

The effect of injection speed on the law of heavy oil initiation and seepage flow research

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Abstract. In order to make the heavy oil flow, the repulsion pressure gradient should be larger than the start-up pressure gradient. The results show that the smaller the injection speed is, the smaller the start pressure gradient is, and the subsequent seepage process has a smaller and smoother replacement pressure gradient, and there is an effective limit of the start pressure gradient. Using the non-stationary method to calculate the relative oil-water permeability and water saturation, the bound water saturation does not differ much with increasing injection speed, and the residual oil saturation increases. Therefore, in order to start the heavy oil more easily in the mine production can be started at a lower production rate, the study of injection speed is important for the heavy oil start-up and development effect.

Keywords: Heavy oil; injection speed; initiation pressure gradient; seepage characteristics.

1. Introduction

At present, heavy oil resources account for about two-thirds of the global oil and gas resources reserves[1]. The development of heavy oil reservoirs occupies a very important position in the development of China's oil fields and has a high development potential.[2] The development of heavy oil reservoirs occupies a very important position in the development of China's oil fields and has high development potential. Although China's heavy oil reservoir resources are abundant, the reservoir environment is complex, with high viscosity, poor mobility, low permeability, and low reservoir permeability.[3][4] It is characterized by low permeability and complex pore structure of the reservoir. Heavy oil is rich in gum, asphaltene and other macromolecular compounds, and the molecular structure of heavy oil is an inhomogeneous colloidal dispersion system, which leads to the characteristics of heavy oil fluids with high viscosity and non-Newtonian fluid characteristics in the flow, and the seepage characteristics in porous media are different from those of conventional crude oil, and the seepage law changes, generally showing non-linear seepage^[5]. There may be a start-up pressure gradient, and the heavy oil can start to flow only when the displacement pressure gradient exceeds the start-up pressure gradient.[6][7] The start-up pressure gradient may exist. The domestic research on heavy oil start-up pressure gradient is limited but not deep enough, although the relationship between start-up pressure gradient and flow in heavy oil reservoirs of low permeability carbonate rocks has been explained^[8], but there is a lack of research on the law of the effect of injection speed on heavy oil

start-up and and seepage flow, while start-up pressure gradient is an important link to study nonlinear seepage flow. At present, the methods to measure the start-up pressure gradient of heavy oil include indoor physical simulation experiments, numerical experiments and well test interpretation. The main methods to measure the start-up pressure by indoor physical simulation experiments are: steady-state method, unsteady-state method, capillary equilibrium method, bubble method, etc.[9][10][11] Compared with other methods, the bubble method is faster and more accurate. In this experiment, the bubble method is used to determine the pressure gradient of heavy oil start-up pressure. Then the relative permeability curve is calculated by the non-stationary method.^{[12][13]} The study of oil-water phase permeability law is the key to reservoir development. The study of the effect of injection speed on the start-up and seepage of heavy oil is important for the efficient development of heavy oil reservoirs, which can improve the production and recovery of heavy oil^[14], and also provide the theoretical basis for the development of reasonable heavy oil reservoir exploitation plan in the later stage.

2. Bubble method experiment

2.1 Experimental apparatus and materials

Experimental instruments: artificial core making device, Jiangsu Hongbo Machinery Manufacturing Co., Ltd; advection pump, Shanghai Sanwei Scientific Instruments Co., Ltd; sand filling tube, Nantong Xinhua Cheng Scientific Research Instruments Co., Ltd; constant

temperature box (HX- II type), Nantong Huaxing Petroleum Instruments Co., Ltd; electronic balance, intermediate vessel, etc.

Experimental materials: simulated formation water, formation dewatered crude oil (a domestic oil field, basic properties as shown in Table 1), petroleum ether, kerosene, etc.

Table 1. Basic data of heavy oil test samples

number	Sampling wells	Saturation fraction/%	Aromatic fraction/%	Coll oid %	Asphal tene %	Viscosity (50°C)/mPa·s
1#	EZwell	47.65	15.49	19.09	0.48	328

The physical parameters of the artificial cores are shown in Table 2.

Table 2. Table of core physical parameters

Artificial rock core	Length/cm	Diameter/cm	Porosity/%	Permeability/ $\times 10^{-3} \mu\text{m}^2$
Meso-osmosis	40	2.5	39.8	500

2.2 Experimental methods

(1) Injection speed determination

According to the actual production of the reservoir, the seepage velocity at the casing section of the well was taken as the basis for the injection velocity of the sand-filled pipe experiment, and the variation of fluid seepage velocity with radius at the section around the well was calculated as shown in Figure 1. By comparing the experimental settings of injection speed and seepage velocity (Figure 2), the injection speed was set to 0.25 mL·min⁻¹, 0.5 mL·min⁻¹, and 1 mL·min⁻¹.

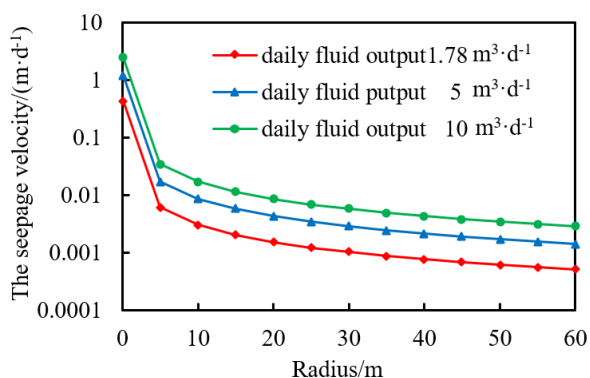


Figure 1. Variation of fluid seepage velocity with radius in the stratigraphic section around the well

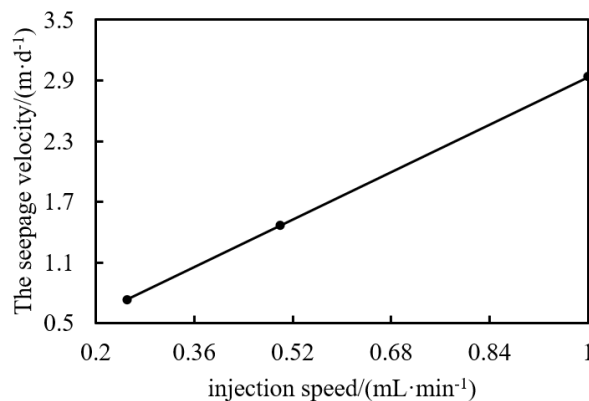


Figure 2. Experimental setup of injection velocity versus seepage velocity

(2) Start-up stress test method

In this experiment, the bubble method (Figure 3) is used. By setting a certain injection speed to repel the core, a small amount of liquid is injected into the line at the outlet end to form droplets (using methyl blue staining for easy observation), and when the droplets in the line start moving, the pressure at the injection end is read as the initiation pressure and the time used is the initiation time.



Figure 3. Air bubble method to measure the starting pressure

(3) Experimental protocol

Three sets of injection speeds were set: 0.25 mL·min⁻¹, 0.5 mL·min⁻¹, and 1 mL·min⁻¹ to investigate the effect of injection speed on the start-up and seepage characteristics of heavy oil.

2.3 Experimental steps

The experimental flow chart is shown in Figure 4, and the experimental steps are.

- (1) Record the basic data of the selected sand-filled pipe core: length, cross-sectional area, etc.
- (2) The fabricated sand-filled tube model was placed on an electronic scale, weighed, and the dry weight was recorded.
- (3) Place the sand-filled tube in a thermostat, constant temperature at 30°C, add back pressure at the outlet end, inject saturated water at the injection speed of 0.25 mL·min⁻¹ until the pressure gradient is stable, then record the pressure difference and put it on an electronic scale and weigh the wet weight.
- (4) Put the sand-filled tube core in the thermostat again for saturated oil operation until no water comes out at the outlet, at which time the water in the sand-filled tube model is the bound water, and the volume of the water driven out is the volume of saturated in oil.

(5) In the thermostat, the injection speed was set to $0.25 \text{ mL}\cdot\text{min}^{-1}$, $0.5 \text{ mL}\cdot\text{min}^{-1}$, and $1 \text{ mL}\cdot\text{min}^{-1}$ in order to repel the cores, and the starting pressure gradient and starting time were measured by the bubble method and recorded.
 (6) The temperature of the thermostat was kept at 30°C , the permeability of the core was $500 \times 10^{-3} \mu\text{m}^2$, and the saturated core of 1# oil sample (viscosity $936 \text{ mPa}\cdot\text{s}$ at 30°C) was selected, and the injection speeds were set to $0.25 \text{ mL}\cdot\text{min}^{-1}$, $0.5 \text{ mL}\cdot\text{min}^{-1}$, and $1 \text{ mL}\cdot\text{min}^{-1}$, respectively. The oil and fluid production were recorded by a stopwatch, a pressure transducer, and a measuring cylinder.

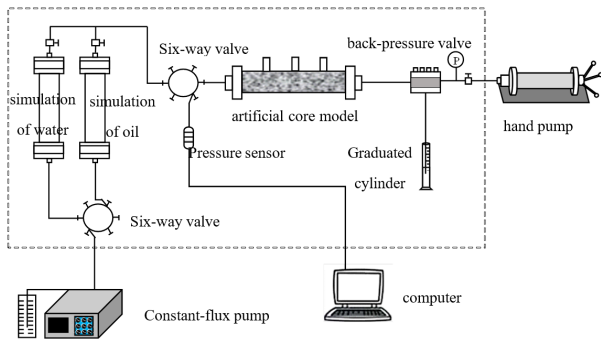


Figure 4. Experimental flow chart

3. Experimental results and discussion

3.1 Influence of different injection speeds on the start-up of heavy oil

The experimental results are shown in Figure 5. It can be seen that, in the core of the same permeability, with the increase of injection speed, the start-up time of heavy oil decreases, and the decrease increases gradually; while the start-up pressure gradient increases with the increase of injection speed, and the increase of magnitude also increases accordingly; when the injection speed increases from $0.25 \text{ mL}\cdot\text{min}^{-1}$ to $0.5 \text{ mL}\cdot\text{min}^{-1}$, the change of start-up pressure gradient and start-up time is small, but from $0.5 \text{ mL}\cdot\text{min}^{-1}$ to $1 \text{ mL}\cdot\text{min}^{-1}$, the starting pressure gradient increased by 9.8 times and the starting time decreased by only 1.3 times, indicating the existence of an effective starting pressure gradient limit.

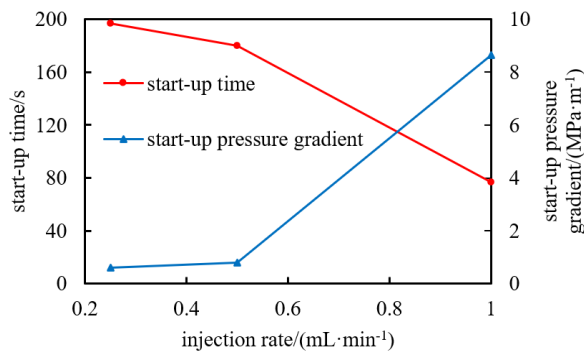
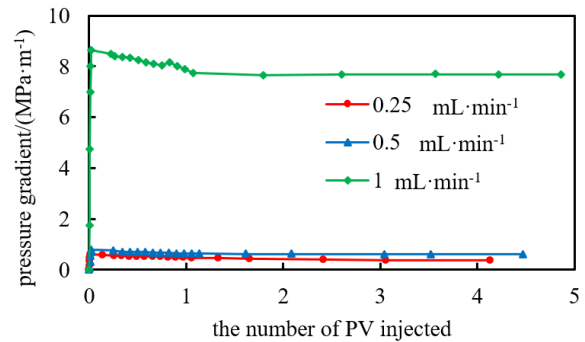


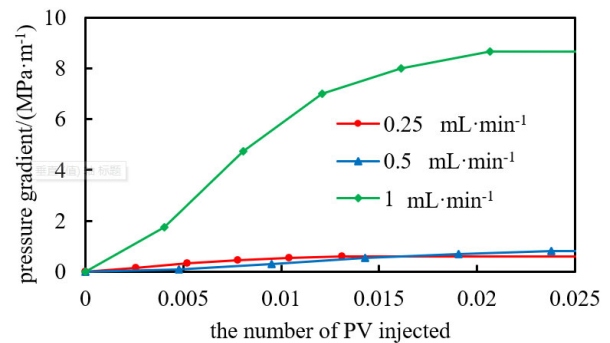
Figure 5 Start-up of heavy oil at different injection speeds

Figure 6 shows the changes of the repulsion pressure gradient with the number of PV injected at different injection speeds when the permeability is certain, it can be seen that as the number of PV injected increases the pressure gradient gradually rises to the maximum value and then begins to decline, and after reaching a certain magnitude, it gradually stabilizes. This indicates that the heavy oil has not yet started at the beginning, when the repulsion pressure gradient is larger than the heavy oil start pressure gradient, the heavy oil starts to start, and after starting the repulsion pressure gradient starts to decline and gradually reaches a stable level; and the larger the injection speed, the larger the pressure gradient at stabilization.

As in the heavy oil flow, heavy oil flow resistance mainly comes from internal friction (between oil molecules, between gum molecules, between asphaltene dispersion phase, between oil molecules and gum molecules, between oil molecules and asphaltene dispersion phase, etc.) and interfacial tension^[15]. In the heavy oil from stationary to flowing state, the frictional resistance changes from static friction to kinetic friction, and the molecular structure in the heavy oil is damaged to a certain extent, so that the kinetic friction is smaller than the static friction, so after the heavy oil is started, the repulsion pressure gradient needs to drop by a certain amount.



(a) Repulsion process



(b) Start-up process

Figure 6. Variation of repulsion pressure gradient at different injection speeds

Figure 7. shows the relationship between the ramp-up rate and pressure gradient in the ramp-up stage. It can be seen that there is a good linear relationship between the pressure gradient and the ramp-up rate, indicating that when the ramp-up rate is too fast, the heavy oil in the core does not have time to flow, resulting in a higher start-up pressure. In order to be able to start the heavy oil more easily in the mine production can be started at a lower production rate.

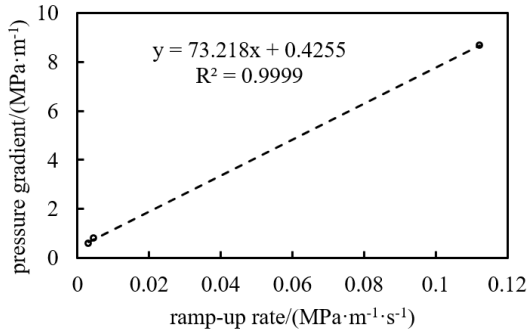


Figure 7. boost rate versus pressure gradient

3.2 Influence of injection speed on the seepage characteristics of heavy oil

The relative permeability curves calculated using the non-stationary method are shown in Figure 8. It can be seen that: with the increase of injection speed, the iso-permeability point of oil-water relative permeability curve moves to the left and the two-phase co-permeability zone decreases. Figure 9 shows the bound water saturation and residual oil saturation at different injection speeds. It can be seen that the bound water saturation does not differ much with the increase of injection speed, and the residual oil saturation increases.

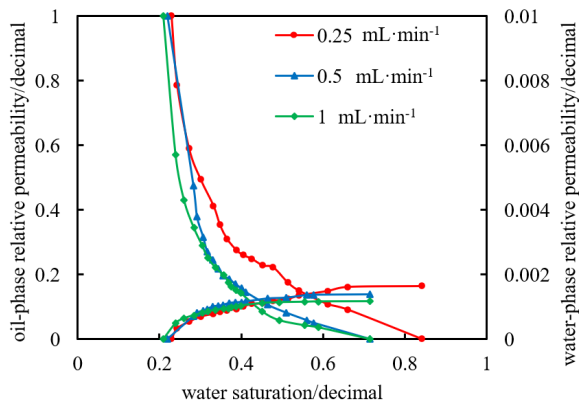


Figure 8. Oil-water relative permeability curves at different injection speeds

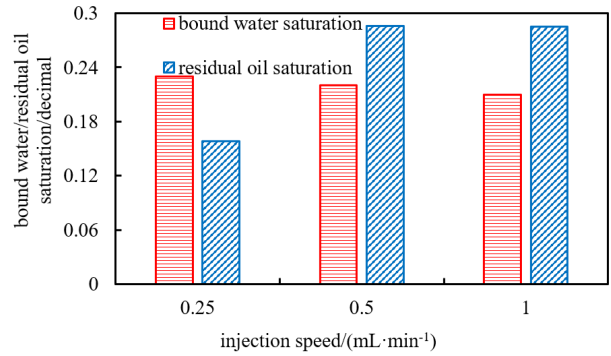


Figure 9. Bound water saturation and residual oil saturation at different injection speeds

Figure 10 shows the time to see water and the degree of water-free recovery at different injection speeds, and Figure 11 shows the recovery rate at different injection speeds. It can be seen that as the injection speed increases, the time to see water becomes shorter, the water-free recovery rate first becomes faster and then stabilizes, and the water drive recovery rate decreases. Since the larger the injection speed, the larger the corresponding replacement pressure difference, the faster the advancement speed of the leading edge of the water drive, and the faster the time to water.

Therefore, the injection speed (replacement pressure difference) should be properly controlled to slow down the advancing speed of the leading edge of the water drive, so as to increase the wave area and achieve late water or low water content in the recovery fluid as much as possible, thus indicating that a reasonable injection speed is conducive to improving the recovery rate of heavy oil reservoirs.

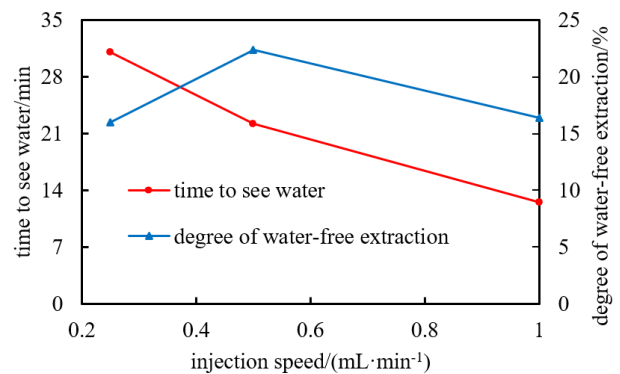


Figure 10. Time to see water and degree of water-free extraction at different injection speeds

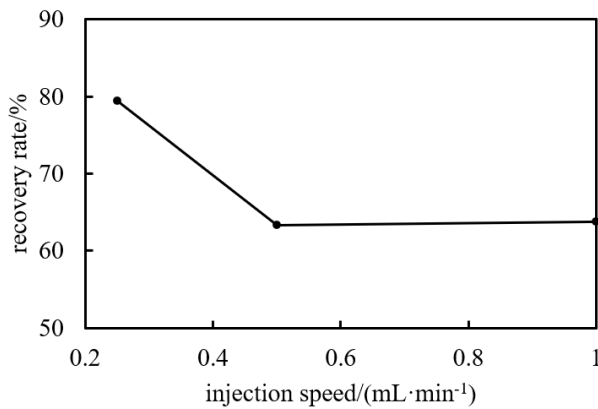


Figure 11. Recovery rate at different injection speeds

4. Conclusion

The indoor sand-filled pipe replacement experiment simulates the start-up process and seepage development effect of heavy oil under certain environment, and the experimental results show that.

(1) The smaller the injection speed, the smaller the start-up pressure gradient, and the smaller and smoother the repulsion pressure gradient in the subsequent seepage process. There is a good linear relationship between the pressure gradient and the ramp rate at different injection speeds. When the ramp rate is too fast, the heavy oil in the core does not have time to flow, resulting in a higher start-up pressure. In order to start the heavy oil more easily in the mine production, it can be started at a lower production rate.

(2) Using the non-stationary method to calculate the oil-water relative permeability curve, the heavy oil percolation law deviates from Darcy's law, and the oil drive efficiency becomes better as the injection speed decreases, which is expressed in the phase percolation curve as the area of oil-water two-phase co-percolation zone increases, the bound water saturation does not differ much, and the residual oil saturation decreases. Try to achieve late water or low water content in the recovery fluid, while a reasonable injection speed is beneficial to improve the recovery rate of heavy oil reservoir.

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