An Improved Numerical Model of the High Energy Gas Fracturing (HEGF) Process

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Abstract – High Energy Gas Fracturing (HEGF) is a stimulation technique for improving the recovery of oil and gas from a production well by generating multiple fractures surrounding the wellbore with high pressure gas that is released from the burning of propellants at the depth of interest. This paper reports our recent work on the numerical modelling of the propellant gas fracturing. In this study we develop a numerical model for the description of the primary physics effects associated with HEGF such as propellant burning process inside the tool, pressure build-up due to the propellant gas generated from the combustion, fracture initiation and propagation. The main contribution of this work compared to other published researches is that the downhole pressure throughout the HEGF process is fully modeled, especially with the detailed description of the pressurization inside and outside the tool where two different stages of the propellant burning process, i.e. progressive and regressive burning, are clearly characterized. Our new model has been applied to a production well in Southeast Asia, and the result from this work agrees well with field data recorded at the depth of interest during the HEGF process.

Keywords - High energy gas fracturing (HEGF); propellant gas fracturing; propellant gas stimulation.

I. INTRODUCTION

For some wells that have severely damaged near-wellbore zone and/or for the recent wells that are producing oil and gas from tight reservoirs (with low permeability), well stimulation is needed for production enhancement, especially with skin reduction and productivity index (PI) improvement. Typical stimulation techniques are to create fractures that penetrate into the formation and establish better pathways for oil and gas to flow from the reservoir into the wellbore. Among other fracturing techniques, the high energy gas fracturing (HEGF) has proved itself a cost-effective method for oil and gas well stimulation in recent years in Asia countries.

HEGF is based on the proprietary ballistic technology from the U.S. military. Instead of injecting liquid from the surface for wellbore pressurization as in hydraulic fracturing, HEGF uses gas generated from the in-situ combustion of propellant grains packed inside a metal container, known as the canister that is lowered to the interval to be treated in the wellbore [1]. Once the high energy gas (referred hereafter as to propellant gas) inside the canister reaches the bottom-hole pressure, it expels the port plugs from the canister and pressurizes the wellbore until the first rock fracture initiation. Thanks to the great availability of the propellant gas in the interval to be treated as well as the high mobility of the propellant gas, the downhole pressure doesn’t decrease after the first fracture initiation and propagation as in hydraulic fracturing. Instead, it continues to increase, and this explains why multiple fractures can be created in the directions other than the one that is perpendicular to the minimum horizontal stress [2].

In this paper, the main researches that have been done on the numerical modeling of HEGF are first reviewed in Section II, and the improved modeling workflow for HEGF is then presented in Section III where the primary physics taking place during the fracturing process are quantitatively described. Finally, the application of the improved model for an oil well as a pilot study in Southeast Asia is discussed in Section IV.

II. LITERATURE REVIEW AND LIMITATIONS OF CURRENT TECHNIQUES.

Since it was first experimentally studied in late twentieth century at Sandia National Laboratories [2], many researches on HEGF have been conducted. Only those related to the numerical modeling of HEGF are briefly reviewed in this section.

The fundamental work on the computational model for HEGF that established the solid background in this area was first reported by Nilson et al. (1985) who predicted the propagation of gas-driven fractures induced by propellant combustion taking into account the interaction between the borehole pressure and the propellant gas flow in the fractures [3]. In that work, the conservation of mass and momentum were used to model the gas flow through a fracture while the fracture propagation was predicted on the basis of quasi-steady equilibrium from linear elastic fracture mechanics.
In another original work contributing to the research area, the closed volume ballistic modelling was used to estimate the borehole pressurization by the combustion of propellant grains [4]. In that work, the burning rate of a propellant grain was showed to be strongly dependent on the propellant shape, and the borehole pressure can be predicted by using the aforementioned relationship together with the Abel-Nobel equation of state that characterizes the behavior of the propellant gas in the borehole.

Later, Schatz (1992) proposed an improved modeling on the propellant gas fracturing of rock with the following improvements [5]: (a) wellbore fluid motion by the gas generated from the in-situ combustion of propellant grains; (b) gas flow in perforation tunnels in cased and perforated boreholes; (c) fracture number prediction instead of assuming as in the previous models. The work, however, did not focus on the propellant combustion.

The numerical model reported by Yang and Risness (2001) for the design of the propellant fracturing job mainly focused on predicting the borehole pressure profile, estimating the performance of the HEGF, and investigating the sensitivity study of the borehole pressure and the potential productivity increase with respect to design parameters [6]. Recently, Zazovsky (2004) reported a new numerical modelling involving some physical phenomena such as propellant combustion and gas generation, well fluid compression and movement, wellbore pressurization, and the fracture propagation [7]. Although the propellant combustion was mentioned in these two researches, the effect of the propellant shape on the combustion was not investigated.

Although the researches mentioned above established the fundamentals for the numerical modeling of HEGF, most of them focused on the cases where propellant combustion takes place outside the HEGF tool. In the recent years, HEGF technology in which propellant grains are packed and burnt inside the tool has proved itself an effective well stimulation technique thanks to this structure, the combustion of perforated grains is improved with progressive burning mechanism as described later in this section [8]. The burning rate of propellant grains (u) is simply represented as sole pressure-dependent as follow [6]:

\[ u = \frac{de}{dt} = u_0P^n \]  

where e is the web thickness burnt (m) as shown in Figure 1, t is time (s), u_0 is the burning rate coefficient (m/Pa.s), P is the gas pressure (Pa), and n is the pressure index. The two empirical parameters n and u_0 were tabulated for some popular propellant types [4].

After the ignition takes place, a portion of the propellant grains burnt converts to propellant gas to build up the pressure. Let \( \Phi \) be the ratio of the mass of the propellant grains burnt over the total mass at certain time:

\[ \Phi = \frac{m_b}{m_p} = f \left( K_1 + K_2f + K_3f^2 \right) \]

where \( m_b \) is the mass of the propellant grains burnt (kg); \( m_p \) is the total mass of the propellant grains (kg); \( f \) is the fraction web burnt; \( K_1, K_2 \) and \( K_3 \) are form coefficients characterizing the burning pattern of specific propellant types [4, 8].

To build a reliable and practical model for HEGF with propellant grains packed inside the canister, the propellant combustion inside the canister should be fully characterized. The two consecutive burning processes of multi-perforated propellant grains mentioned above are taken into account to model the pressure build-up both inside and outside the canister as presented in the next section.

### III. NEW PROPOSED METHODOLOGY

The main components of our proposed modeling approach to HEGF are presented in this section. They include (a) propellant combustion and gas generation, (b) downhole pressurization, and (c) fracture initiation and propagation. Specifically, two consecutive burning stages of multiple-perforated propellant grains, namely progressive and regressive, are fully modelled in this study.

#### A. Propellant Combustion

A combustion of propellant grains is a series of chemical reaction happening fast and continuously. In this work, multi-perforated propellant grains are used that have multiple holes perforated throughout the grain (Figure 1). Thanks to this structure, the combustion of perforated grains is improved with progressive burning mechanism as described later in this section [8].

The pressurization by the propellant gas generated from the combustion at any instant of time can be estimated through the Nobel-Abel equation of state [4] as follow:

\[ P = \frac{m_p}{m} = \left( K_1 + K_2f + K_3f^2 \right) \]
where $c$ is the co-volume (m$^3$/kg), $R$ is the universal gas constant ($J/(mol.oK)$), $T_b$ is the flame temperature (oK), $V_p$ is the volume of space occupied by propellant gas (m$^3$) and $n_p$ is the number of moles of the propellant gas (mol). The number of propellant gas moles ($n_p$) is computed by the mass of propellant gas dividing the propellant gas molecular.

In this work, the combustion inside the canister as well as in the wellbore, and its contribution to the pressurization have been fully investigated. Incorporating Eq.(2) into Eq.(3) yields

$$P(V_c - V_p) = \frac{m_p \Phi c}{M_p} RT_b$$

where $V_c$ is the original free space inside the canister (m$^3$), $V_p$ is the volume of space left by the burnt propellant grains (m$^3$), $m_p$ is the total mass of the propellant grains inside the canister, $M_p$ is the propellant gas molecular (g/mol). The volume $V_p$ can be calculated by definition as follow:

$$V_p = \frac{(1-\Phi)m_p}{\rho_p}$$

where $(1-\Phi)m_p$ is the term for the mass of the propellant grains burnt, $\rho_p$ is the density of the propellant grains (kg/m$^3$).

As mentioned above, the combustion of the multi-perforated propellant grains in reality occurs in the two consecutive stages: the first stage is the progressive burning and the latter is the regressive burning stage. In this work, unlike the other researches mentioned above, we have derived mathematical formulation for both combustion stages. Indeed, by rearranging Eq.(4), we obtain the relationship $\Phi_{pro} = f(P)$ in the progressive burning stage as follow:

$$\Phi_{pro} = \frac{m_p \Phi c}{M_p} \frac{RT_b}{\rho_p}$$

where $\Phi_{pro}$ is the mass fraction of propellant grains burnt in the progressive burning stage. The pressure generated from the combustion inside the canister can be calculated by combining Eq.(1), Eq.(2) and Eq.(6).

In practice, when the pressure inside the canister reaches the static wellbore pressure ($P_w$), the port plugs are expelled and the propellant gas escapes from the canister. As a result, the released gas almost instantaneously occupies the surrounding wellbore volume and the wellbore pressurization begins.

The fraction of the weight of the propellant grains burnt ($\Phi_{pro}$) after the port plugs are expelled can be derived by slightly modifying Eq.(6) to yield:

$$\Phi_{pro} = \frac{P(V_c + V_{sub} + V_I) - P_{m_{loss - p}} - m_{loss - p}RT_b}{\rho_p} \frac{M_p}{\rho_p}$$

where $V_{wb}$ is the wellbore volume (m$^3$), $V_I$ is the space left by the movement of the wellbore fluid (m$^3$), $m_{loss - p}$ is the mass of propellant gas drainage through the perforation wall (kg). By combining Eq.(1), Eq.(2) and Eq.(7), the pressure build-up in the wellbore during the progressive burning process can be computed.

When the burning process proceeds to the second stage of regressive burning, the mass fraction of propellant grains burnt can be computed through the modification of Eq.(7) as follow:

$$\Phi_{reg} = \frac{P(V_c + V_{sub} + V_I) - P_{m_{loss - p}} - m_{loss - p}RT_b}{\rho_p} \frac{M_p}{\rho_p}$$

where $\Phi_{reg}$ is the fraction of the propellant grains burnt in the regressive burning, $\Phi_{pro-e}$ is the fraction at the end of the progressive burning. When the progressive burning ends, the fraction web burnt (f) reaches 1 or $\Phi_{pro-e} = K1 + K2 + K3$. The pressure build-up in the wellbore during the regressive burning stage can be calculated by combining Eq.(1), Eq.(2) and Eq.(8).

After the port plugs are expelled, the propellant gas occupies the outside space and mixes up, rather than dissolve in, with the wellbore fluid to create a gas-liquid mixture in the interval to be treated. This zone expands toward both up and down directions along the wellbore.
where $H_m$ is the displacement of the wellbore fluid (m), $a$ is acceleration (m/s²). The expression to calculate $a$ is given by

$$ a = \frac{P_g}{H_f \rho_f} $$

(10)

where $g$ is gravitation (m/s²), $H_l$ is the height of wellbore fluid (m), and $\rho_f$ is the wellbore fluid density (kg/m³). The volume of space created by the movement of the wellbore fluid at any instant of time ($V_l$) is expressed as

$$ V_l = \frac{\pi D_w^2 H_m}{4} $$

(11)

where $D_w$ is the wellbore diameter (m).

The propellant gas drainage through perforations also occurs since the port plugs are expelled. Assuming that every perforation acts as independent narrow channels, an estimate of the mass of propellant gas exiting through perforations ($m_{loss-p}$) can be done by using the equation for choked flow [10]:

$$ \frac{dm_{loss-p}}{dt} = \beta d_p^2 P N_p $$

(12)

where $\beta$ is the loss coefficient (kg/(m².Pa.s)), $d_p$ is the diameter of perforations (m), $N_p$ is the number of perforations.

C. Fracture Initiation and Propagation

When the wellbore pressure reaches the condition at which the in-situ stress applied on the rock exceeds the strength of the rock, fractures are created. The rock fracture is initiated as the wellbore breakdown condition is satisfied [11]

$$ P \geq 3\sigma_h - \sigma_H - P_r - T_o $$

(13)

where $P$ is the pore pressure (psi), $\sigma_h$ is the minimum horizontal stress (psi), $\sigma_H$ is the maximum horizontal stress (psi), and $T_o$ is the tensile strength of the rock (psi).

The geometry of a single fracture at any instant of time is modelled as a wedge-shaped radial one with a constant height [3]. The condition of whether a fracture of interest can further propagate is that the stress intensity factor $K_I$ at the fracture tip is still in equilibrium with the rock fracture toughness $K_{IC}$ [3]:

$$ K_I = \frac{P_f - \sigma}{\sqrt{L_f^2 - x^2}} dx = \frac{K_{IC}}{2} \sqrt{\frac{\pi}{L_f}} $$

(14)

where $L_f$ is the fracture length, $P_f$ is the pressure in the fracture, $\sigma$ is the confining stress which is calculated as the mean value of the two horizontal principal stresses.

IV. RESULTS AND DISCUSSION

The numerical model presented in the previous section has been applied to an oil well named X-1. The interval to be treated from 2,423m to 2,425.5m has been perforated with 6-spf density. The simulation of HEGF is run across the target interval in the 7-in casing for well X-1. The formation of the interval is sandstone. Since the fracturing equipment is placed at the desired depth through the tubing with 2.875", the equipment with outer diameter of 2 inches is chosen for the well X-1. The general information of the well, formation, and geo-mechanical data are presented in Table 1.

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<th>TABLE I. INPUT PARAMETERS FOR THE WELL X-1</th>
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<td>Tensile strength ($T_o$)</td>
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A. Propellant Combustion

Figure 2 displays the sum of mass of the propellant grains burnt versus time during simulation. As can be seen in Figure 2(a), the slope of the curve increases over time in the first period from 0 ms to 42 ms which is the characteristic of the progressive burning. The rate of the propellants burning in this period increases with time due to an increase in the burning surface area of the multi-perf propellant grains. The curve in Figure 2(b) shows the period of 4 ms from 42 ms to about 46 ms with the reduction of the slope that characterizes the regressive burning.
Figure 2. The mass of the propellant grains burnt versus time for the well X-1.

In Figure 2(a) the curve with the increasing slope over time lasts in the first 42 ms. The progressive burning stage; (b) The curve with the decreasing slope with time takes place in the remaining 4 ms: The regressive burning stage.

It is noticed that most of the propellant grains burns in the progressive burning process and the remains burn in the regressive burning mode. In addition, the total time of the progressive burning is much longer than that of the regressive burning.

B. Borehole Pressurization

The pressure profile throughout the simulation is shown in Figure 3. The pressure build-up inside the canister reaches the initial bottomhole pressure after 19 ms.

This is the point in time when the port plugs are expelled. At this moment, the slope of the pressure curve slightly changes but its value still keeps increasing with time. Afterwards, the pressure reaches the breakdown pressure at 23 ms and multiple fractures are initiated. Just after breakdown, the pressure drops by 400 psi before continuing to reach the peak pressure of 11300 psi after 37 ms. The pressure then gradually decreases to the minimum horizontal stress.

Figure 2(a) and Figure 3 also show that the progressive burning period not only includes the propellant combustion inside the canister but also covers the entire borehole pressurization stage. This period still continues a bit more time after the downhole pressure has reached the peak value.

Figure 4(a) shows the vertical movement of the wellbore fluid surrounding the fracturing tool/canister is not significant (less than 2 ft) throughout the simulation time. Figure 4(b) demonstrates the mass of the propellant gas drainage through the surface of perforations. Since the perforation surface area is minimal and the fracturing process takes place in a short period of time, the mass of gas lost through the perforations is not remarkable.

Figure 5 shows the comparison in pressure curve shape between the result by Zazovsky (2004) [8] and that from our study.
As can be seen in Figure 5(a), the pressure curve in the build up stage is quite linear and its value is kept constant after the pressure drops from the peak value. On the other hand, the pressure curve obtained from this study shows a more realistic shape. Not to mention about the good match with the observed data, the agreement in the pressure curve shape shows the correctness and reliability of our modeling approach to HEGF.

Our work yields more realistic result whereas the pressure curve from [7] is almost linear in the pressure build-up stage and constant in the rest of the process.

Figure 6(a) displays the pressure curve computed by Yang and Risness (2001) [6] which has a similar shape with that from the model in this work. The main difference between the two resultant curves is that the pressure curve described in [6] starts from the initial bottomhole pressure (Pwo) meaning that they did not consider the combustion inside the canister. In our study, we fully model this physics.

The pressure curve obtained from Yang and Risness’s model begins from the initial wellbore pressure (Pwo) or the combustion inside the canister is neglected whereas the proposed model in our work captures this physics.

The average length of an individual fracture with time is displayed in Figure 7. At the end of the fracture propagation period, the fractures reach an average length of about 2.70 m. It is noticed that the curve of fracture length has a quite similar shape with the curve of the mass of propellant grains burnt in Figure 4. This is due to the fact that the mass of the propellant gas controls the speed of the fracture propagation.

D. Comparison with Field Data

To verify the model proposed in this study, the calculated pressure is compared with that observed during the HEGF in the well X-1. The borehole pressure data was recorded during the fracturing job through pressure gauge located at the end of the tool. The measured pressure data was, therefore, only available outside the canister. Although there is a slight difference between the estimated peak pressure and the observed pressure, as shown in Figure 8, these curves fit well to each other.

V. CONCLUSIONS

A numerical model has been built to describe the main physical phenomena associated with the propellant gas fracturing such as the burning process of the propellant grains, the wellbore pressurization, the displacement of the wellbore fluid, the propellant gas drainage through perforations, and the fracture initiation and propagation. Specifically, unlike other work mentioned in this paper, both of the progressive and regressive burning processes of the propellants are thoroughly investigated. Another contribution of this study is that the pressure build-up inside the fracturing tool is fully modeled.

The borehole pressure profile resulted from the application of the proposed model to a case study shows a reasonably good agreement with the observed pressure data, which verifies the reliability of the model.
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REFERENCES


