Typical Features Contrast of Hot Water Flooding and Steam Flooding

LI Fang-Fang[1,*], SHI Changlin[1], Yao Weiying[1], GAO Zhenglong[1], WU Wei[1] and LIU Shanshan[2]

[1]*CNOOC Ener Tech-Drilling and Production Co, 300452, Tianjin*

[2]*Drilling Fluid Division, Great Wall Drilling Company of CNPC, 100101, Beijing*

Abstract: Steam flooding and hot water flooding are the two main important thermal recovery methods for heavy oil reservoirs. Due to physicochemical properties difference of steam and hot water, the mechanism and production performance of hot water and steam flooding vary greatly. In this paper, steam and hot water flooding experiments under different temperature were conducted using Qi 40 heavy oil in Liaohe Oilfield in China to obtain typical features such as displacement efficiency, relative permeability, water cut and dimensionless productivity index of the two. The results show that steam and hot water flooding performance are quite different from each other under the same temperature. Compared with water flooding, displacement efficiency of steam flooding is 8.98%, 10.97% higher under 100℃ and 200℃ respectively, in addition, oil relative permeability is much higher and residual oil saturation is much lower at the same temperature. Water state and temperature are main reasons of displacement efficiency, relative permeability and productivity index difference; vapor state and higher temperature resulting in higher oil recovery, oil relative permeability and oil production index.

Keyword: Steam flooding, hot water flooding, relative permeability, water cut.

1. INTRODUCTION

There is abundant heavy oil reserves in China, and thermal enhanced recovery techniques such as steam and hot water flooding are widely used for heavy oil reservoirs (Wang Dawei, 2008). The main mechanisms of hot water flooding include: increase injection ability, reduce oil viscosity and remarkable thermal expansion (Cynthia Ross, 2008; Zhang Fangli, 2007). While for steam flooding except for the above mechanisms, steam distillation is another major mechanism, and its contribution to oil recovery can even higher than thermal expansion. What's more, wettability change, miscible displacement, oil emulsion can also contribute oil recovery (Harmsen, G. J, 1971; Zhang Yitang, 2006).

Due to the physicochemical properties difference between hot water and steam, the production performance of them may differ greatly. Hot water has favorable viscosity and density compared with steam, which can increase vertical and area sweep efficiency (Dong Xiaohu, 2011; Dietrich J.K, 2010). But enthalpy of hot water is much lower than steam, so oil expansion and oil viscosity reduction are very limited. Steam can bring huge heat to reservoir and reduce oil viscosity greatly; but its low viscosity may cause severe steam channeling. Once steam channeling occurs, futile cycle of steam may result in high water cut, low sweep efficiency and low heat utilization (R.L. Eson, 1992; Cao Yanbin, 2012).

To further understand hot water and steam flooding mechanism and study temperature influence on oil recovery, typical features include displacement efficiency, relative permeability, water cut and non-dimensional productivity index of hot water and steam flooding under different temperature were obtained in laboratory. The result may provide basic data for numerical simulation and theoretical basis for development adjustment of heavy oil reservoirs.

2. STEAM FLOODING AND HOT WATER FLOODING EXPERIMENTS

The oil used is dead oil from Qi 40 Block and its viscosity-temperature relationship is shown in Table **1**. The water used is distilled water since there was no clay minerals in sand pack.

The size of sand pack is Φ25×100mm, with permeability of 1.2-1.5μm^2, porosity of 32-36%. Experiment flow include displacement system, sand pack model, back pressure system, heating system and effluent separation and metering system. Figure **1** shows schematic drawing of the experiment apparatus. Experimental schemes include 100℃ hot water flooding, 100℃ steam flooding, 200℃ hot water flooding and 200℃ steam flooding.

*Address correspondence to this author at the CNOOC Ener Tech-Drilling and Production Co, 300452, Tianjin; Tel: +86 13072033595;
E-mail: chanel_lf@126.com

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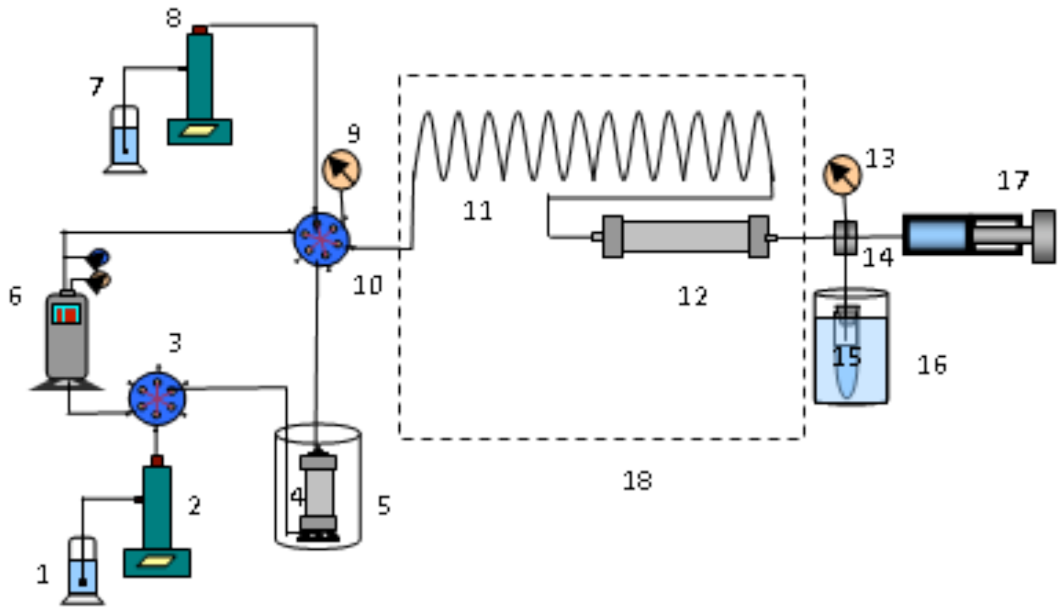
Table 1: Viscosity-Temperature Relationship of Crude Oil

T/℃	40	80	100	120	160	200	220	240	280
u/mPa.s	5062	251.4	91.5	48.6	20.6	7.6	5.6	2.8	1.2



1,7- Water container 2,8 -ISCO pump 3,10-Six-way valve 4-Oil tank 5-Resistance heating device 6-Steam generator 9,13-Precision pressure sensor 11-Heating coil 12-Sand pack 14-Back pressure valve 15 - Oil and water metering device 16 -Condensation device 17 - Back pressure pump 18 – Incubator.

Figure 1: Schematic drawing of the experiment apparatus.

Steam and hot water flooding experiments were conducted according to China Oil and Gas Industry Standard SY / T6315-2006. The experimental process is as follows: (1) Vacuum sand pack and saturated with distilled water, measure porosity and permeability. (2) Set back pressure 0.3-1.0 MPa higher than water saturation pressure, heat incubator to experimental temperature for more than 12 hours and measure water phase permeability. (3) Saturated with crude oil to establish irreducible water saturation, measure oil phase permeability. (4) For water flooding, keep back pressure constant. For steam flooding, set back pressure 0.5 MPa lower than water saturation pressure to maintain vapor state, as saturation temperature is a function of pressure. Record liquid production, upstream and downstream pressure with time. (5) When water cut is higher than 99.5% and displacement pressure is stable, measure water phase permeability.

3. RESULT AND DISCUSSION

Physical properties of saturated steam and saturated hot water are shown in Table **2** (searched in Thermal Recovery of Oil and Bitumen, R.M. Bulter, 1991). As can be seen, physical properties of steam are quite different from hot water under the same

Table 2: Saturated Water and Saturated Steam Physical Properties

Temperature	100℃			200℃		
Properties	Density (kg/cm^3)	Viscosity (mPa.s)	Enthalpy (kJ/kg)	Density (kg/cm^3)	Viscosity (mPa.s)	Enthalpy (kJ/kg)
Saturated water	958	0.282	419.166	864.65	0.1314	852.27
Saturated steam	0.593	0.01227	2675.57	7.861	0.01571	2792.01

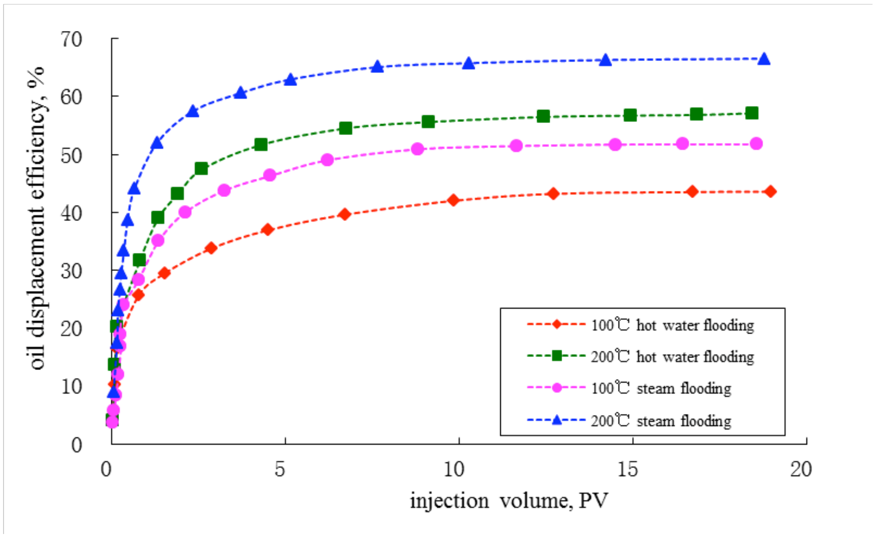


Figure 2: Oil displacement efficiency of hot water and steam flooding under different temperature.

temperature. When saturated water heating into steam, it increases in volume by 1,700 times at standard temperature and pressure, this change resulting in steam density and viscosity decreased sharply (Liu Wenzhang, 1998). At temperature of 200℃, density, viscosity and enthalpy of saturated water are 110, 8.36 and 0.30 times of saturated steam respectively.

4. DISPLACEMENT EFFICIENCY

Oil displacement efficiency microscopically represent oil cleaning degree by displacing agents. For oil reservoirs with similar porosity structure, permeability and wettability, displacement efficiency is manly related to the properties of reservoir fluids and displacing agents (Tang G.Q, 2004; Schrmbre J.M, 2005). Figure **2** shows displacement efficiency of steam flooding and hot water flooding under different temperatures. As can be seen, ultimate oil displacement efficiency of 100℃ hot water flooding, 200℃ hot water flooding, 100℃ hot water flooding and 200℃ hot water flooding are 43.67%, 55.72%, 52.65% and 66.69 % respectively.

Higher temperature and lower pressure are beneficial for heavy oil recovery. With higher temperature, steam and hot water bring more heat to reservoir which resulting in less heat loss and greater viscosity reduction. In fact, with temperature increase, viscosity of oil decreases more rapidly than water (Abdullah *et al*., 2009). Consequently, the mobility ratio is improved, and the displacement efficiency is also increased. As water saturated temperature is a function of pressure, lower pressure would help water turn to vapor state, at temperature of 200℃. The enthalpy of saturated steam is almost 3 times of saturated water. Not only more heat of steam bring would reduce oil viscosity greater, but also steam has distillation capacity which would vaporize light and medium components in crude oil and form solvent displacement, more remaining oil recovered by this way (Harmsen, G. J., 1971).

5. RELATIVE PERMEABILITY CURVE

Relative permeability curve is very important for describing two-phase percolation law in porous media, and it is the basic data for reservoir simulation. Over the past several decades, contradictory results have been reported on temperature effects on Water/Oil relative permeability (Schrmbre J.M, 2005; Tang G.Q,

Table 3: Typical Parameters of Hot Water and Steam Flooding under Different Temperature

	100℃ Hot Water Flooding	**200℃ Hot Water Flooding**	**100℃ Steam Flooding**	**200℃ Steam Flooding**
Swi（%）	23.4	25.9	23.15	25.34
Sor (%)	43.9	32.8	32.9	25.2
Water free recovery（%）	12.9	15.9	30.24	38.56
Ultimate oil recovery（%）	42.69	55.73	57.18	66.24

2004). Table **3** shows irreducible water saturation, residual oil saturation, water-free recovery and ultimate oil recovery of hot water and steam flooding under different temperature.

As can be seen, with temperature increase, irreducible water saturation increase, residual oil saturation decrease, water free recovery and ultimate oil recovery increase. For residual oil saturation: 100℃ hot water flooding > 100℃ steam flooding > 200℃ hot water flooding > 200℃ steam flooding. At temperature of 200℃ , water free recovery of steam flooding is 22.66% higher than hot water flooding, and ultimate oil recovery of steam flooding is 10.51% higher than hot water flooding.

Figure **3** showed steam-oil and hot water-oil relative permeability under different temperature. As can be seen, with temperature increase, oil phase relative permeability increase, water phase relative permeability increase, and steam phase relative permeability decrease. Both water and steam phase relative permeability endpoints are very low due to tiny steam or water oil viscosity ratio.

For a certain reservoir, flow ability can be represented by phase mobility-the ratio of phase permeability to phase viscosity, due to the tiny steam viscosity, steam flows very easily in porous medium, and can form severe steam channeling. Relative permeability curve can also reflect wettability change of the rock, as temperature increase, irreducible water saturation increase and oil saturation at Krw/s=Kro decrease, demonstrating rock becoming more water wet. As temperature increase, gum and asphaltene

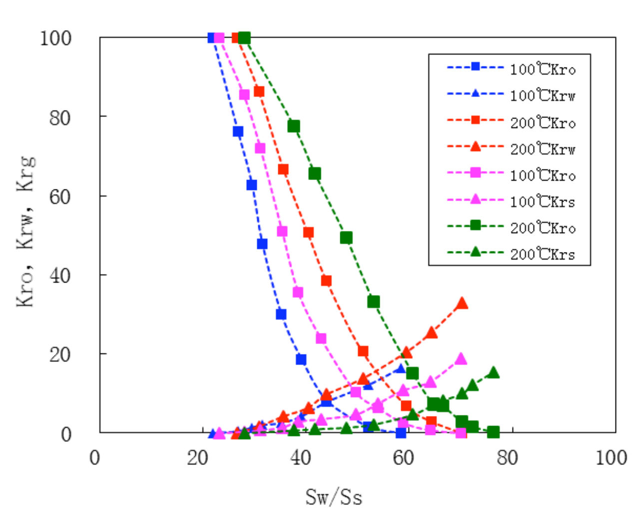


Figure 3: Relative permeability of hot water and steam flooding.

adsorbed on the rock surface begin to dissolve and strip from the rock resulting in oil water interfacial tension and capillary force decrease (Liu Wenzhang, 1998).

6. WATER CUT

Figure **4** shows water cut of hot water and steam flooding under different temperature. As can be seen, the shapes of water cut was not typical 's' type, but 'Γ' type, low water cut period was very short for both hot water and steam flooding, demonstrating most oil recovered in high water cut period for heavy oil reservoir. Water cut increase much slower for steam flooding at higher temperature than hot water flooding due to more favorable oil viscosity reduction. The relationship between water cut and oil saturation in laboratory provide direct evidence of production performance of field. As for heavy oil recovery, steam is a better choice than hot water.

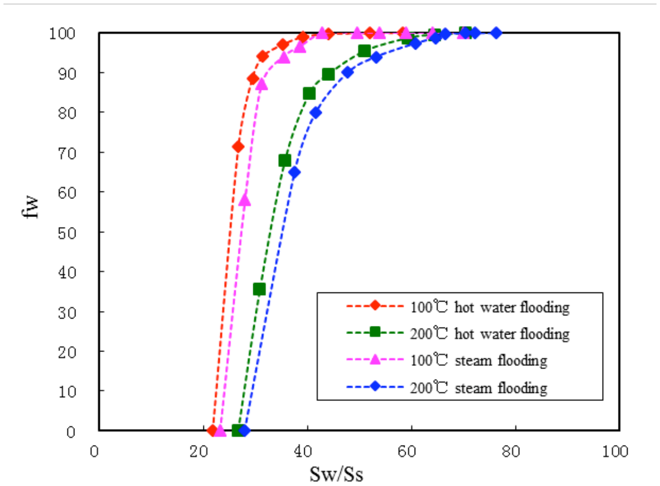


Figure 4: Water cut of hot water and steam flooding under different temperature.

7. DIMENSIONLESS FLUID AND OIL PRODUCTIVITY INDEX

Dimensionless liquid production index is the ratio of liquid production index at a certain water cut and liquid production index at water cut equals to 0 (under irreducible water condition), which can be used to evaluate the liquid production ability of the well and predict production performance (Wang Tao, 2009). Fluid production index is mainly related to reservoir type and reservoir fluid properties. Using the relative permeability curve, the change of dimensionless fluid production index with the water cut can be obtained.

Dimensionless liquid production index can be described as:

$$J_{DL} = Q_L / Q_{L(f_w=0)} = (Q_o + Q_w) / Q_{o\max} \quad (1)$$

Substitute Darcy equation of oil and water into (1), then;

$$J_{DL} = K_{ro} + K_{rw} \cdot \mu_o / \mu_w \quad (2)$$

Similarly,

$$J_{DO} = K_{ro} \quad (3)$$

where Q_o, Q_w—oil and water production rate, ml/min; $Q_{o\max}$—oil production rate at water cut equals to 0, ml/min; K_{ro}, K_{rw}—oil, water phase relative permeability, fraction; μ_o, μ_w—oil, water viscosity, mPa.s.

As can be seen from equation (2), the dimensionless liquid production index is a function of relative permeability, and relative permeability is a function of water cut, therefore, the relationship between the dimensionless liquid production index and water cut can be established. Similarly, the dimensionless oil production index can be obtained, as shown in Figure **5**.

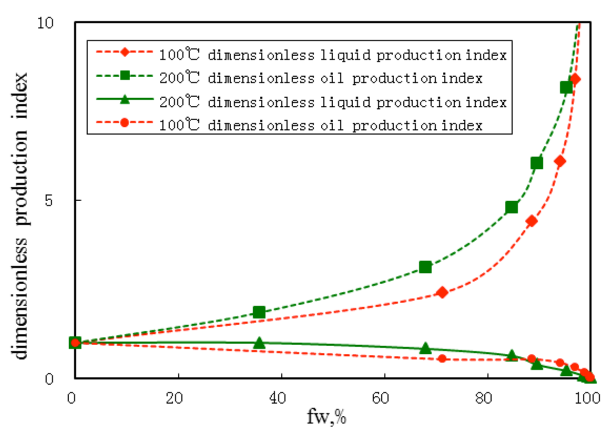


Figure 5: Dimensionless liquid/oil production index of hot water flooding.

As can be seen from Figure **5**, after water cut breakthrough, dimensionless oil production index begin to decrease and dimensionless liquid production index begin to increase. When water cut higher than 80%, dimensionless oil production index decrease sharply and dimensionless liquid production index increase greatly. This phenomenon can be explained by viscous difference between oil and water. At low water cut stage, porous medium is occupied by viscous oil, due to its high viscosity, it is quite difficulty for water displacing it, and liquid production was low. But in high water cut stage, the flow phase in porous medium is mainly water, due to its low viscosity, it flows very smoothly, therefore dimensionless liquid production index increase greatly. The dimensionless production index with water cut also indicating a long two phase flow period of heavy oil recovery.

In addition, as can be seen in Figure **5**, both dimensionless fluid production index and dimensionless oil production index of hot water flooding at 200℃ are higher than hot water flooding at 100℃ at water cut less than 80% due to the more favorable oil water mobility.

CONCLUSION

In this paper, experiments were carried out for hot water flooding and steam flooding of heavy oil under different temperatures. Through data analysis, the displacement efficiency, relative permeability, water cut and dimensionless fluid production index were obtained.

(1) Displacement efficiency of 100℃ hot water flooding, 200℃ hot water flooding, 100℃ hot water flooding and 200℃ hot water flooding are 43.67%, 55.72%, 52.65% and 66.69% respectively, the enthalpy difference of steam and hot water is the main reason of displacement efficiency difference.

(2) As temperature increases, irreducible water saturation increases, residual oil saturation decreases and wettability of rock became more water wet. The relative permeability change of hot water flooding and steam flooding under different temperature revealed important EOR mechanism of heavy oil recovery.

(3) Water cut, dimensionless production index can be obtained with relative permeability. Both water cut type and dimensionless production index revealed long two phase production period of hot water and steam flooding. Since oil displacement efficiency and oil relative permeability is much higher, water cut raise much slower of steam flooding, it is recommend steam injection of the aimed heavy oil reservoir.

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