^2} \right) * T \tag{28}$$

Substituting the above equations in Eq. (14), the final model equation is obtained. Note however that the pressure in Eq. (14) is not an explicit function of depth, and therefore it has to be solved numerically.

While the pressure at the injection point can be now be estimated accurately. The time delay has not been considered yet. When a change takes place in the surface injection pressure changes it takes some time to observe its effect on the downhole injection point. Now, we will attempt to include the time lag in the model. .

The mass balance equation in a control volume in the annulus results in:

$$\frac{(\rho v A)_h - (\rho v A)_{h+\Delta h}}{dh} = \frac{(\rho_{t+\Delta t} - \rho_t)A}{dt} \tag{29}$$

By simplifying:

$$\frac{(\rho v)_h - (\rho v)_{h+\Delta h}}{dh} = \frac{(\rho_{t+\Delta t} - \rho_t)}{dt} \tag{30}$$

$$-\frac{d(\rho v)}{dh} = \frac{d\rho}{dt} \tag{31}$$

Using real gas law, we can write the velocity $v = \frac{dh}{dt}$ as:

$$v = \frac{A}{A}\frac{dh}{dt} = \frac{1}{A}\frac{dV}{dt} = \frac{1}{A}\frac{d}{dt}\left(\frac{zRT}{P}\right) \tag{32}$$

$$v = \frac{RT}{A}\frac{d}{dt}\left(\frac{z}{P}\right) \tag{33}$$

Earth rock layers can be assumed as the heat source and thus after a while, the gas would reach equilibrium temperature with surrounding rock layers.

$$-\frac{d}{dh}\left(\frac{PM}{zRT} * \frac{RT}{A}\frac{d}{dt}\left(\frac{z}{P}\right)\right) = \frac{d\rho}{dt} \tag{34}$$

$$-\frac{M}{A}\frac{d}{dh}\left(\frac{P}{z} * \frac{d}{dt}\left(\frac{z}{P}\right)\right) = \frac{d\rho}{dt} \tag{35}$$

Again substituting the real gas law in Eq (35):

(please remove Eq. (36)) (36)

$$-\frac{1}{A}\frac{d}{dh}\left(\frac{P}{z} * \frac{d}{dt}\left(\frac{z}{P}\right)\right) = \frac{1}{RT}\frac{d}{dt}\left(\frac{P}{z}\right) \tag{37}$$

Carrying out the differentiation with respect to (p/z) in Eq. (37), we obtain: (38)

we obtain: $-\frac{1}{A}\frac{d}{dh}\left(\frac{P}{z} * -\frac{P^2}{z^2}\frac{d}{dt}\left(\frac{P}{z}\right)\right) = \frac{1}{RT}\frac{d}{dt}\left(\frac{P}{z}\right)$

Rearranging Eq. (38) yields:

$$\frac{d}{dh}\left(\frac{z}{P}\frac{d}{dt}\left(\frac{P}{z}\right)\right) = \frac{A}{RT}\frac{d}{dt}\left(\frac{P}{z}\right) \tag{39}$$

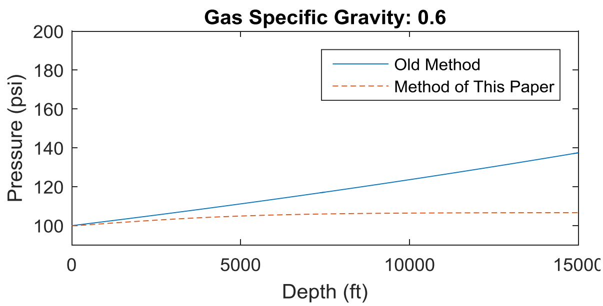
olving Eq. (39) with the boundary condition given by Eq. (40), one can predict the pressure at any point at any time.

$$P\left(0,t\right)=P_{injecion}\left(t\right) \tag{40}$$

As Eq. (39) is a nonlinear function of pressure, temperature, location and time it has to be solved numerically.

3. RESULT AND DISCUSSION

Several case studies are conducted for the pressure estimation at the injection point, using the simple model given by Eq.7 and the novel more comprehensive models presented in this work.



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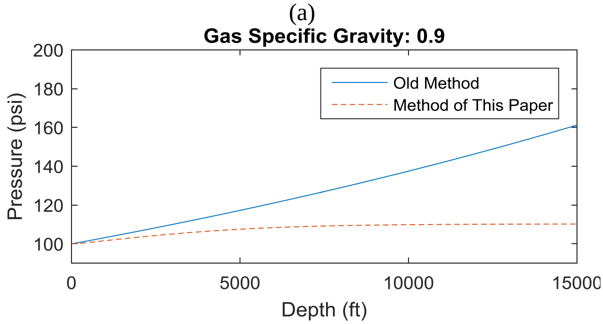

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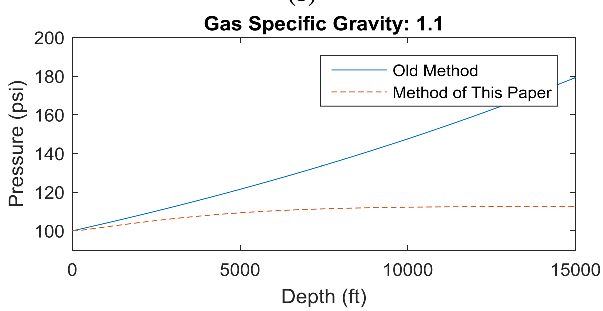


(c)

Figure 1. The difference between pressure estimation at injection point by simplified method and the method of this paper for different injection gas, a) gas specific gravity = 0.6, b) gas specific gravity = 0.9, c) gas specific gravity = 1.1

The three parameters including gas specific gravity, injection pressure and injection temperature are selected and a sensitivity analysis carried out. A basis with gas specific gravity of 0.9, injection pressure = 8000 psia and injection temperature of 530 R is selected, which can be a typical well, and based on that the sensitivity analysis is ran. In Figure 1 different gas with different specific gravities are discussed.

Figure 1 shows that the temperature profile for all cases of different specific gravity of gas are similar but as the specific gravity increases, the difference between the previous simplified methods (by assuming average temperature in well and ideal gas) and the method of this paper increases. It changes between 15 and 70 psia and in all cases the simplified method estimation is higher than the method of this paper. This difference is not important in most cases, but in control problems it can cause a delay in preventing some disasters such as flow instability, as mentioned earlier, the flow instability is the phenomenon that sometimes happens in gas lifted wells and can cause high vibration which damages downhole and surface facilities. This phenomenon prediction is based on the pressure of the injection point, if pressure at injection point cannot be estimated accurately, the flow instability cannot be predicted and prevented. Now back to the base case, in continuing the cases, the effect of applying different injection pressures will be discussed. Figure 2 shows that as the injection pressure increases, the amount of difference in pressure estimation by the two methods (methods of this paper and simplified method) increases, although it is small in comparison to the injection pressure, but in control problems which need a high accuracy even this amount of difference can be crucial, as explained earlier flow instability is highly depends on the pressure at injection point this small change of pressure estimation may cause that the inability for predicting the instability happening before it occurs. As mentioned earlier, another parameter for observing its effect on the model accuracy is the injection pressure which is shown in Figure 3. This figure shows the effect of injection temperature on the pressure profile. It is clear that the temperature cannot change in a wide range. This figure shows that as the temperature increases, the difference between the simplified method and the method of this paper decreases. At higher temperature, the sensitivity of the difference to temperature decreases.

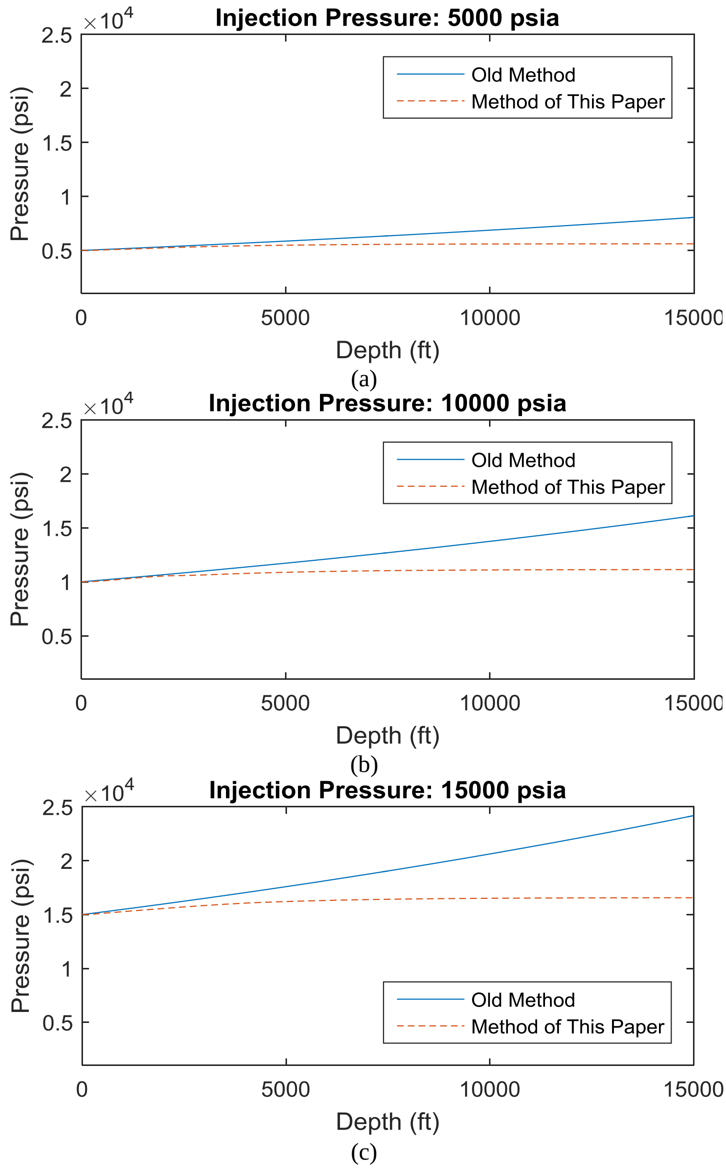
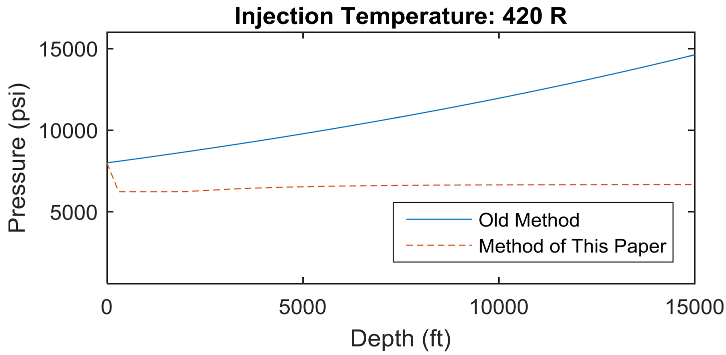
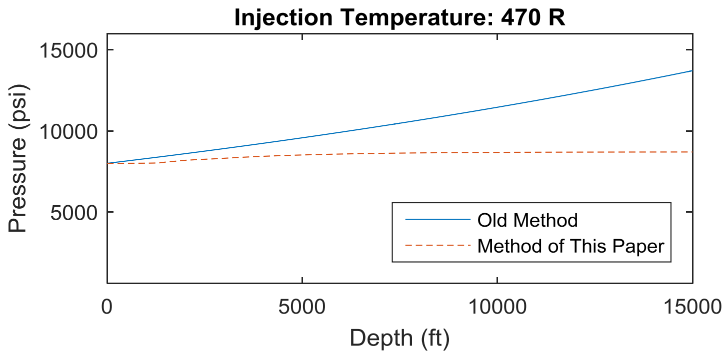


Figure 2. The difference between pressure estimation at the injection point by the simplified method and the method of this paper for different injection pressures. a) Injection pressure = 5000 psia b) Injection pressure = 10000 psia c) Injection pressure = 15000 psia



(a)



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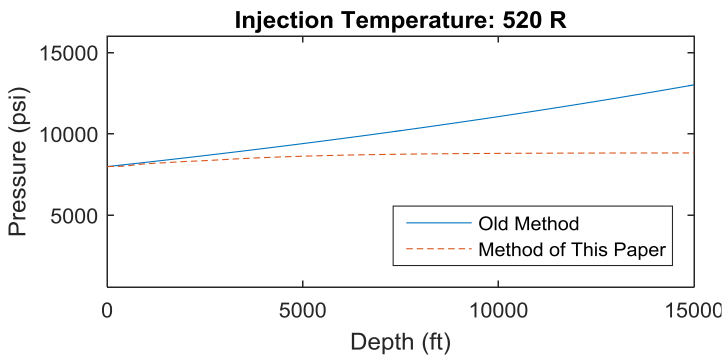

(c)

Figure 3. The difference between pressure estimation at the injection point by the simplified method and the method of this paper for different injection pressure a) Injection Temperature = 420 R, b) Injection Temperature = 470 R, c) Injection Temperature = 520 R

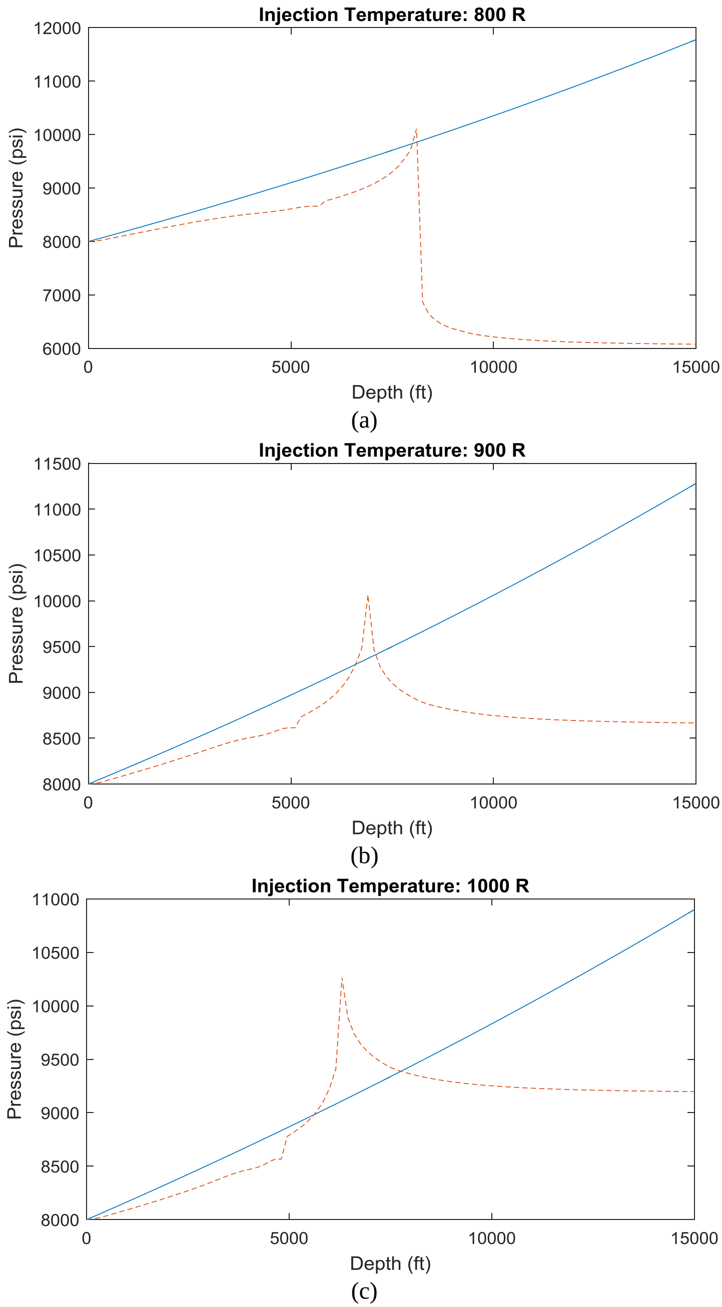

Figure 4. The pressure profile of injected gas a) Injection Temperature = 800 R, b) Injection Temperature = 900 R, c) Injection Temperature = 1000 R

Figure 4 shows some strange plots at some strange temperatures. Thus, must be very vigilant about the temperature of lift gas, because it would not obey the behavior which is on our mind. In this situation, using the old simplified model can result in huge errors. It should be mentioned that the temperature of the gas can change based on the season or based on the source which is extracted and because of that knowing the effect of temperature is important.

4. CONCLUSION

Accurate modelling of injected gas flow in the annulus yields results in temperature and pressure estimates at the downhole inlet point which could be important for detecting and preventing flow instabilities in gas lift control.

Nomenclature

A	annulus area (ft^2)
D	depth (ft)
g	Earth gravity acceleration (ft/s^2)
h	depth (ft)
h	Depth from surface (ft)
H	Heaviside step function ()
M	molecular weight (lb/lbmol)
m	mass flow rate (lb/s)
p	pressure (psi)
P	pressure (psia)
R	universal gas constant ($ft.lb_f$/lbmol.F)
T	Temperature (R)
t	time (s)
V	volume (ft^3/s)
v	velocity (ft/s)
z	gas Compressibility factor
α	Temperature gradient above injection point (F/ft)
δ	Dirac function
ρ	density (lb/ft^3)

Subscript

0	reference
av	average
i	injection point
in	input
inj	injection depth
out	output
pc	pseudo critical
surface	surface
t	tubing

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