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RESEARCH ARTICLE

Study on the Flow Characteristics of Shengli Oilfield Super Heavy Oil

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Abstract:

Objective:

The rheological properties of oil severely affect the determination of percolation theory, development program, production technology and oil-gathering and transferring process, especially for super heavy oil reservoirs. This paper illustrated the basic seepage morphology of super heavy oil in micro pores based on its rheological characteristics.

Methods:

The non-linear flow law and start-up pressure gradient of super heavy oil under irreducible water saturation at different temperatures were performed with different permeable sand packs. Meanwhile, the empirical formulas between start-up pressure gradient, the parameters describing the velocity-pressure drop curve and the ratio of gas permeability of a core to fluid viscosity were established.

Results:

The results demonstrate that temperature and core permeability have significant effect on the non-linear flow characteristics of super heavy oil. The relationship between start-up pressure gradient of oil, the parameters representing the velocity-pressure drop curve and the ratio of core permeability to fluid viscosity could be described as a power function.

Conclusion:

Above all, the quantitative description of the seepage law of super heavy oil reservoir was proposed in this paper, and finally the empirical diagram for determining the minimum and maximum start-up pressure of heavy oil with different viscosity in different permeable formations was obtained.

Keywords: Super heavy oil, Non-linear flow, Velocity-pressure drop curve, Start-up pressure gradient.

1. INTRODUCTION

Heavy oil is a strategic source of hydrocarbons as the reserves are of the same order of magnitude as that of the conventional oil. However, the incredible low production and enormous challenge in transporting the heavy oil contrasts with the increase demand obviously, especially because of their very high viscosity and special flow characteristics in the porous media. To determine how to improve the current development technology and enhance the heavy oil recovery, knowledge of rheology and flow characteristic of heavy oil are required.

The rheology of oil has been studied by many researchers in order to design and operate heavy oil production systems efficiently. Regarding pressure, temperature and emulsion stabilities, a number of experiments with live-oil and dry oil samples were conducted to test the oil viscosity under different conditions and obtain the inversion point. The measured viscosities varied with temperature while it kept constant within the range of tested flow rates, suggesting that fluids were Newton. With more comprehensive study on emulsion rheology, the effect of emulsion viscosity on the multiphase flow of the produced stream was investigated [1, 2].

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Besides, to understand the rheology of heavy crude oil better, the presence of polar material such as asphaltene and resin in heavy oil was also studied in detail [3 - 5].

The non-Newtonian behavior of heavy crude oil is a well-known phenomenon, which has been the studying focus in the reservoir engineering for a long time [6 - 9]. Considering the inertial losses, the law for the flow of viscous plastic fluids in porous media was established [10]. The common relation between flow rate and pressure drop which was used for different simulations of heavy oil recovery in real reservoirs was obtained. Furthermore, exhaustive research on the relations among start-up pressure gradient of heavy oil, the parameter describing velocity-pressure drop curve and the ratio of permeability measured with gas to fluids viscosity [11 - 14] has been shown in the previous studies. But few studies have been conducted for super heavy oil, let alone that on the rheological behavior of the oil.

The objective of this paper is to study on the flow characteristics of super heavy oil in the porous media based on its rheological behavior at different temperatures, such as start-up pressure gradient and velocity-pressure drop curve. To acquire the diagram for determining the minimum and maximum start-up pressure with different oil viscosities in different reservoirs, regression analysis on experimental results was accomplished necessarily.

2. STUDY ON THE RHEOLOGY OF SUPER HEAVY OIL

Theoretical Analysis Rheology describes the relationship between shear rate and shear stress for fluid flow, which can be applied to determine the fluid type. Considering the importance of rheology utilized in various aspects, capillary model shown in Fig. (**1**) was adopted to analyze the rheological mechanism.

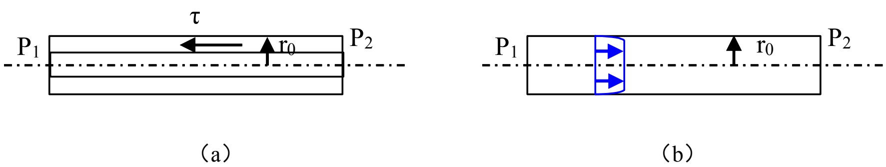

Fig. (1). Capillary Model.

2.1. Flow Characteristic of Bingham Fluid in Single Capillary

For the impressed pressure is equal to the friction of fluid flows in the capillary

$$\tau = -\frac{r}{2}\frac{dp}{dL} \quad (1)$$

where r is the radius of the capillary;

τ is yield stress.

Under the same pressure gradient, the shear stress increases with distance from capillary center. The value of shear stress on the capillary wall is $\tau_w = -\frac{r_0}{2}\frac{dp}{dL}$. Besides, fluids begin to flow in the capillary only when τ_w is larger than τ_0. And mobile fluids will increase with the increase of pressure gradient in the capillary.

2.2. Flow Rate

There is no shear stress within the radius range of r_p in the capillary,

$$\tau_o = -\frac{r_p}{2}\frac{dp}{dL} \quad (2)$$

The shape of velocity distribution in capillary shown in Fig. (**1a**) is like a paraboloid. This means velocity in single capillary can be derived from (Fig. **1b**)

$$v = \frac{r_i^2}{8\mu_p}\left(-\frac{dp}{dL}\right)\left[1 - \frac{4}{3}\frac{2\tau_0/r_i}{-dp/dL} + \frac{1}{3}\left(\frac{2\tau_0/r_i}{-dp/dL}\right)^4\right] \quad (3)$$

The start-up pressure can be calculated when the value of bracket mentioned above is zero.

$$\lambda = -\frac{dp}{dL} = \frac{2\tau_0}{r_i} \tag{4}$$

where, λ is start-up pressure.

The mean velocity in capillary tube can be obtained by utilizing V = θv and $K = \theta r_i^2/8$,

$$V = \frac{K}{\mu_p}\left(-\frac{dp}{dL}\right)[1 - \frac{4}{3}\frac{\lambda}{-dp/dL} + \frac{1}{3}(\frac{\lambda}{-dp/dL})^4] \tag{5}$$

2.3. Flow Characteristic of Bingham Fluid in Porous Media

It is generally known that the radius of capillary is inversely proportional to the value of minimum start-up pressure gradient and the velocity increases with the increase of pressure gradient in the same capillary. Presence of minimum start-up pressure can be found easily from Formula (5) when Bingham fluid flows in capillary. For the real reservoir, super heavy oil as a Bingham fluid is not able to flow in micro pores unless the pressure is larger than the minimum start-up pressure in the biggest capillary. And more fluid in smaller capillary is able to flow as the pressure gradient increases.

The math expressions of non-linear flow law for super heavy oil were established by regression analysis on many experimental results. And the formulas are as follows.

$$v = 0 \qquad \frac{\Delta p}{\Delta x} \le A \tag{6}$$

$$v = a(\frac{\Delta p}{\Delta x})^2 + b\left(\frac{\Delta p}{\Delta x}\right) + c \qquad A \le \frac{\Delta p}{\Delta x} \le C \tag{7}$$

$$v = \alpha\left(\frac{\Delta p}{\Delta x}\right) + \beta = \alpha(\frac{\Delta p}{\Delta x} - B) \qquad C \le \frac{\Delta p}{\Delta x} \tag{8}$$

where, v is fluid velocity, cm/min;

Δp/ Δx is impressed pressure gradient, MPa/cm;

A is the minimum start-up pressure gradient;

B is the threshold pressure, MPa/cm;

C is the maximum start-up pressure gradient;

μ is the fluid viscosity, mPa·s;

a, b, c are constant related with core permeability and fluid viscosity;

α,β respectively represent the slope and intercept of quasi linear.

In order to better divide the flow behavior for different stages in the real reservoir, such as non-linear flow, quasi-linear flow and Darcy flow, the velocity can be accurately calculated based on the formulas (6)-(8). Thus the parameters used in reservoir simulation will be real and effective.

Oil Sample Analysis To better reflect the characteristic of super heavy oil, a comparison between super heavy oil and heavy oil that mainly includes four components, oil viscosity and density was performed, of which the results are shown in Table (**1**). It is much easier to be found that there is an obvious difference in four components, especially the content of resin and asphaltene, leading the increase of super heavy oil viscosity by several orders of magnitude. And this may also be used to explain the characteristic of the rheological behavior of super heavy oil. Then to determine the fluid type of super heavy oil in terms of its rheology, experiments to study the relationship between shear stress and shear rate are conducted at different temperatures, whose results are shown in Fig. (**2**).

Table 1. Basic parameters of different oil

Oil type	Saturate	Aromatic	Resin	Asphaltene	μ_o, mPa.s	ρ_o, g/cm^3
Super heavy oil	16.17	30.68	39.33	13.82	237600	1.017
Heavy oil	45.21	38.72	12.3	3.77	352	0.872

Note: The oil viscosity was measured with the controlled shear rate rheometer (Brookfield R/S+) under 60 °C. And the oil density was tested with densitometer under 60°C.

It is observed from Fig. (**2a**) that the rheological curve of super heavy oil is a line disconnected with zero point, suggesting there is a certain yield stress. While Fig. (**2b**) shows that the lines pass through the origin. And the slope of these lines decreases as the temperature increases. To better understand the rheological behavior of different oils, the constitutive equations shown in Table (**2**) were derived by fitting rheological curves in Fig. (**2**). It can be easily found that the intercept of these lines with y-coordinate of super heavy oil decreases as the temperature increases until reaching 95°C, at which it can be taken as the inversion point for fluid becoming Newton. And the super heavy oil can be identified as Bingham fluid, for yield stress decreases with the increase in temperature. However, the heavy oil studied in this paper is Newton fluid when the temperature is higher than 60°C.

Table 2. Rheological equations of different oil at different temperatures

Temperature°C	Constitutive Equations	
	Super Heavy Oil	Heavy Oil
60	τ=237.6γ+17.56	τ=0.416γ
70	τ=71.70γ+7.758	τ=0.220γ
80	τ=25.13γ+2.862	τ=0.144γ
85	τ=15.84γ+1.368	τ=0.103γ
90	τ=10.28γ+0.448	τ=0.100γ
95	τ=6.92γ	τ=0.093γ

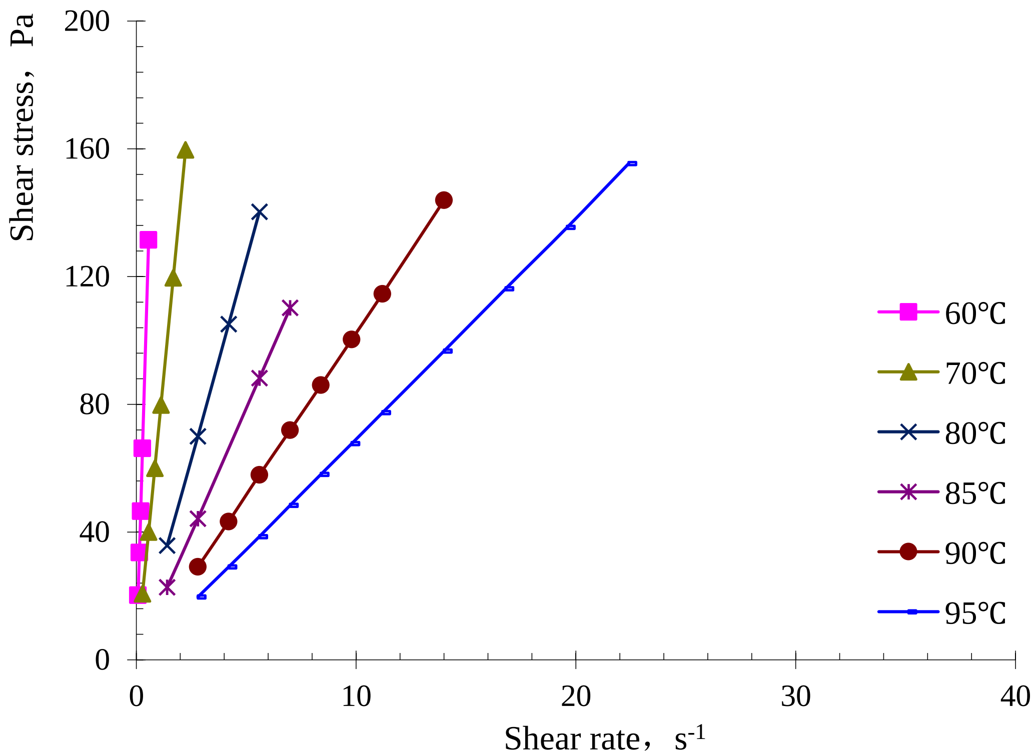

Fig. (2). Rheological curves of super heavy oil from Shengli Oilfield at different temperatures.

3. STUDY ON FLOW CHARACTERISTIC OF SUPER HEAVY OIL

Experimental Preparation and Method: The super heavy oil from Shengli Oilfield and formation water with 9569.64mg/L salinity were used in this paper. Steady state method and the capillary equilibrium method were applied to measure velocity-pressure drop curve and the start-up pressure of oil. The experimental flow chart is shown in Fig. (**3**).

The dotted line in the chart represents the incubator. The sand pack was water flooded with ISCO pump (Teledyne USA ISCO-A260D) at a certain flow rate and the pressure was recorded by computer after the system reached steadiness. Then conditions changed such as flow rate, temperature and sand pack permeability to obtain velocity-pressure drop curves.

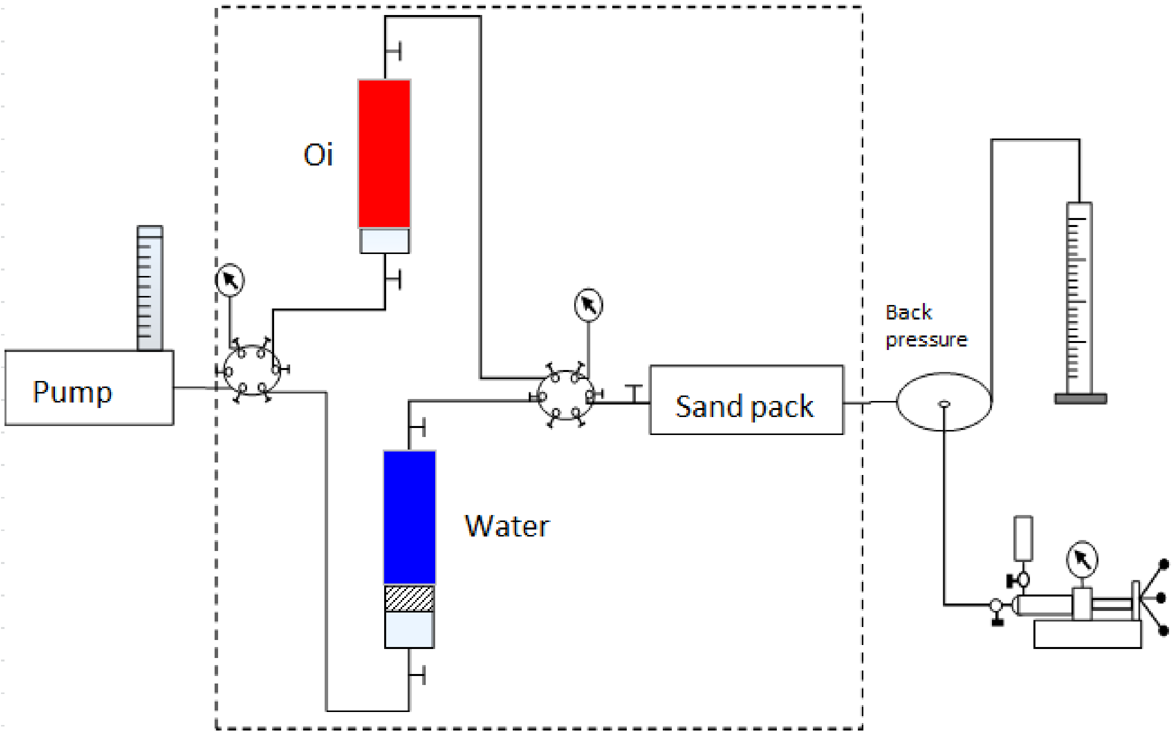

Fig. (3). Experimental flow chart.

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1. Velocity-Pressure Drop Curve at S_{wc}

The velocity-pressure drop curves were conducted with cores of different permeabilities($8000\times10^{-3}\mu m^2$, $2000\times10^{-3}\mu m^2$, $450\times10^{-3}\mu m^2$) at different temperatures (60°C ,80°C, 110°C ,140°C); the results are shown in Fig. (**4**).

For different permeable cores under less pressure gradient, the velocity can be expressed as $v = a(\frac{\Delta p}{\Delta x})^2 + b\left(\frac{\Delta p}{\Delta x}\right) + c$ and a concave-down non-linear segment emerges in the velocity-pressure drop curve. However, as pressure gradient increases to a certain value, the velocity-pressure drop curve appears as a line, where velocity can be expressed as $V = \alpha(\frac{\Delta p}{\Delta x} - B)$. Compared with the low permeability cores, the velocity-pressure drop curves of high permeability cores are of bigger slopes and shorter nonlinear segments. Besides, temperature has crucial influence on the length of non-linear segment, because of the decrease of percolation resistance and especially the sharp reduction of oil viscosity with temperature. Above all, both temperature and permeability have an obvious effect on the flow of super heavy oil.

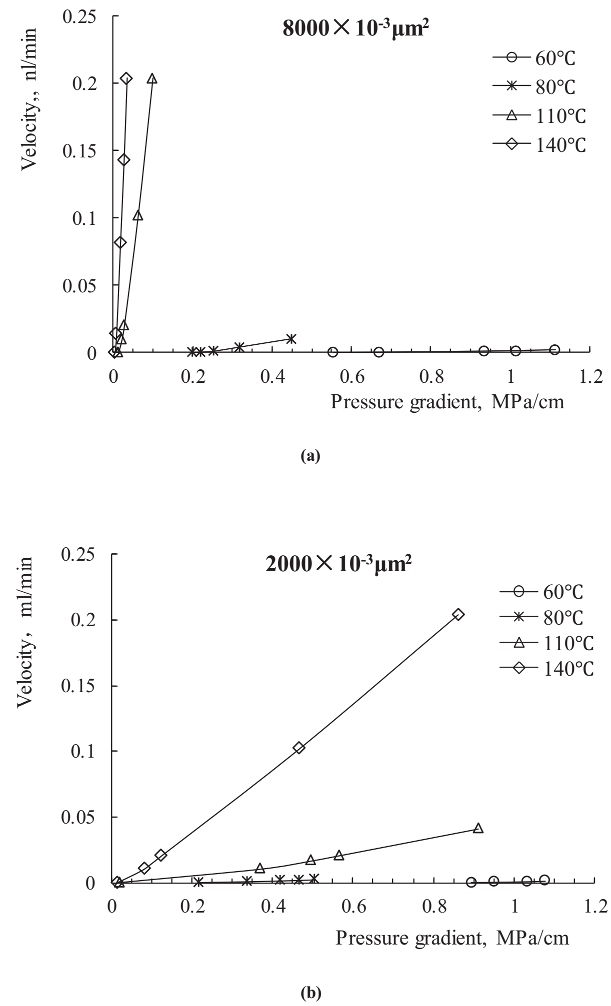

Fig. (4). Velocity-pressure drop curves with different permeable sand packs at different temperatures.

4.2. Minimum Start-up Pressure Gradient of Oil at S_{wc}

The result in Fig. (**5**) demonstrates that the relationship between minimum start-up pressure gradient and k_g/μ_o could be described as a power function, of which the correlation coefficient reaches to 93%. And the minimum start-up pressure gradient of oil has an inverse correlation to k_g/μ_o when its value is less than $0.1\times10^{-3}\times\mu m^2/(mPa.s)$.

According to Formula (8), the threshold pressure can be expressed as,

$$\left(\frac{\Delta P}{\Delta x}\right)_{\text{thres}} = \text{B} = \frac{\alpha}{\beta} \quad \textbf{(9)}$$

In order to make the derivative value to the pressure gradient of formula (7) and (8) equal, formula (10) can be deduced, based on the fact that the slope of linear and nonlinear segments of velocity-pressure drop curve is the same at the maximum start-up pressure gradient.

$$2\text{a}\left(\frac{\Delta p}{\Delta x}\right)_{max} + b = \alpha \quad \textbf{(10)}$$

The maximum start-up pressure gradient is

$$(\frac{\Delta p}{\Delta x})_{max} = \frac{\alpha - b}{2a} \tag{11}$$

Overall, both threshold pressure and the maximum start-up pressure gradient have a good correlation with k_g/μ_o, whose correlation also presents as a power function; the results are shown in Figs. (**6**) and (**7**), respectively. Besides, the experimental data of start-up pressure gradient are listed in Table **3**.

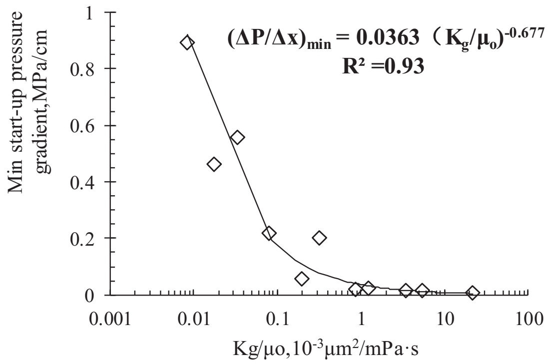

Fig. (5). Relationship between minimum start-up pressure gradient and kg/μo.

Table 3. Start-up pressure gradient with different oil viscosities in different permeable sand packs

Temperature °C	Kg ($10^{-3}\mu m^2$)	Viscosity mPa.s	Min Start-up Pressure Gradient (MPa/cm)	Threshold Pressure (MPa/cm)	Max Start-up Pressure Gradient (MPa/cm)
60	8000	237600	0.5559	0.7544	1.1857
	2000	237600	0.8933	—	—
80	8000	25127.5	0.1997	0.2331	0.2842
	2000	25127.5	0.2173	0.2903	0.4534
	450	25127.5	0.4640	0.5714	0.9643
110	8000	2258.3	0.0138	0.0260	0.0553
	2000	2258.3	0.0200	0.2194	0.5500
	450	2258.3	0.0553	0.1608	0.6739
140	8000	365.12	0.0050	0.0074	0.0143
	2000	365.12	0.0160	0.0485	0.1130
	450	365.12	0.0253	0.0385	0.3293

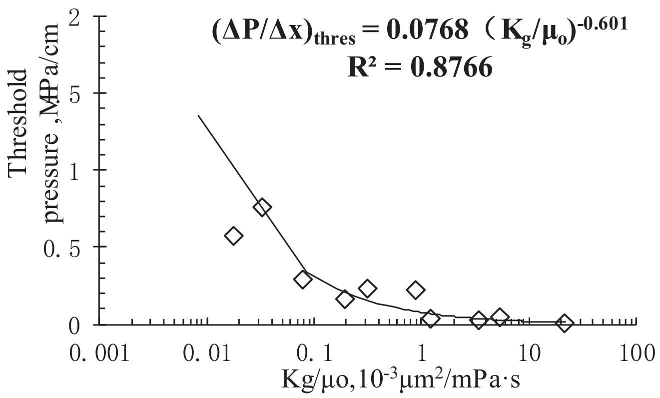

Fig. (6). Relationship between threshold pressure and kg/μo.

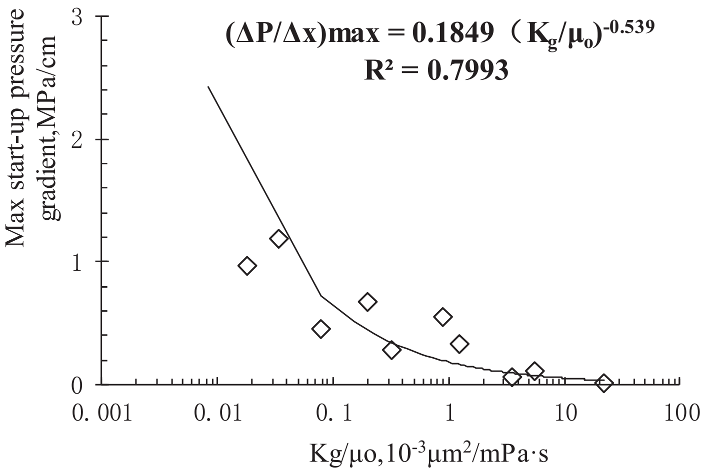

Fig. (7). Relationship between maximum start-up pressure gradient and kg/μo.

4.3. Regression Analysis on Experimental Result

According to formula (6)~(8), both groups of the parameters including a, b and c used to describe the nonlinear segment and α , β representing the linear segment are able to be obtained by fitting the non-linear and linear curve with quadratic function and linear function, of which the results are shown in Table **4**.

Table 4. Parameters of Velocity-pressure drop curves with different oil viscosities in different permeable sand packs

Temperature°C	Kg /($10^{-3}\mu m^2$)	Viscosity /mPa.s	Non-Linear Segment			Linear Segment	
			a	b	c	Slope α	Intercept β
60	8000	237600	0.0035	-0.0026	0.0003	0.0057	-0.0043
	2000	237600	0.0198	-0.0337	0.0143	—	—
80	8000	25127.5	0.2537	-0.097	0.0092	0.0472	-0.011
	2000	25127.5	0.0118	-0.0014	-0.0002	0.0093	-0.0027
	450	25127.5	0.0014	0.0001	-0.0004	0.0028	-0.0016
110	8000	2258.3	20.072	0.5354	-0.0115	2.7543	-0.0716
	2000	2258.3	0.042	0.0126	-0.0003	0.0588	-0.0129
	450	2258.3	0.0092	0.0218	-0.0012	0.0342	-0.0055
140	8000	365.12	230.02	0.7476	-0.0095	7.322	-0.0542
	2000	365.12	0.7338	0.0835	-0.0015	0.2493	-0.0121
	450	365.12	0.0583	0.1722	-0.0042	0.2106	-0.0081

In this paper, a large number of experiments were conducted, permeability was measured with perm-plug method and fluid viscosity was found to have an impact on the start-up pressure gradient of oil and the velocity-pressure drop curve shape. Therefore, the relational expressions between a, b, c, α, β and K_g / μ_o were established, whose results are shown in Table **5**. Then for a real heavy oil reservoir, velocity-pressure drop curve can be acquired by empirical formula mentioned above when the permeability and fluid viscosity are known.

Table 5. Character parameters of oil phase seepage at Swc

Describing parameters	Regression formulas at Swc	Correlation Coefficient
Min start-up pressure gradient (MPa/cm)	(ΔpL)min=0.0363(kgμo)-0.677	R2=0.93
Threshold pressure (MPa/cm)	(ΔpL)thres=0.0768(kgμo)-0.601	R2=0.8766
Max start-up pressure gradient (MPa/cm)	(ΔpL)max=0.1849(kgμo)-0.539	R2=0.7993
Non-linear segment	a=0.5139(kgμo)2-0.8114kgμo+0.7928	R2=0.9922
	b=-0.0016kgμo2+0.068kgμo-0.0035	R2=0.7406
	c=-0.002ln(kgμo)-0.0025	R2=0.4808
Quasi-linear segment	α=0.1658(kgμo)1.0607	R2=0.9097
	β=0.0127(kgμo)0.4599	R2=0.7775

4.4. Start-up Pressure Diagram for Super Heavy Oil

The theoretical template for determining the minimum and maximum start-up pressure gradient of super heavy oil is diagrammed in Fig. (**8**). And the flow area of reservoir can be divided into three parts: quasi-linear, non-linear and non-liquid parts, considering the decrease of pressure gradient along the distance from the well bottom. Incidentally, the difference between minimum and maximum start-up pressure gradient decreases with the increase of K_g/μ_0, which implies that the non-linear segment gets shorter with higher core permeability and lower oil viscosity.

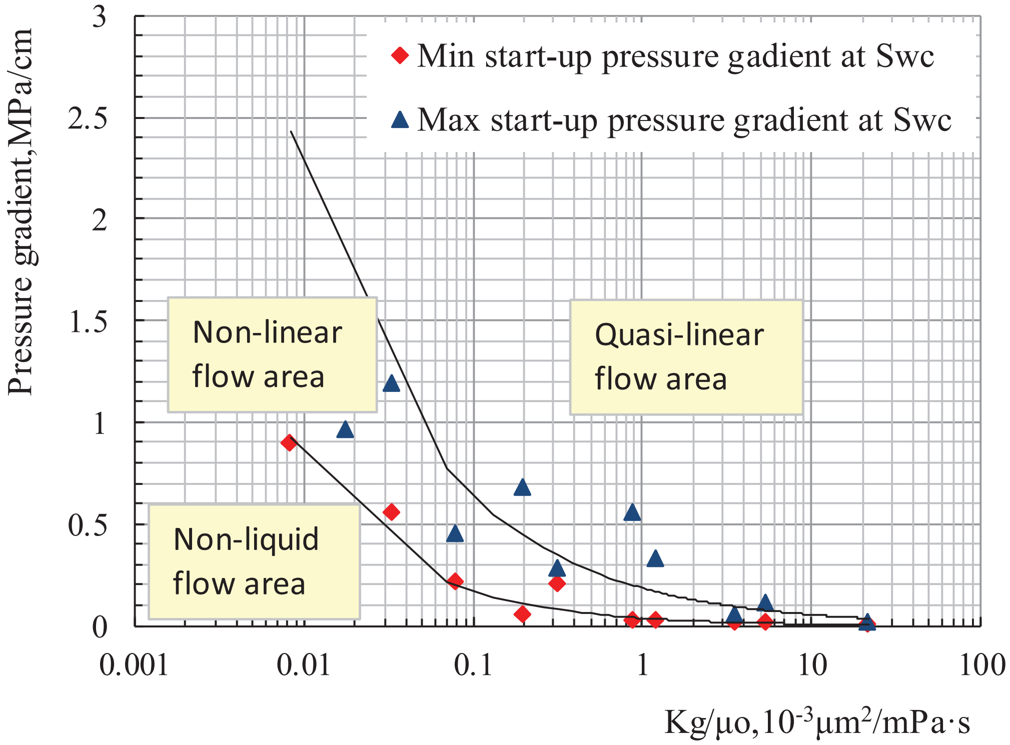

Fig. (8). Diagram for determining the min and max start-up pressure gradient of super heavy oil in different permeable reservoirs.

CONCLUSION

- Both permeability and temperature have significant impact on the flow of super heavy oil. And the relationship between velocity and pressure gradient in different stages was established in this paper.
- The value of k_g/μ_o has an inverse correlation with the percolation resistance, suggesting that the surface of solid has some influence on boundary layer fluids. And the relationship between kg/μo and the minimum, threshold and maximum start-up pressure gradient was described as a power function.
- The mathematical expressions for describing the relationship between k_g/μ_o and the minimum, threshold and maximum start-up pressure gradient of super heavy oil were first proposed in this paper. And the diagrams for the minimum and maximum start-up pressure gradient of super heavy oil in different permeable reservoirs were also obtained.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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