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저류층 인자가 킥의 감지와 킥의 부피에 미치는 영향

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Effects of Reservoir Parameters on Kick Detection and Pit Volume Gain

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1. Introduction

As proven petroleum reserves decline through continued production, exploration for new oil and gas resources will extend into environments which present significant economic risks and technical hurdles. Since safety is one of the biggest concerns in drilling operations, the oil industry routinely trains its personnel in areas which are critical for safe and economical drilling procedures. One of these major areas is well control. A kick is defined as an unscheduled flow of formation fluids into a wellbore. A kick occurs whenever the resultant wellbore pressure is less than the formation pressure in an exposed zone capable of producing kick fluids. The typical causes of reduced wellbore pressure are insufficient mud weight, inadequate fluid level in the hole, and swabbing.

Well control includes not only kick prevention and kick detection but also the process of removing kick fluids from the kicking well and circulating heavy drilling mud under controlled conditions. Most kicks enter the well at the bottom. For such kicks, the basic principle of well control is to keep the bottomhole pressure (BHP) as constant as possible at a value that is at least equal to the formation pressure.

The main objective of a kick simulator is to predict pressure and volume behavior of kick fluids as a function of time. Well control simulation has received attention in recent years because of its applicability and flexibility, and many computer models[1-7] have been developed to analyze the behavior of a kick. However, most of the models do not include reservoir parameters and none of them considers mud compressibility effect on kick detection and well stabilization after the well shut in.

This paper presents a well control computer model to analyze the behavior of a gas kick at the early stage of kick detection and well stabilization after the well shut in.

2. Governing Equations

The appropriate assumptions and governing equations are critical to simulate realistic two-phase well control operations. The two-phase model in this study is based on the following assumptions:

- two-phase flow
- one-dimensional flow along the flow path
- water-based mud
- compressible mud
- known mud temperature gradient with depth
- kick occurs at the bottom of the well while drilling

2-1. Two-Phase Mixture Region

Eight variables describe the two-phase flow system completely. They are pressure, temperature, gas and liquid fractions, gas and liquid densities, and gas and liquid velocities. There are still five unknowns such as gas and liquid velocities, gas fraction, pressure, and gas density based on the above assumptions. Therefore, five equations are required to calculate the unknown variables with boundary conditions. These are the conservation of mass equation for mud, the conservation of mass equation for gas, the conservation of linear momentum equation for the mud-gas mixture, the equation of state to compute gas density, and the two-phase correlation to calculate in-situ gas velocity.

2-2. Single-Phase Region

Single-phase flow exists inside the drill-string and in part of the annulus. The annulus could have four regions: a single-phase region above the two-phase mixture, the two-phase mixture region, a single-phase region for the old mud, and a single-phase region for kill mud below the two-phase mixture. Only one or two regions will exist in the beginning and at the end of well control operations.

For the single-phase flow, a general pressure loss equations can be used.[6)]

$$\frac{\Delta p}{\Delta L} = 980\rho + \frac{\Delta p_f}{\Delta L} + \rho\frac{v^{n+1} - v^n}{\Delta t} \qquad (1)$$

Eq. (1) includes hydrostatic pressure gradient, frictional pressure loss(FPL) gradient, and acceleration loss gradient.

Even though frictional pressure loss is small in the annulus for a large well diameter at low kill rate, FPL is critical for slim-hole wells or inside the choke line for offshore wells. FPL is considered to achieve more realistic simulation of kick behavior for all flow geometries and flow rates. The Power-law fluid model is assumed. Detailed equations are available in reference 7.

The estimation of two-phase FPL is required to calculate the two-phase mixture momentum balance equation. The two-phase well control model utilizes the Beggs and Brill correlation.[8)]

2-3. Calculation of Gas Properties

Even though gas density is small compared to drilling mud density, the correct evaluation of gas density is essential to calculate the hydrostatic pressure of the two-phase mixture and to predict bubble rise velocities. The gas compressibility factor, which is a function of pseudo-reduced properties, is calculated from the equation proposed by Dranchuk *et al.*[9)]

Gas viscosity is obtained using the Lee *et al.* correlation.[10)] Surface tension, which is necessary to estimate bubble rise velocity, is determined by the Katz *et al.* method, which is a function of pressure and temperature.[11)]

Gas slip velocity is one of the parameters needed to describe a two-phase system. It also affects initial gas distribution and kick migration velocity during well shut-in. The total time for kick fluids to reach the surface from the bottom of the wellbore strongly depends on bubble rise velocities. The bubble rise velocity is a function of mud and gas flow rates, fluid properties, and geometry of the conduit. After an intensive literature survey, the Hasan and Kabir model[12)] was chosen in this study.

3. Solution Procedures

3-1. Drilling to Kick Detection

The two-phase model starts the simulation by taking a kick while drilling. Gas inflow rate is calculated by assuming an infinite-acting homogeneous reservoir.[13)] The gas distribution is calculated by the Hasan and Kabir correlation using the mud circulation rate and gas influx rate from the formation. All parameters in the two-phase mixture region are evaluated at the middle point of the two-phase mixture weighted by the effective gas fraction. Since initial gas kick volume is relatively small, the above approximation gives excellent results to compute pressure of the kick and the flowing bottomhole pressure.[6)] The effective flow rate for the single-phase region is the summation of mud circulation rate and gas inflow rate.

One of the primary kick warning signs is increased mud return rate. The next step is to confirm that the well is flowing after the surface pump is shut down. This is the same as the "Drilling" stage except for reduced flow rate without circulating mud. The same calculations are repeated here.

3-2. Well Shut-in

The next important step after detecting a kick is to shut the well in to prevent further influx from the formation. However, there is some flow from the formation as long as the BHP is less than the formation pressure. Since the total system volume is the same after well shut-in, further inflow results in BHP increase. If BHP rises up to the formation pressure, the system has reached pressure equilibrium. At this point shut-in drill-pipe pressure (SIDPP) and shut-in casing pressure (SICP) are recorded.

The amount of pressure build-up for the given duration can be calculated from Eq. (2), if a gas kick is assumed compressible.[6)]

$$p^{n+1} = p^n \frac{z^{n+1} m^{n+1}}{z^n m^n} \qquad (2)$$

Where, m is the number of moles of the gas kick.

In this study, mud compressibility is also considered to compute pressure buildup during well shut in.

$$p^{n+1} = p^n + \frac{\Delta V_{kick}}{\left(C_{mud} V_{mud} + C_{kick} V_{kick}\right)} \tag{3}$$

$$C_{kick} = \frac{1}{p} - \frac{1}{z}\frac{dz}{dp} \tag{4}$$

4. Results and Discussion

Table 1 shows all default data used in this study unless otherwise specified. Table 1 represents typical well configurations in the Gulf of Mexico for deep water wells. Water depth is 914 meter and total well depth is 4,572 meters. Three different formation permeabilities are employed to see the effects of gas kick influx rates. In order to simulate actual field well control operations in detail, the following scenario is assumed:

1. Drilling to the target depth (2-minute duration)
2. Taking a kick while drilling
3. Kick detection by a preset pit volume warning level of 1.59 liters (10 bbls)
4. Stop drilling after the kick detection
5. Shutting pump down to confirm the kick (10-second time duration)
6. Shutting the well in (20-second time duration)
7. Well stabilization

Fig. 1 displays pit volume gain based on the scenario above. More problems are expected for high formation permeability. For 1000 md formation permeability, it takes only 1.6 minutes for a 1.61 m^3 (10.14 bbls) gas kick gain. It takes a short time so that the rig crew should watch all kick indicators very closely. There is an additional 1.24 m^3 (7.8 bbls) kick due to 30 seconds reaction delay from kick detection to well shut-in. Pit volume gain at the surface remains constant after well shut-in while the number of moles of gas kick increases continuously until well stabilization.

For 10 md formation permeability, it takes about 13.2 minutes for 1.59 m^3 (10.02 bbls) of gas kick. There is only 0.16 m^3 (1.0 bbls) of additional pit gain after kick detection. Note that the kick volume detected is very close to the preset pit warning level. It also takes a longer time for well stabilization. Therefore, a well control team in the field has more time to prepare any necessary actions to bring the kicking well under control. Several minutes of time delay is also affordable.

Fig. 2 shows surface casing pressure based on the scenario above. Before closing a blowout preventer, surface casing pressure is zero. SICP at the surface increases after well shut-in until the BHP balances with the formation pressure. The lower the formation permeability, the longer the time to stabilize the well pressures. Stabilized SIDPPs are the same for all three cases regardless of initial pit volume gain because SIDPP is a function of formation pressure, mud density in use, and well depth. SIDPP is independent of kick size or formation permeability.

Fig. 3 shows a comparison of surface casing pressure buildup after well shut-in with and without mud compressibility. Formation permeability is 10 md and initial pit volume gain is 1.75 m^3. If mud compressibility is ignored (Eq. 2), the surface choke pressure gives fast stabilization with less number of gas kick moles than that with mud compressibility. For realistic pressure buildup, mud compressibility should be considered. Otherwise, it will provide wrong number of gas moles at the shut-in conditions as can be seen in **Fig. 4**.

5. Conclusions

The following conclusions have been drawn from this study:

- A kick with high formation permeability could result in a very large pit gain if the kick is not detected and reacted to quickly. It also gives fast well stabilization after well shut in..
- Mud compressibility should be considered for realistic simulation of pressure build up after well shut in.

NOMENCLATURE

C = compressibility, $1/(\text{dynes/cm}^2)$
m = number of moles
p = pressure, dyne/cm^2
t = time, second
V = volume, cc
v = velocity of the fluid, cm/s
z = gas deviation factor
ΔL = measured length of an interval, cm

Subscripts
f = friction

Superscripts
n = old time level
$n+1$ = new time level

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Table 1 – Default input data in this study

Mud density, gm/cc	1.68
Plastic viscosity, cp	23.0
Yield point, dynes/cm^2	76.6
Bit nozzle opening number	3
Bit nozzle diameter, 1/32nd in.	14.0
Well vertical depth, m	4572
Length of drill-collars, m	137.2
Depth of last casing seat, m	3658
ID of last casing, cm	22.659
Open hole diameter, cm	21.59
OD & ID of drill-pipe, cm	12.7 x 11.201
OD & ID of drill-collar, cm	16.51 x 5.08
Pump rate while drilling, liters/min	1514
Water depth, m	914.4
Marine riser diameter, cm	48.26
Choke line ID, cm	10.16
For kick analysis:	
Fomation over pressure, kPa	5378
Pit volume warning level, m^3	1.59
Gas specific gravity	0.65
Mud compressibility, 1/kPa	0.87E-6
Surface temperature, °C	21.1
Sea floor temperature, °C	6.1
Bottomhole temperature, °C	72.8
Formation skin factor	2
Formation porosity, fraction	0.25
Rate of penetration, m/hr	18.29

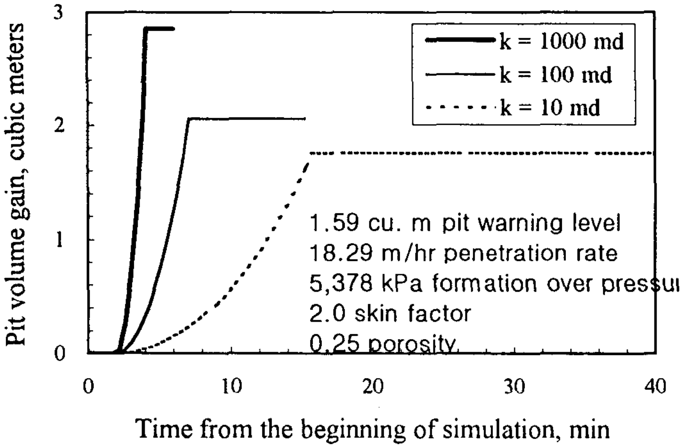

Fig. 1 - Pit volume gain from drilling to pressure stabilization after well shut-in.

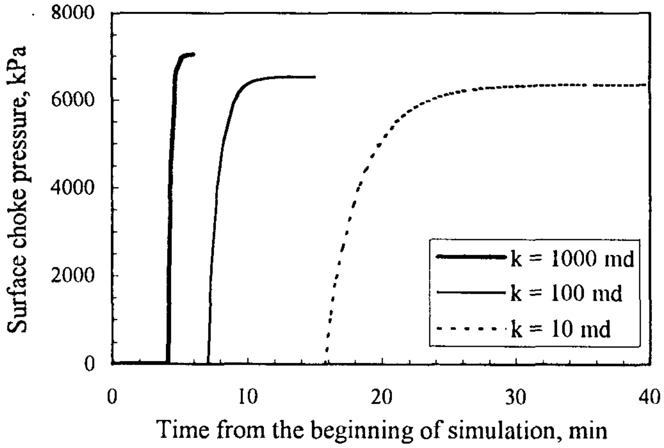

Fig. 2 - Surface choke pressure from drilling to pressure stabilization after well shut-in.

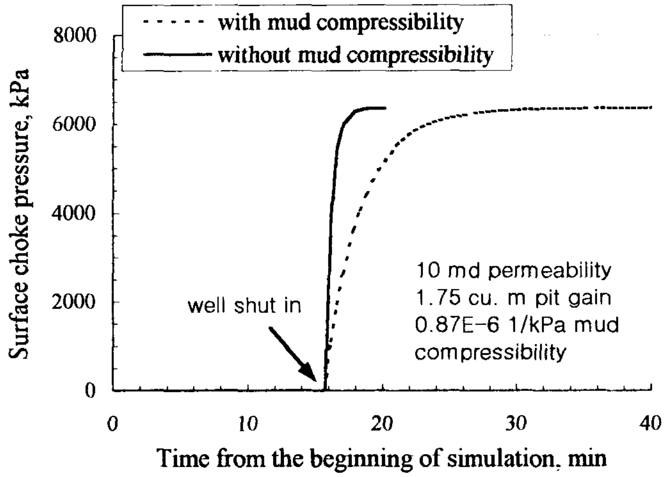

Fig. 3 - The effects of mud compressibility on the surface choke pressure build up.

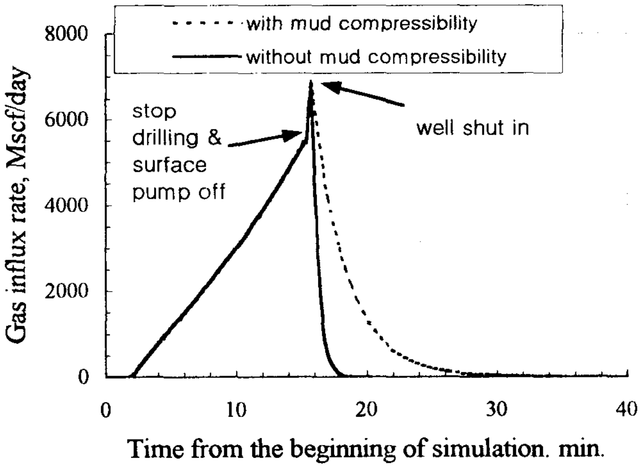

Fig. 4 - The effects of mud compressibility on kick influx.