Characteristic Features of the Movement of Elastic-Visco-Plastic Liquid in Pipes and Layers

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Abstract: Hydrocarbon properties, specifically paraffins, asphaltenes, and resins, greatly affect various field practices such as oil drilling, well operations, field development, and pipeline transportation. These compounds impart viscoelastic properties to oils, which means they exhibit both viscous and elastic behavior. Consequently, the internal structure of these oils changes at a slower rate compared to external conditions, leading to non-equilibrium effects.

To understand the viscoplastic elastic properties, we propose a model that considers the relaxation properties of the system. This model reveals that over time, these properties result in reduced filtration processes and decreased well productivity for hydrocarbons in porous media. We develop a representation of porous media movement in pipes to better understand this behavior.

During the filtration process, the liquid behaves as if it consists of suspended small particles with long relaxation times and viscoelasticity. These particles deform as they pass through the pipe and porous medium, effectively solidifying and becoming fixed. This understanding of viscoelastic properties can be effectively utilized during drilling operations.

In specific scenarios, it may be advisable to drill intervals with abnormal oil when the dynamic water pressure in the well is significantly lower than the formation pressure. This recommendation takes advantage of the unique properties of viscoelastic oils.

Keywords: Viscoplasticity; Elasticity; Velocity; Volume Flow

1. Introduction

In summary, when drilling and transporting fluids, one encounters fluids with elastic viscoplastic properties. Understanding the behavior of these fluids requires studying branches such as mathematical physics and special function theory. Various factors, including properties of rocks and fluids, physical conditions, and pressure, influence the drilling and development processes. Fluid motion can occur through potential energy or other additional sources, such as fluid injection to maintain pressure. The behavior of an oil or gas reservoir is analyzed and regulated based on the concept of reservoir regime, which considers different forms of potential energy. By influencing the formation, oil or gas production can be increased. The concept of formation regime characterizes certain features of the formation's behavior, but is not sufficient to fully understand the system. Elasticity of the fluid and formation plays a significant role in the formation regime. The movement of fluid in a well is initiated by the elastic deformation of the fluid and formation, starting from the bottom and extending to remote areas. In oil fields with abnormal fluids, pressure decreases can result in significant extraction of oil due to volumetric elasticity, then not only the elastic reserve of the liquid and the reservoir would be zero, but also the redistribution of pressure in the reservoir would occur instantly.

2. Rheological Model

Academician A.Kh.'s works have made significant contributions to both scientific and practical aspects. One important finding of the research is the gradual decrease and stabilization of pressure in a vessel filled with a viscoelastic fluid over time. The rate of pressure drop and the difference between initial and final values depend on the initial value and rheological properties of the elastic system.

Experimental results show improved hydrodynamic properties of non-Newtonian oil. Additionally, a "residual memory" of viscoelastic properties is discovered after a brief period of oil unloading. Elastic visco-plastic fluids are utilized in three main areas of oil and gas production: diagnostics and application, determination and regulation of properties, and development of a model describing fundamental properties.

In recent years, the global oil and gas industry has seen an increase in the exploitation of viscous oil fields, resulting in a rise in the production of anomalous Penytonian oils. This presents challenges in the extraction process. High-viscosity oils, especially those with elastic-visco-plastic properties, have more complex rheological characteristics. Such oils have been discovered in various regions including Central Asia, Azerbaijan, Komi, Tataria, South Africa, Egypt, etc.

Academician A.H. Mirzajanzadeh's work introduces a new application of elastic liquids. The author demonstrates that when a viscoelastic liquid flows out of a pipe, the diameter of the flowing jet surpasses the pipe's diameter by 3-4 times. This effect presents challenges in detailed process description. The theory suggests that this phenomenon may arise due to the combination of fluid elasticity and the converging nature of streamlines at the pipe's entrance.

Field analysis shows that incorporating high molecular weight polymer compounds in cement solutions enhances the displacement of clay solutions to the well by cements. This results in elastic-visco-plastic properties in the cement mortar due to the addition of polymer compounds, leading to wall slip at the pipe walls. This property alters the velocity distribution diagram at the fluid interface.

Laboratory studies reveal that the presence of normal stresses and sliding velocities in elastic-visco-plastic solutions ensures complete displacement of clay solutions from the wellbore cover and eccentric space. These properties in cement mortars can be achieved by adding water-soluble polymer additives. The use of this fluid as a separator between cement and clay mortars significantly improves the completeness of clay mortar displacement. Notably, incorporating an elastic-visco-plastic fluid as a plug during the drilling process is highly recommended. Flushing wells in the presence of this plug before cementing enhances hole cleanliness and well strengthening. The elastic-visco-plastic properties of the liquid increase the transverse dimensions of the jet and ensure a more comprehensive coverage of well and formation cross-sections. Research has shown that the filtration rate of an elastic-visco-plastic fluid can be expressed as:

$$\nu = -\frac{k}{\mu}\left(\frac{1}{\rho\beta}\frac{d\rho}{dx} - i_0\right) \quad (1)$$

Taking into account boundary conditions (3), this formula can be written as:

$$Q = \frac{kF}{\mu}\left(\frac{1}{\beta L}\ln\frac{\rho_k}{\rho_z} - i_0\right) \quad (2)$$

The analysis indicates that the design and control of oil and gas field development, as well as the operation of underground storage facilities, are closely linked to determining reservoir properties and studying filtration parameters. This necessitates a detailed assessment of formation heterogeneity, including thickness, area, lithological and tectonic screens. Numerous studies in the literature have addressed this scientific problem (Mirzajanzade A.Kh, 1997; Masket 2004; Shchelkachev, 2001).

It is important to note that hydrodynamic methods for studying formations and wells, involving the measurement of formation and bottomhole pressures, are referred to as piezometric methods. There are two main types of well studies: steady-state and non-steady-state modes. Methods based on the study of unsteady processes of bottomhole pressure changes are closely related to the theory of elastic regime. Additionally, when considering viscous-plastic fluids, the filtration process and pipe movement are altered. During well start-up or shutdown, a long-term regime arises, characterized by pressure redistribution in both the riser pipes and the porous medium.

By using self-recording downhole pressure gauges, pressure fluctuations in the wellbore can be recorded and a pressure recovery curve can be constructed. Commonly, when conducting hydrodynamic studies, bottomhole pressure recovery is observed after shutting down a well that has been operating with a constant flow rate for an extended period. This can be determined using formula (2).

The shape of the pressure build-up curve is influenced by reservoir properties, pipe design, fluid properties, and other factors. From the shape of the recovery curve, parameters such as permeability, piezoelectric conductivity, and the skin effect can be determined, as well as the additional filtration resistance caused by well and bottom-hole zone characteristics. To facilitate data processing, pressure recovery graphs are often transformed, changing their curvilinear shape to a straight line.

Foreign literature sources (Ikoku, 1979; Joshi, 1991) indicate that the most commonly used method for determining well and reservoir parameters based on pressure recovery data is the construction of a converted pressure recovery graph in semi-logarithmic coordinates (pressure drop versus logarithmic time), resulting in a straight line relationship. Based on the theory of elastic-visco-plastic fluid, functional relationships between bottomhole pressure dynamics and time since the well was put into operation with a constant flow rate can be derived (Marl, 1965).

$$\Delta P = P_k - P_c = \frac{Q\mu}{2\pi kh}\left[-E_i\left(-\frac{r_c^2}{4\eta t}\right)\right] = \frac{Q\mu}{4\pi kh}\left(\ln\frac{4\eta t}{r_c^2} - 0.5722\right) = \frac{Q\mu}{4\pi kh}\left(\ln\frac{4\eta t}{r_c^2} - \ln 1.781\right) = \frac{Q\mu}{4\pi kh}\left(2.2\lg\frac{4\eta t}{1.781 r_c^2}\right)$$

$$= 0.1832\frac{Q\mu}{kh}\lg\frac{2.246\eta t}{r_c^2} \quad (3)$$

It should be noted that the last expression can be rewritten in another form:

$$\Delta P = 0.1832\frac{Q\mu}{kh}\lg\frac{2.246\eta}{r_c^2} = 0.1832\frac{Q\mu}{kh}\lg t \quad (4)$$

Or more simply:

$$\Delta P = A + B\lg t \quad (5)$$

$$A \quad B\lg\frac{2246\eta}{r_c^2} \qquad B \quad 01832\frac{Q\mu}{kh}$$

From these formulas it is clear that the change in bottomhole pressure in a working well with a constant flow rate of the production well is a linear function of the logarithm of time. Considering these conditions, we can say that the graph of changes in bottomhole pressure after putting a well into operation, determined by formula (5), is a straight line taking into account the physical properties of oil(Timmerman,1982).

For some conditions, it is necessary to determine the recovery curve, that is, the change in bottomhole pressure after the well is shut down.

We assume that before shutting down a well operating for a long time with a constant flow rate and physical properties of oil, there was a steady distribution of reservoir pressure around the well in the formation:

$$P = P_c + \frac{Q\mu}{2\pi kh}\ln\frac{r}{r_c} \quad (6)$$

Or

$$P = P_k - \frac{Q\mu}{2\pi kh}\ln\frac{R_k}{r} \quad (7)$$

In this case, the piezometric line is a logarithmic type curve. The instantaneous shutdown of a production well at moment t=0 is simulated by turning on a fictitious source with a flow rate located at a given point in the formation.

To compare data from different fluids, we present numerical problems based on data borrowed from work 3. Let us assume that a homogeneous fluid with Newtonian properties is moving in a given formation.

Example 1.

$$k = 1\text{Darcy} = 10^{-12}\text{m}^2;$$

$$\mu = 1\text{spz};$$

$$\Delta P = 10^6\frac{\text{kg}}{\text{m}^2};$$

$$F = 100\text{m}^2;$$

$$\mu = 1\text{spz} = 10^{-14}\frac{\text{kg}\cdot\text{s}}{\text{m}^2};$$

$$\eta = \mu;$$

$$L = 1000\text{m};$$

As the calculation equation:

$$\ln\frac{\rho_k}{\rho_z} = (P_k - P_z);$$

$$Q = \frac{kF}{\mu}\frac{P_k - P_z}{L} = \frac{kF}{\mu}\frac{\Delta P}{L}$$

Example 2.

According to the above data, a viscous-plastic fluid moves in a homogeneous formation. Let us determine the reservoir flow rate under these conditions. After simplifications, the filtration equation for viscoplastic liquids can be written as , where, for oils.

Substituting the numerical values of the previous problem, we have

$$Q = \frac{10^{-12}\text{m}^2\cdot 100\text{m}^2}{10^{-4}\frac{\text{kg}\cdot\text{s}}{\text{m}^2}}\frac{(100-12)\cdot 10^4\frac{\text{kg}}{\text{m}^2}}{1000\text{m}} = 0.00088\frac{\text{m}^3}{\text{s}} = 76.03\frac{\text{m}^3}{\text{d}}$$

Example 3.

Using the specified data, we add the coefficient of volumetric elastic expansion of the liquid to the calculation formula. According to the works of V.N. Tselkachev, this parameter on average can be taken as. Then, according to the laws of hydraulics, we have

$$\begin{aligned} Q &= \frac{kF}{\eta}\left[\frac{P_k - p_z}{L}(1+\beta\bar{P}) - i_0\right] \\ &= \frac{10^{-12}\text{m}^2\cdot 100\text{m}^2}{10^{-4}\frac{\text{kg}\cdot\text{s}}{\text{m}^2}}\left[\frac{100\cdot 10^4\frac{\text{kg}}{\text{m}^2}}{1000\text{m}}\left(1 + 10^{-4}\frac{\text{m}^2}{\text{kg}}\cdot 20\cdot 10^4\frac{\text{kg}}{\text{m}^2}\right) - \frac{12\cdot 10^4\frac{\text{kg}}{\text{m}^2}}{1000\text{m}}\right] \\ &= \frac{10^{-12}\text{m}^2\cdot 100\text{m}^2}{10^{-4}\frac{\text{kg}\cdot\text{s}}{\text{m}^2}}\left[1000\frac{\text{kg}}{\text{m}^3}\cdot 20 - 120\frac{\text{kg}}{\text{m}^3}\right] = 0.00188\frac{\text{m}^3}{\text{s}} = 162.43\frac{\text{m}^3}{\text{d}} \end{aligned}$$

3. Conclusions

(1) The elastic energy reserve in the formation, which refers to the amount of liquid extracted when pressure decreases due to volumetric elasticity of the fluid and formation, can be significant.

(2) If both the formation and the fluid saturating it were completely incompressible, not only would the elastic reserve of fluid in the formation be zero, but there would also be instant redistribution of pressure, resulting in decreased coverage of the formation.

(3) When an elastic formation and the fluid saturating it have very small coefficients of volumetric elasticity, the process of pressure redistribution in the formation takes a long time, which partially increases the oil recovery of formations with non-Newtonian oils.

(4) The duration of pressure redistribution in the reservoir is due to the specific nature of filtration, which is directly influenced by resistance forces during the movement of viscous-plastic fluid in the reservoir.

4. Notations

ν – filtration speed;

k – formation permeability relative to elastic-visco-plastic fluid;

μ – structural viscosity of this liquid;

ρ – density of liquid;

β – coefficient of volumetric elastic expansion of liquid;

– initial shift gradient;

Q – volumetric flow rate of liquid;

F– cross-sectional area of the formation;

– fluid density at the formation feeding office;

– fluid density at the entrance to the gallery (that is, at the exit from the formation);

L– length of the layer;

– reduced radius of the well;

h – reservoir thickness;

η – piezoelectric conductivity coefficient;

t – time;

– contour or reservoir pressure;

– bottomhole pressure.

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