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Research Paper

Prediction of annular pressure caused by thermal expansion by considering the variability of fluid properties

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HIGHLIGHTS

- Polynomials are proposed to obtain the variability of fluid properties.
- Experiments and error analysis are performed to validate the polynomials.
- The proposed polynomials can be applied to an improved prediction model.
- The polynomials and model improve the accuracy of the annular pressure prediction.
- It is important to adopt the polynomials and improved model in engineering.

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ABSTRACT

To accurately predict annular pressure build-up, which is caused by the thermal expansion of fluid in deepwater wells, a prediction model should consider that the thermal expansion coefficient and compressibility of the fluid vary with temperature and pressure. By means of 2-D Lagrangian interpolation, polynomial expressions are proposed to obtain the expansion coefficient and compressibility of water. A series of laboratory experiments is conducted to validate these polynomials. The numerical and experimental errors and error propagation are analyzed, indicating that the relative errors between the theoretical and experimental data are acceptable in engineering. To apply these polynomials to the estimation of annular pressure, the prediction model is improved. A case study and some crucial factors are analyzed. The results show that compared with published models that did not properly consider the fluid properties, the improved model, which is based on the proposed interpolation polynomials, advances the prediction accuracy. It is important to adopt the improved model and interpolation polynomials to predict the risk in engineering because, in most cases, previously published models may lead to unacceptable errors and an underestimation of the pressure. These findings help engineers predict annular pressure more accurately and contribute to the safety design of deepwater wells.

1. Introduction

If a deepwater well is not top cemented, some completion fluid will be trapped in the sealed annular space, and the fluid will expand after being heated by the production fluid. Then, the annular pressure will significantly increase with the temperature; this process is called annular pressure build-up (APB) [1]. In deepwater wells, APB is a potential risk and considerably endangers wellbore integrity. Serious accidents have been reported in many areas, including the Gulf of Mexico [2,3], Atlantic Canada [4], Brazil [5] and Indonesia [6], indicating that APB can cause heavy loss. To avoid such damage, many methods, such as utilizing an open shoe, a rupture disk, a compressible fluid, and heat-insulating strings, have been developed in recent years to alleviate APB [7–12]. Prior to applying these techniques, accurate prediction of APB is essential to evaluate the risks in deepwater wells.

Many researchers have been studied the theory of APB and proposed prediction models. In 1986, Klementich and Jellison proposed a model to predict APB by considering the effects of temperature change, string ballooning and cementing [13]. Adam et al. [14,15] illustrated that a single string is inadequate for accurate prediction and presented a model that took multiple strings into consideration. Halal and Mitchell [16] developed a prediction model by taking the fluid thermal expansion and radial movement of casing into consideration. Oudeman and Bacarezza [17], in 1995, performed a field test to validate these theoretical models; the results showed that the fluid influx or efflux has a great influence on the APB in an unsealed annulus. Gao [18] established

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Nomenclature

α	fluid expansion coefficient (°C^{-1})
k	fluid compressibility (MPa^{-1})
ρ	density (kg/m^3)
T	temperature (°C)
P	pressure (MPa)
R_L^{post}	posterior error estimation of interpolation polynomials (kg/m^3)
R_α	error of expansion coefficient (°C^{-1})
R_k	error of compressibility (MPa^{-1})
δP_{exp}	deviation of experimental data (MPa)
P_i	recorded pressure at each experiment (MPa)
N	number of experiments
$\overline{P}$	average pressure (MPa)
V_a	volume of residual air (m^3)
V_a'	volume of air after pressure increase (m^3)
V_c	volume of pressure vessel (m^3)
T_o	initial temperature at a calculation step (°C)
P_o	initial pressure at a calculation step (MPa)
V_{ann}	volume of sealed annulus (m^3)
ΔP	pressure increase (MPa)
ΔT	temperature increase (°C)
ΔV_c	vessel volume change (m^3)
ΔV_T	volume change caused by thermal expansion (m^3)
ΔV_P	volume change caused by pressure increase (m^3)
h	height of pressure vessel (m)
u_a	displacement of inner diameter (m)
a	inner diameter of pressure vessel (m)
α_s	coefficient of linear expansion of steel (°C^{-1})
μ	Poisson's ratio
D	wall thickness (m)
E	elastic modulus (MPa)
δP_{pre}	error propagation of predicted pressure (MPa)
P_{exp}	experimental pressure (MPa)
P_{pre}	predicted pressure (MPa)
R_{pro}	error propagation of relative errors (%)
V_L	volume of fluid influx or efflux (m^3)
V_f	volume of fluid (m^3)

a practical model to calculate the radial and axial stress of casings by considering fluid thermal expansion and casing ballooning. In 2006, Oudeman and Kerem [19] developed a general model to calculate APB and carried out a field test to validate this model, which considered the following factors: fluid thermal expansion and compression, volume change in the sealed annulus, and fluid influx or efflux. This classic model proposed by Oudeman in 2006 concisely explained the source of APB and has been widely used by most of the researchers who study this topic. Hasan et al. [20] predicted APB from the perspective of wellbore temperature. They proposed two models, the semi-steady state and transient models, to predict the annulus temperature and compared the advantages and disadvantages of the two models. Yang et al. [21], Yin and Gao [22], Shuang et al. [23], Liu et al. [24], and Zhang et al. [25] predicted the annular temperature based on the energy conservation principle and calculated APB by considering the fluid thermal expansion and casing deformation. The results of these studies [21–25] illustrated that, when the temperature change in a wellbore is fairly high, severe APB can cause casing collapse and that mitigation methods should be adopted immediately to alleviate this risk.

However, previously proposed prediction models have some limitations because they did not accurately take the fluid properties into consideration. Specifically, the limitations are listed below:

1. Some models did not consider the variability of the fluid thermal expansion coefficient and compressibility but treated the two parameters as constant at the normal temperature and pressure.
2. Although some of the previously presented models accounted for the variability of fluid properties, they considered that the fluid expansion coefficient and compressibility vary with temperature but do not vary with pressure. The fluid properties they used assume a constant pressure of 0.1 MPa.

Both considerations may lead to inaccurate prediction because real fluid thermal expansion coefficient and compressibility values vary with temperature and pressure. In addition, ignoring this nonlinear behavior of the fluid may cause errors [26]. Therefore, to accurately predict APB, it is necessary to consider the variability of the fluid thermal expansion coefficient and compressibility and propose a method to calculate these two parameters.

This paper proposes polynomial expressions to obtain the thermal expansion coefficient and compressibility of water by 2-D Lagrangian interpolation. A laboratory experiment is carried out to validate these polynomials. Then, the proposed polynomials are applied to the APB prediction theory. Finally, a field example and some key factors are analyzed to compare the results of the proposed model with those of published models.

2. Interpolation polynomials and experimental validation

2.1. Interpolation polynomials of expansion coefficient and compressibility

2.1.1. Establishment of polynomials

As temperature and pressure increase, the fluid expansion coefficient and compressibility would vary with temperature and pressure. First, this paper proposes a method to calculate the expansion coefficient and compressibility at different temperatures and pressures.

Without a loss of generality, in the prediction model of APB, water is used as the fluid medium because the base fluid of the trapped fluid in an annulus is always water [19]. It is difficult to directly obtain the expansion coefficient and compressibility at any temperature or pressure, so this paper will calculate these parameters from the fluid density. The expansion coefficient and compressibility can be expressed by Eqs. (1) and (2) [20].

$$\alpha = (1/V_f)(\partial V_f/\partial T)_P = -(1/\rho)(\partial \rho/\partial T)_P \tag{1}$$

$$k = (1/V_f)(\partial V_f/\partial P)_T = (1/\rho)(\partial \rho/\partial P)_T \tag{2}$$

If the function that can determine the relationship of density with temperature and pressure is developed, it will be possible to obtain the expansion coefficient and compressibility by using Eqs. (1) and (2). To reasonably assume the density function, this work will first analyze the variation in density with temperature and pressure. Several densities at different temperatures and pressures are listed in Table 1 [27].

Fig. 1 presents the relationship of density and temperature at different pressures. Fig. 1 shows that the density decreases continuously with an increase in temperature when the pressure is constant. It is possible to describe the relationship between density and temperature by using a quadratic polynomial or polynomial of a higher order.

Notably, the density at 0.1 MPa is not presented in Fig. 1. Because the main purpose of this paper is to calculate the expansion coefficient and compressibility for engineering applications, this work focuses on the fluid properties in real pressure conditions, which are much higher than 0.1 MPa. In addition, when the temperature is higher than 100 °C, the rapid decrease in density at 0.1 MPa may disturb the regularity analysis at high pressures. Thus, this work does not consider the water density at 0.1 MPa. For the same reason, the water density at 0 °C doesn't be taken into consideration in the following discussion.