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An analytical model for pore volume compressibility of reservoir rock

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ABSTRACT

The pore volume compressibility of reservoir rock is usually measured by volume method and the relation between compressibility and porosity follows the Hall plot. However, the volume method yields a high pore volume compressibility value and a negative correlation between compressibility and porosity. Both results illustrate that unconventional reservoirs with low porosity has higher elastic energy than conventional reservoirs with high porosity, which disagrees with the production practice.

In this paper, volume method of pore volume compressibility is investigated and problems of Hall plot are analyzed. Then a novel analytical model on pore volume compressibility of reservoir rock is derived to resolve these problems. The reason on the improper results using volume method is discussed. The calculated results from our new model are validated by the experimental tests using mercury immersion method for pore volume compressibility measurement. The effects of compressibility on original oil in place and the flow radius are analyzed.

The analytical model shows that pore volume compressibility of reservoir rock is related not only to porosity but also to elastic modulus and Poisson's ratio. There is a positive correlation between pore volume compressibility and porosity. The compressibility value of our model is much lower than that measured using volume method. The reason of the improper results from volume method is the micro interstice in core holder. Without the effects of micro interstice (mercury immersion method or loading and unloading stress treatment before the test), the measured pore volume compressibility shows a relatively low value and a positive correlation between pore compressibility and porosity, which validate the results of our analytical model. The pore volume compressibility calculated by volume method and Hall plot will overestimate the elastic energy of the reservoir and bring substantial errors in evaluation of original oil in place and the flow radius.

1. Introduction

The pore volume compressibility of reservoir rock provides the elastic energy for fluid production in reservoirs [1–3]. In order to evaluate the capability of pore volume deformation and the elastic energy of reservoirs, pore volume compressibility is defined and measured by experiments [4,5]. For most reservoirs, pore volume compressibility is one of the most important parameters, because it is widely involved in reservoir engineering, including well testing, productivity analysis and material balance study [3,6–11].

As the fluid pressure decreases, the effective stress of rock increases and the rock skeleton is compressed. The skeleton compression results in the pore volume decrease [12]. Therefore, pore volume compressibility of reservoir rock is defined as relative variation of pore volume as pore pressure declines [13], expressed by

$$c_p = \frac{dV_p}{V_p dp} \tag{1}$$

According to Eq. (1), the volume method is designed to directly measure the pore volume compressibility. Fig. 1 shows the experimental setup of volume method [14,15]. The confining pressure pump provides the constant confining pressure to represent overburden stress. The core is saturated with fluid and the pump supplies the pore pressure to a certain value. Then, the pressure regulating valve is used to decease the fluid pressure. As the pore pressure declines, the pore volume is compressed and a certain volume of fluid is expelled out of the core. The expelled fluid volume can be converted to the pore volumetric reduction at a given pore pressure. The volume method can intuitively reproduce the reservoir production process and directly calculate the pore compressibility using Eq. (1).

Because the volume method for pore volume compressibility is quite

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Nomenclature

A	area of section BB', m^2	N_p	cummulative oil production, m^3
B_o	oil volume coefficient, m^3/m^3	Δp	pressure drop of reservoir, MPa
c_{eff}	effective compressibility of reservoir , MPa^{-1}	p	pore pressure of rock, MPa
c_o	the oil compressibility, MPa^{-1}	r_f	flow radius, m
c_p	rock pore compressibility, MPa^{-1}	s_o	oil saturation, dimensionless
c_t	total compressibility of reservoir oil, MPa^{-1}	s_w	water saturation, dimensionless
c_w	water compressibility, MPa^{-1}	ν	poisson's ratio, dimensionless
E	elastic modulus of rock	V_p	pore volume of rock, m^3
E_s	elastic modulus of skeleton, MPa	V_s	skeleton volume of rock, m^3
k	permeability of reservoir, D	ϕ	rock porosity, dimensionless
N	the reserve of oil reservoir, m^3	σ_{over}	overburden stress rock, MPa
		σ_s	skeleton stress of rock, MPa
		μ	viscosity of oil, mPa·s

time-consuming, Hall [14] proposed a correlation between pore volume compressibility c_p and initial porosity ϕ, which is afterwards named as "Hall plot". Based on matching results of numerous laboratory tests by volume method, the Hall plot is in a high consistency with experimental data, shown in Fig. 2a.

The Hall plot illustrates the empirical relation between pore volume compressibility and porosity, which is widely adopted for its high convenience [16–19]. Following the research of Hall, Newman [15] performed laboratory measurements on 256 cores of sandstone and limestone to show the effects of lithology and effective stress on pore volume compressibility. The measured data by volume method also indicates that the effect of lithology on pore volume compressibility is not obvious [6,15].

However, the measurement of pore volume compressisbility by volume method causes two major problems. One is that the relation between pore volume compressibility and porosity shows an improper tendency: the pore volume compressibility decreases as rock porosity increases (Fig. 2a). This indicates that the porous medium with lower porosity is easier to compress than that with higher porosity if the lithology of two rocks is identical. Therefore, most unconventional reservoirs with low porosity should contain more elastic energy than conventional reservoirs, which disagrees with the production practice in unconventional reservoirs [20,21]. The proper tendency should be the positive correlation between pore volume compressibility and porosity. This tendency has already been observed in the compressibility measured by indirect method [22,23]. In these works, pore volume compressisbility increases as porosity increase and the lithology of different rocks has a dramatic impact on the value of pore volume compressisbility.

The other problem is that the pore volume compressibility measured by volume method is usually larger than that of reservoir liquid. The common ranges of compressibilities of solid, liquid and gas are $0–1 \times 10^{-4}$ MPa^{-1}, $10^{-4}–100 \times 10^{-4}$ MPa^{-1} and 100×10^{-4} MPa^{-1} ~ ∞, respectively (Fig. 2b) [24]. Especially, in tight reservoirs with porosity less than 0.01, the result from Hall plot illustrates that the pore of rock is more compressible than fluid. Again, this means the unconventional reservoirs with low porosity has higher elastic energy, which contradicts the production practice. This phenomenon has already been noticed in numerous researches [22,25–28]. The indirect measurements for pore volume compressibility, including mercury intrusion method [23] and ultrasonic velocity method [27,28], show the pore volume compressibility of reservoir rock is approximately 1×10^{-4} MPa^{-1}, which is much lower than the results from volume method.

In order to overcome these problems resulting from volume method and to explain the positive correlation between pore volume compressibility and porosity, an analytical model is developed in this paper to calculate the pore volume compressibility of reservoir rock. Based on our previous study [29], the relation between the pore volume compressibility and porosity is derived and the analytical model for pore compressibility is proposed. This method only requires the commonly measured parameters of rock mechanics as model input. Furthermore, the reason that traditional volume method leads to an improper result is discussed. The objectives of this research are: 1) to thoroughly understand the relation between pore volume compressibility and porosity, and 2) to investigate the possible factors in volume method which yield the reverse result.

2. The analytical model for pore volume compressibility

Assume that reservoir rock is a continuum medium, and there is a cross section BB' in the rock with an area A. There exist three stresses at section BB' of the rock, including overburden stress (σ_{over}), fluid pressure (p) and the skeleton stress (σ_s), illustrated in Fig. 3. Because the rock belongs to a steady state underground, the static forces on section BB' are in equilibrium. The forces above and below section BB' satisfy

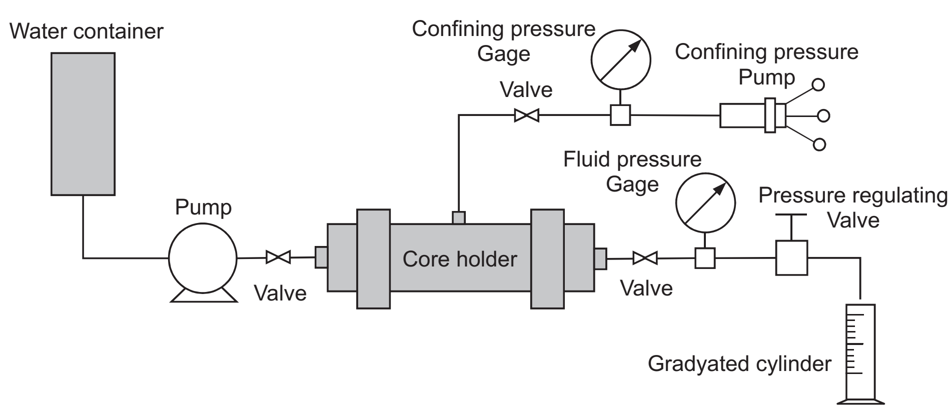

Fig. 1. Experimental setup of volume method.