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Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
ISSN (online): 2289-7879 | Vol. 6, No. 1. Pages 19-33, 2015

Modelling Unsteady Flow of Gas and Heat Transfer in Producing Wells

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Abstract – *During well operation transient flows develop as soon as production begins and further withdrawal continues to cause disturbances which resulted into flow propagation throughout the period with time. The whole scenario experienced significance changes in energy exchange mechanism of the wellbore and formation which lead to unsteady production. Previous predictions are mostly based on steady state condition but the actual situation of gas well is unsteady due to the operation and geometry of the well. This paper presented a model based on unsteady state flow of gas in the producing well taking into consideration the general physical situation of the well(the formation, the wellbore and surface materials).Systems of partial differential equations which account for the unsteady flow with their necessary boundary conditions are presented and solved by finite scheme method.*

Keywords: Modelling, Unsteady flow, FSM, Heat Transfer, Gas Well

1.0 INTRODUCTION

Wells that have the capacity to produce gas without artificial lift method are described as producing wells while those with low production capacity and which attract the application of artificial lift technique are injection wells. Flow in such wells is important but always difficult to predict due to the transient nature of fluid temperature and the formation temperature. Since gas is becoming an extremely important source of energy it has become very important to predict the role of the wellbore and surrounding formation in gas lift operation. Predicting well performance remains a major problem because experimentally it has been proved that it is not easy to dictate temperature and pressure distribution due to well geometry and its surrounding formation. In the past focus was mainly on studying the wellbore and its formation under no transient conditions but this may lead to partial prediction of its performance. However industries are looking for more reliable ways of predicting gas well performance to help in detecting the problems of gas wells at all times. Production of gas from a porous media is essentially a transient process, because a transient gradient develops as soon as production begins and further withdrawals continue to cause disturbances which propagate throughout the reservoir [1]. The flow fluctuation of gas in a gas well can adequately be described by one dimensional model [2]. This is because one dimensional flow gives a satisfactory solution to many problems where the cross-sectional area and shape changes study along the flow path [3].

To predict the unsteady performance of a producing gas well must have full knowledge of the well which is comprised of the surrounding formation, the wellbore, the surface equipment

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
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and geometrical characteristics. Some authors presented that during production unsteadiness develops as soon as gas begins to flow through the well due to its geometry and materials. When gas flows in a well its density, velocity and pressure gradient all vary with pressure and time. Kirkpatrick [4] was the first researcher who started work on the prediction of temperature profile in a producing gas well. His work was to install injection valves and thermometer to measure both the injected fluid temperature and the wellbore temperature. He presented a simple flowing temperature and pressure gradient that can be used to predict gas lift valves at the injection depth. The valve mechanism presented take into account the problems of back pressure and all other sorts of flow propagation.

Ramey [5] followed up Kirkpatrick's work and developed an approximate method for predicting temperature distribution in gas well at steady state condition. His work has been used by many authors in production and injection wells. Ramey was considered as the father of heat transmission, his heat transmission mechanism focused mostly on problems that involves injection of hot fluid in the well bore. The solution assumed that heat transfer in well bore is based on steady state while heat transfer to the earth will be unsteady radial construction. Ramey developed his model on the assumption that physical and thermal properties does not vary with time. Ramey and Hasan [6], considered the effect of pressure dependent, viscosity and gas law deviation. In their work they applied the principles of Mass conservation for isothermal fluid flow through porous media.

Sagar et al [7] considered the unsteady behavior of the producing well but only discussed the fractured well at constant rate not predicting bottom hole formation pressure and temperature with its ability to deliver. Although temperature, pressure, velocity and density are independent variables their prediction should not be done individually. In previous research, temperature and pressure is the only unknown at each node. Therefore predicting the unsteady condition of the producing gas well can greatly improve the design of production facilities in flowing gas well engineering. Scatter [8] discovered that the main factor affecting heat loss in Ramey's work are injection time, injection rate, injection depth, temperature and pressure in the casing of supper heated steam or in case of saturated steam. With this they improve Ramey's method by considering phase changes that occur within the steam injection projects but again assumed the flow to be steady.

Coulter and Bardon [9] developed the most widely used method for calculating the bottom hole pressure in gas wells neglecting the kinetic energy term based on steady state condition. They applied trapezoidal rule to solve their model, however many authors apply this method and consider constant compressibility factor and steady state solutions. Xu et al [10] simultaneously predict the pressure and temperature distribution using fourth order Runge-Kutta method on the basis of steady state flow. However literature has shown that assuming density and compressibility to be constant would produce unsatisfactory result because gas is highly compressible and neglecting its compressibility in determining the flow during production will result in inaccurate production result. Of the several works on wellbore fluid flow in place, mostly assumed steady state solution and some detail of the geometrical features of the well were sometimes assumed or neglected.

Young et al. [11] solve the general energy equation and change in kinetic energy with numerical integration and used it to evaluate the assumption over wide range of conditions. In his work he discovered that assuming temperature and compressibility to be constant generate errors at their average values. He then evaluated some major approximations by applying most widely used method for calculating steady state single gas phase well. Agarwal [12]

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presented a fundamental study of the importance of well bore storage with a skin effect to short time transient flow. In their studies they stated that steady state skin effect is invalid at every short time (short period) in addition the time required to reach the usual straight prediction is normally not affected significantly by a final skin effect. The problem with their studies is that they have not stated what will happen over the long term and discussed storage in the well but low. Babatundo [13] developed a method that will calculate the bottom hole pressure in single phase gas wells from wellhead measurement. He reported that the assumption of constant temperature and compressibility are unsatisfactory for deep high pressure wells and then developed a method that will eliminate the need for unnecessary assumptions by reducing Cullender and Smith equation to polynomial and solving it by Newton Rapson method. According to Osadacz [14], flow of gas either in pipes or well are unsteady due to well geometry and changes of condition with time and that unsteady flow is best described by one dimensional partial differential equations. Zhao and Xu [15] presented an alternative method for estimating the relaxation distance parameter in the well bore. Their work was based on fluid phase theory of gas and mass, momentum and energy conservation with the actual situation of gas well. They consider inclination angle, well structure, tubing string, radial heat transfer of the wellbore, different heat transfer mechanisms in the annular and the physical condition of the stratum based on steady state condition. Hasan and Kabir [16] proposed a heat transfer model to predict transient temperature behavior in formation at all times. Hasan and Kabir [17] presented that fluid temperature prediction as a function of depth and time in the wellbore is important and this can be achieved by considering the physical properties of the wellbore and the pressure gradient. They discussed the total heat transfer mechanism in the wellbore and the surrounding geothermal gradient to the infinite location is a transient due to exchange of heat between the fluid and the surrounding formations. Hasan and Kabir [18] developed an analytical expression based on first principles which can compute time dependence fluid temperature at any point in the wellbore during both drawdown and build up testing. Yongming et al [19] studied Ramey’s work and discovered that well head was removed because it is unreliable and can be influenced by error in measurement procedure. In addition also steel is a good conductor of heat and cause variation of temperature in the surface equipment. On this basis they presented a model based on mass, momentum and energy conservation and iterating flow pressure, temperature, gas velocity and well density were considered to overcome the limitation of the past models. Bin Bin [20] presented a model that investigates the occurrence of density wave instability in gas lift wells. He uses both linear stability analysis and numerical simulation is performed. He presented that casing heading was first found in the unstable natural flowing wells completed without packer which can be determined using analytical method. Candia and Mario [21] considered the mechanistic model for incompressible transient flow of pressure, temperature and velocity of two phase gas-oil in oil well (oil and water) mixture. The work presented by Candia and Mario does not consider the compressibility of gas and its unsteady flow condition during production.

Hameed et al [22] presented a simple programmable model to obtain temperature profiles in both conduits at any time. The model was applied to oil wells in Iran. Wu et al. [23] built a model of coupled differential equations concerning pressure, temperature density and velocity in gas wells according to the conservation of mass, momentum and energy assuming the flow to be at steady state. They present an algorithm-solving model by the fourth-order Runge Kutta method using basic data from 7100m deep in the Dayi Well 7100m China, for case study calculations and a sensitivity analysis is done for the model. Gas pressure, temperature, velocity and density along the depth of the well are plotted with different productions, different geothermal gradients and different thermal conductivities, intuitively reflecting gas flow law and the characteristics of heat transfer formation. Tong et al [24] presented a model of heat diffusion Q from wellbore to formation. Orodu et al [25] presented a predicted model based on analytical approach in order to predict gas flow in gas condensate reservoirs. They observed the effect of drop out on productivity at lower pressure and the condensate unloading pressure which comparable to commercial soft wire. They also they studied well deliverability prediction of gas flow in a gas condensate reservoir near critical wellbore problem in one dimension. Li et al [26] developed a model for determination of wellhead pressure and bottomhole pressre based on the principles of fluid dynamics, the conservation of mass and momentum which were applied in the development of the model. They pointed out in their work that it is very difficult to find an analytical solution for z-factor.

Scatter [27] developed a couple system of partial differential equation for the variation of pressure, temperature, velocity and density at different time and depth in high pressure, high temperature well for two phase. Their solution follows the splitting techniques with Eulerian Generalized Reiman problem (GRP) schemes. Fonzong [28] developed a transient nonisothermal wellbore flow model for gas well testing. Their governing equation is based on depth and time dependent Mass, Momentum and gas state equation. The work indicated that flowing and static pressure from the well head provide a limited range of temperature changes.

The aim of this paper is to present a model for unsteady flow of gas in a producing gas well which will take in account variation of compressibility factor, pressure, density, velocity and thermal conductivities of materials in the wellbore that changes with both space and time without any assumption.

2.0 METHODOLOGY

In predicting steady flow of gas in a producing gas well, traditional methods have been used. Scatter [8] developed the most widely used equations for calculating the bottom hole pressure in gas wells neglecting the kinetic energy term and solved by trapezoidal rule. The method was adapted by many authors such as Daneshyar [2] and Finley [29].The steady state prediction of wellbore pressure, temperature, velocity and density distribution are calculated using fourth order Runge-Kutta method but such method demanded longer computational time and is suitable only for space change and when density is constant. However, when predicting unsteady flow of gas in a producing gas well an accurate and low computational cost method is always sort. The application of finite scheme method recently in pipelines for natural gas transportation has been known as an efficient technique for the analysis of unsteady flows. Despite the efficiency of these techniques flow analysis has not been applied in the gas well. The approach is reviewed in order to achieve an efficient computational scheme for the unsteady flow of gas in a producing gas well. In this work homogenous Euler equations under non isothermal flow are numerically solved using the implicit Steger-Warming flux vector splitting Method (FSM). Figure 1 shows the schematic diagram of producing well

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
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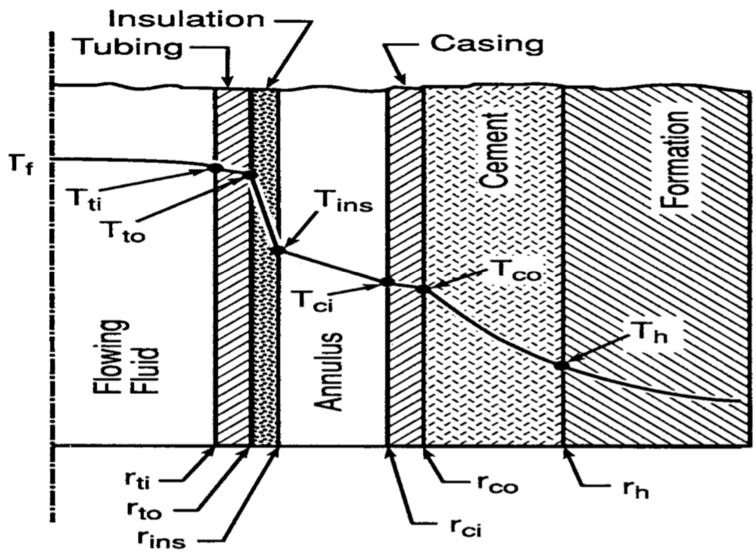

Figure 1: Schematic diagram of Producing and Injection Gas Well

2.1 Governing Equations

The one dimensional unsteady state, compressible fluid, nonisothermal flow and considering gas density and flux change with time and space, the governing equations in Euler type are as follows.

$$\frac{\partial \rho}{\partial t}+\frac{\partial G}{\partial x}=0 \tag{1}$$

$$\frac{\partial G}{\partial t}+\frac{\partial}{\partial x}\left(\frac{G^2}{\rho}\right)+\frac{\partial P}{\partial x}+\rho g \sin\theta+\frac{\lambda G\left|G\right|}{2D\rho}=0 \tag{2}$$

where G is given by ρu , λ is a friction factor, D is the well diameter, g is gravitation and θ is the inclination angle.

$$\rho=\frac{PM}{ZRT} \tag{3}$$

Equations (1) and (2) can be written in conservative form as

$$\frac{\partial W}{\partial t}+\frac{\partial E(W)}{\partial x}-H(W)=0 \tag{4}$$

where

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$$W = \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}, \qquad E(W) = \begin{bmatrix} w_2 \\ \dfrac{w_2^2}{w_1} + a^2 w_1 \end{bmatrix} \qquad H(W) = \begin{bmatrix} 0 \\ \dfrac{\lambda w_2^2}{2Dw_1} \end{bmatrix} \tag{5}$$

In equation (5) a^2 is the nonisothermal speed of sound and is given by, $a^2 = \dfrac{\gamma P}{w_1}$,

w_1 is the gas density, w_2 is the mass flow rate and u is the axial velocity.

2.2 The Finite Scheme Method

The Steger-Warming flux vector Splitting scheme method (FSM) is chosen as the numerical scheme because literature has shown that it does not have the problem of numerical instability. In delta formulation, the finite difference form of the method is

$$\begin{aligned} &-\left(\frac{\Delta t}{\Delta x} A_{j-1}^{+}\right)\Delta Q_{j-1} + \left(I + \frac{\Delta t}{\Delta x}\left(A_j^{+} - A_j^{-}\right) - \Delta t B_j\right)\Delta Q_j + \left(\frac{\Delta t}{\Delta x} A_{j+1}^{+}\right)\Delta Q_{j+1} \\ &= \frac{\Delta t}{\Delta x}\left(E_j^{+} - E_{j-1}^{+} + E_{j+1}^{-} - E_j^{-}\right) + \Delta t H_j \end{aligned} \tag{6}$$

The subscript j indicate the spatial grid point while the superscript indicates the time level and

$$\Delta Q = Q^{n+1} - Q^{n} \tag{7}$$

In equation (6) I is an identity matrix and A and B are Jacobian matrix defined by

$$A = \frac{\partial E}{\partial W}, \qquad B = \frac{\partial H}{\partial W} \tag{8}$$

and A^{+}, A^{-} are positive and negative parts of the Jacobian matrix A which takes care of the flow propagation and defined as follows.

$$A^{+} = \begin{bmatrix} \dfrac{a^2 - u^2}{2a} & \dfrac{u+a}{2a} \\ \dfrac{(u+a)^2(a-u)}{2a} & \dfrac{(u+a)^2}{2a} \end{bmatrix} \qquad A^{-} = \begin{bmatrix} \dfrac{u^2 - a^2}{2a} & \dfrac{a-u}{2a} \\ \dfrac{(u+a)(a-u)^2}{2a} & -\dfrac{(a-u)^2}{2a} \end{bmatrix} \tag{9}$$

In (6) also E^+ and E^- are the positive and negative part of E defined as

$$E^+ = \begin{bmatrix} \dfrac{w_1(u+a)}{2} \\ \dfrac{w_1(u+a)^2}{2} \end{bmatrix} \qquad E^- = \begin{bmatrix} \dfrac{w_1(u-a)}{2} \\ \dfrac{w_1(u-a)^2}{2} \end{bmatrix} \tag{10}$$

Applying equation (6) to each grid point, a block tridiagonal system is formed. The equation is then solved at each time step which resulted in ΔQ . Next Q can be calculated using equation (7).

2.3 Steady State

To predict the unsteady flow characteristics of the entire well the finite scheme method is used. Its boundary condition is the steady state solution. Flow equations consisting the conservation of mass, momentum and energy which constitute the basis for all computations involving fluid in gas well as their application permits the calculation of changes in temperature with distance. For the calculation of pressure at each point we also adopt the Cullender and Smith method because it proves to be more accurate and for the temperature we apply Hasan and Kabir method. Neglecting kinetic energy term, the pressure drop for typical gas well under steady state condition with P in psia$T$ in Ronkine, q in MMscf/D, d in inch and x in ft is given as is

$$\frac{dP}{dx} = \frac{f\rho v^2}{2d} + \rho g \sin\theta \tag{11}$$

For $\rho = \dfrac{PM}{ZRT}$ $\qquad v = \dfrac{q}{A}$ $\qquad q = q_{sc}B_g$ $\qquad B_g = \dfrac{P_{sc}TZ}{T_{sc}P}$

Substituting these values in (11) and separating variables we obtain the Cullender and Smith equations

$$\frac{M}{R}\int_0^x dx = \int_{P_{tf}}^{P_{wf}} \frac{\dfrac{P}{ZT}}{\left(\dfrac{P}{ZT}\right)^2 g\sin\theta + C} \tag{12a}$$

where

$$C = \frac{8\rho_{sc}^2 q_{sc}^2 f}{T_{sc}^2 \pi^2 d^5} \tag{12b}$$

Equation (12a) is consistent to any unit [2], and can be integrated.

$$18.75\gamma_g X = \int_{tf}^{wf} I dp \tag{12c}$$

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ISSN (online): 2289-7879 I Vol. 6, No. 1. Pages 19-33, 2015

Letting

$$I = \frac{\frac{P}{ZT}}{0.001\left(\frac{P}{ZT}\right)^2 \sin\theta + F^2} \tag{13a}$$

$$F^2 = \frac{0.667 f q_{sc}^2}{d^5} \tag{13b}$$

Thus we get

$$P_{mf} = P_{tf} + \frac{0.3415\lambda H}{I_{mf} + I_{tf}} \tag{14a}$$

$$P_{wf} = P_{mf} + \frac{0.3415\gamma H}{I_{wf} + I_{mf}} \tag{14b}$$

2.4 Compressibility Factor Model

Compressibility factor is an important parameter in determining the behavior of flow in a producing well. We apply the Standing and Katz correlation which is most widely used in petroleum industries for calculating Z *factor*.

If $P \leq 35Mpa$

$$Z = 1 + \left(0.31506 - \frac{1.0467}{T_{pr}} - \frac{0.5783}{T_{pr}^3}\right)\rho_{pr} + \left(0.053 - \frac{0.6123}{T_{pr}}\right)\rho_{pr}^2 + 0.6815\frac{\rho_{pr}^2}{T_{pr}^3} \tag{15a}$$

Else

$$Z = \left(90.7x - 242x^2 + 42.4x^3\right) y^{(1.18+2.82x)} - \left(14.7x - 9.76x^2 + 4.58x^3\right) y + \frac{1 + y + y^2 + y^3}{(1-y)^3} \tag{15b}$$

Where

$$F(y) = -0.01625\rho_{pr} \exp\left(-1.2(1-x)^2\right) + Ay^{(2.18+2.82x)} + \frac{y + y^2 + y^3 - y^4}{(1-y)^3} - By^2 \tag{15c}$$

$$A = 90.7x + 242.2x^2 + 42.4x^3 \qquad B = 14.76x - 9.76x^2 + 4.58x^3 \tag{15d}$$

$$\rho_{pr} = \frac{0.27 P_{pr}}{ZT_{pr}} \qquad T_{pr} = \frac{T}{T_{pc}} \qquad P_{pr} = \frac{P}{P_{pc}} \tag{16}$$

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ISSN (online): 2289-7879 I Vol. 6, No. 1. Pages 19-33, 2015

T_{pc} is the critical temperature, P_{pc} is critical pressure T temperature and pressure *P*, of natural gas are all known and $x = \frac{1}{T_{pr}}$.

2.5 Heat Transfer Model

Reservoir fluid is hot when compared with fluids outside. When this fluid enters a wellbore and begins to flow to the wellhead it comes into contact with surrounding formations having cooler temperature, the fluid will begin to experience changes. The exchange of heat between the hot fluid and the environment lead to unsteady heat transfer. For a constant mass flow rate the earth surrounding the well reaches steady state temperature distribution. Prediction of fluid temperature in the wellbore as a function of depth and time is necessary because it helps in determining the fluid properties and in calculating pressure gradient. The temperature model for temperature change between the fluid and geothermal properties of the formation can therefore be given as

$$T_f = T_e + \frac{q}{2\pi\Delta L}\left[\frac{1}{r_{ti}h_f} + \frac{\log\left(\frac{r_{t0}}{r_{ti}}\right)}{k_e} + \frac{1}{r_{ci}h_{an}} + \frac{\log\left(\frac{r_{co}}{r_{ci}}\right)}{k_c} + \frac{\log\left(\frac{r_w}{r_{co}}\right)}{k_{cem}} + \frac{f(t)}{k_e}\right] \quad (17)$$

where h_f is thermal resistance of the earth formation, h_{an} thermal resistance of annulus, k_e thermal conductivity of earth, k_c thermal conductivity of casing, k_{cem} thermal conductivity of cement, *f(t)* dimensionless function time, r_{ti} inner radius of tubing, r_{to} outer radius of tubing, r_{ci} inner radius of casing, r_{co} outer radius of casing, r_w radius of the wellbore, T_f temperature of the formation, T_e initial undisturbed temperature of the earth and ΔL is the change in space

$$q = 2\pi r_{to} U \Delta L \Delta T \quad (18)$$

whereU is overall heat transfer coefficient and ΔT is the change in temperature. Hasan and Kabir proposed a simplified dimensionless function time which is valid at all times defined by

$$f(t) = 1.1281\sqrt{t_D}\left(1 - 0.3\sqrt{t_D}\right) \qquad \text{if} \qquad t_D \le 1.5 \quad (19a)$$

$$f(t) = \left[0.4063 + 0.5\log(t_D)\left(1 + \frac{0.6}{t_D}\right)\right] \qquad \text{if} \qquad t_D > 1.5 \quad (19b)$$

$$\alpha = \frac{k_e}{\rho c} \qquad t_D = \frac{\alpha t}{r_w^2}$$

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If the surrounding temperature varies with depth then

$$T_e = T_{ei} - gL\sin\theta \tag{20}$$

The temperature model is therefore given by

$$T_f = T_{ei} - gL\sin\theta + (T_e - T_{ei})e^{-L/A} + g\sin\theta\left(1 - e^{-L/A}\right) \tag{21}$$

2.6 Initial and Boundary conditions

According to the temperature and pressure of the bottom of the well we can calculate the corresponding gas density and velocity. The initial and boundary condition are given as follows.

2.6.1 Initial Conditions

$$P(x,o) = p_0 \qquad T(x,0) = T_0 \tag{22a}$$

$$\rho(x,0) = 0.000001\times 3454.48\frac{\gamma P_0}{ZT_0} \qquad V(x,0) = \frac{101000\times 300000 T_0}{293\times 86400 AP_0} \tag{22b}$$

$$P(0,t) = p(t) \qquad T(0,t) = T(t) \tag{22c}$$

2.6.2 Boundary Condition

$$\rho(0,t) = 0.000001\times 3454.48\frac{\gamma P(t)}{ZT(t)} \; V(0,t) = \frac{101000\times 300000 T(t)}{293\times 86400 AP(t)} \tag{22d}$$

$$P(L,t) = \beta p(t) \qquad T(L,t) = \beta T(t) \tag{22e}$$

$$\rho(L,t) = 0.000001\times 3454.48\beta\frac{\gamma P(t)}{ZT(t)} \; V(L,t) = \frac{101000\times 300000\beta T(t)}{293\times 86400 AP(t)} \tag{22}$$

where β is a fluid bulk expansion given by $\beta = \frac{1}{T_c}$.

The bottom hole input parameters are given as follows; Length of well is 7100 meters, critical Temperature, T_c is 189k, Critical Pressure, P_c is 4.57Mpa, flowing fluid temperature at the bottom is 396k, flowing fluid pressure at bottom is 70 Mpa, thermal conductivity of cement is 0.52W/mc, thermal conductivity of gas in the annulus is 0.03 W/mc, thermal conductivity of earth is $1.03*10^{-6}M^2/S$ and thermal diffusion of earth is 2.06 W/mc.

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3.0 RESULTS AND DISCUSSION

We compare our new model with [25] who studied a pipe in X well located in Sichuan Basin, Southwest China. It is observed that our model is in good agreement with Jiuping et al. The parameters used in our work are fluid density, depth of well, friction coefficient, ground temperature, bottom hole pressure, well and thermal conductivities. Temperature is plotted based on the value of pressure as can be seen in figure (2) with different depth. We also verify that when the output remains constant, the temperature increases with the increasing depth of the well. If the depth is kept constant the temperature increases with time.As can be seen from the figure the temperature changes quickly in the early stage but stabilized later over time. At constant depth, the pressure increases with an increase in time as in figure 1, but at constant output the pressure increases with increasing depth. For increase in time, flow increases and the frictional heat lead to increase in the pressure which resulted in quick change in pressure at early stage and later stabilizing over time.

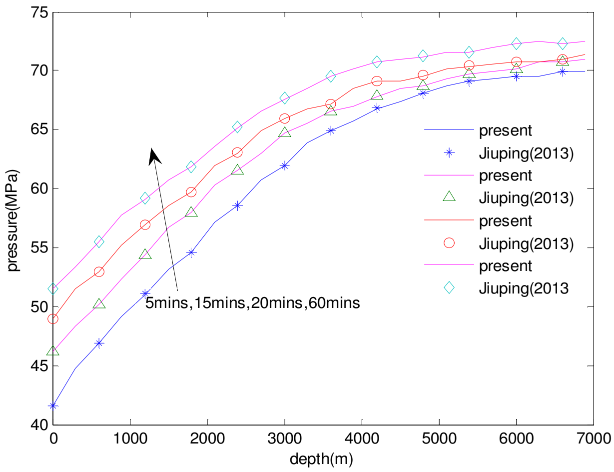

Figure 2: Pressure distribution at different depth.

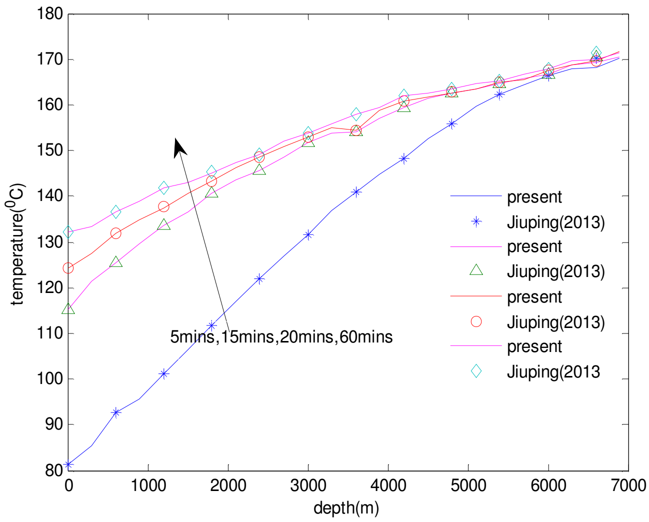

Figure 3: Temperature distribution at different depth.

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ISSN (online): 2289-7879 I Vol. 6, No. 1. Pages 19-33, 2015

Due to the joule thermal effect, the temperature of the hot fluid at the bottom is not equal to the temperature of the formation at the same depth. After the gas rises up along the tubing, the temperature difference with the surrounding increases as the formation temperature reduces. As shown in figure 3 the temperature rises as time increases. We consider different thermal conductivities of the earth at different times and the result shows that it has an effect on the distribution of temperature between the formation and the tubing as shown in figure 4.

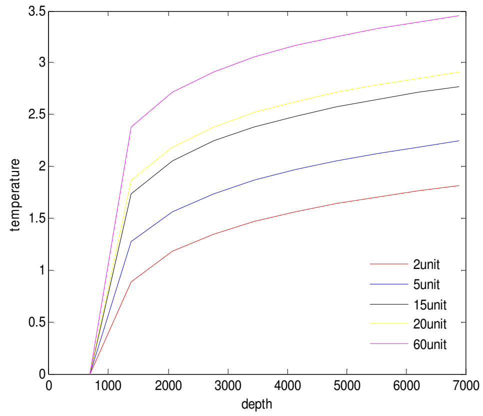

Figure 4: Temperature changes in the surrounding.

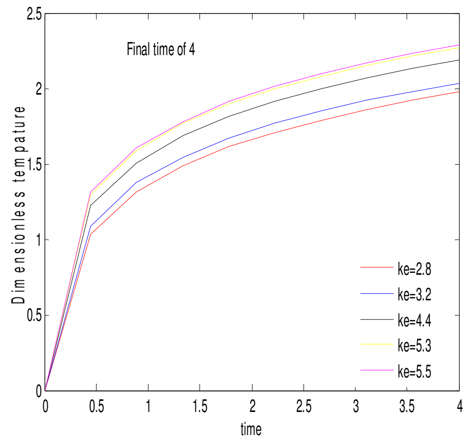

Figure 5: Different values of thermal conductivities depth at different time at different time.

4.0 CONCLUSSION

Previous predictions have shown that the ability to predict flowing fluid temperature and pressure has become necessary in several design problems that arise in gas production. In our work, we present a system of partial differential equations based on Newton's second law of motion. The model is based on mass, momentum and the interrelation of pressure, temperature, gas velocity and density of flowing gas in producing gas well. The solution to the steady state became our boundary condition as required by flow propagation.We solve our model using Finite Scheme ethod (FSM). The result is in good agreement with the work of Wu et al. [23].

ACKNOWLEDGEMENT

Financial support provided by **VOT 01G31,** Research University Scheme, Universiti Teknologi Malaysia is gratefully acknowledged.

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Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
ISSN (online): 2289-7879 | Vol. 6, No. 1. Pages 19-33, 2015

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