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Forming Condition of Foamy Oil Flow in Depletion Development of Heavy Oil Reservoir

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Abstract:

The formation of foamy oil can improve the primary recovery of heavy oil reservoir, but it is not very clear under what conditions foamy oil will form. In this paper, depletion experiments were conducted in one-dimensional sandpacks to investigate the effect of oil viscosity, solution gas-oil ratio, pressure depletion rate and formation permeability on foamy oil, and the forming condition of foamy oil flow was determined. The results show that when foamy oil flow exists, oil recovery curve takes an “S pattern” with a sharp rise in the middle section. Lower oil viscosity makes it difficult to form steady foamy oil flow. As solution gas-oil ratio increases, oil recovery first increases and then decreases slightly. There exists an optimum scope of solution gas-oil ratio for foamy oil flow. Foamy oil can only form when pressure depletion rate is high enough. Foamy oil is difficult to flow and gas channeling may easily occur in lower permeable cores. According to the experimental results, forming conditions of foamy oil are concluded preliminarily: live oil viscosity should not be lower than 210 mPa·s, the optimal range of solution gas-oil ratio is 5-26 Sm3/m3, the lowest pressure depletion rate recommended is 5 KPa/min, and formation permeability should be greater than 3000 mD preferably.

Keywords*: Foamy oil, heavy oil reservoir, depletion development, forming condition.*

I. INTRODUCTION

Primary development in some heavy oil reservoirs has showed anomalous behaviors: low gas-oil ratio, high production rate and high oil recovery[1]. Foamy oil flow observed in depletion has been widely accepted as the reason for the abnormal phenomena[2]. Foamy oil flow is a unique flow behavior that gas is dispersed in the oil in the form of micro-bubble. Owing to high viscosity of heavy oil, it is hard for bubbles to coalesce, collapse and turn into continuous phase, so gas phase mobility decreases and gas channeling could be inhibited effectively[3-4]. As a result, primary recovery increases significantly.

Smith first studied heavy oil solution gas drive systematically. Gas-oil mixture is used to describe the special state that gas is dispersed in the heavy oil in the form of micro-bubble[3]. Maini et al. considered that it is a dispersion system that oil was continuous phase and gas was dispersed phase[4]. Foamy oil is used to describe the flow state. Kumar et al. investigated the effect of pressure depletion rate on gas phase

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mobility by core experiments of solution gas drive[5]. They found gas phase mobility could be affected by pressure depletion rate. Gas phase mobility gradually decreases with the increase of pressure depletion rate. Zhang et al. conducted pressure depletion tests by sandpacks to examine the effect of temperature on foamy oil flow[6]. The results show that the highest recovery does not occur at the highest temperature. Instead, there is a much lower optimum temperature which provides the highest recovery. In conventional solution gas drive, oil recovery decline with the rise of oil viscosity. But in solution gas drive with foamy oil, the effect of oil viscosity on recovery is different from conventional solution gas drive. Under the same condition, the higher the viscosity of dead oil, the more stable the foamy oil and the longer the duration of foamy oil flow. Sheng et al. carried out foamy oil stability evaluation experiments[7]. They thought the stability of foamy oil is proportional to oil viscosity, solution gas-oil ratio and pressure depletion rate. The amount of solution gas dissolved in heavy oil has an important influence on heavy oil recovery. The bigger the solution gas-oil ratio is, the better the stability of foamy oil is. Large solution gas-oil ratio means high saturation pressure and huge displacement pressure difference, which is favorable to solution gas drive. Oil recovery increases with solution gas ratio. Liu et al conducted a series of sand pack experiments and established an empirical formula to quantitatively evaluate the effect of the factors of pressure depletion rate, solution gas-oil ratio and oil viscosity on foamy oil recovery[8]. He found the recovery might be enhanced at higher pressure depletion rate, solution gas-oil ratio and oil viscosity. Pressure depletion rate has the greatest influence on foamy oil recovery. Although lots of researches have been conducted, previous studies are just oriented toward qualitative analysis of influence factors and the condition under which foamy oil flow can form is not yet clear.

In this paper, a series of sandpack depletion experiments were carried out to study the effect of oil viscosity, solution gas-oil ratio, pressure depletion rate and formation permeability on foamy oil recovery. The characteristics of foamy oil flow reflected on oil recovery curve were analyzed and the conditions for formation of foamy oil flow were concluded. The paper can provide guidance for heavy oil reservoir to take full advantage of foamy oil to improve development.

II. MATERIALS AND METHODS

2.1 Materials

The oil used in the experiments was live oil prepared with dead oil and solution gas in PVT barrel. The initial dead oil is from MPE3 block of Venezuela. The solution gas was prepared in laboratory according to the real gas compositions of CH_4 and CO_2 with mole fraction of 87% and 13%.

To study the effect of oil viscosity on foamy oil, four more dead oil samples were prepared by mixing naphtha with the initial dead oil in varying proportions. The viscosities of the five dead oil at reservoir temperature (53.7℃) were 205mPa·s, 680mPa·s, 3760mPa·s, 13065mPa·s and 28040mPa·s with mass fraction of naphtha of 70%, 50%, 35%, 15%, 0% respectively. The viscosities of the five live oil with solution gas-oil ratio of 16 Sm3/m3 at reservoir temperature (53.7℃) were 75mPa·s, 210mPa·s, 1030mPa·s, 3350mPa·s and 6157mPa·s.

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The water used in the experiments was prepared according to the composition of formation water. The formation water is $NaHCO_3$-type with total salinity value of 19120mg/L, an HCO3- concentration of 2450mg/L, a Cl- concentration of 10350mg/L. The viscosity and density of the brine at reservoir condition was 0.86mPa·s and 1007Kg/m3 respectively.

The sandpack models used in the experiments were packed by refined silica sand. To study the effect of formation permeability on foamy oil, five kinds of silica with different grain size were used. The permeabilities of the five cores were 1640mD, 2080mD, 5730mD, 10300mD and 14650mD.

2.2 Apparatus

The schematic of the experimental apparatus used in the work is shown in Fig.1. It mainly consisted of injection system, multifunction displacement system, data acquisition system and production system.

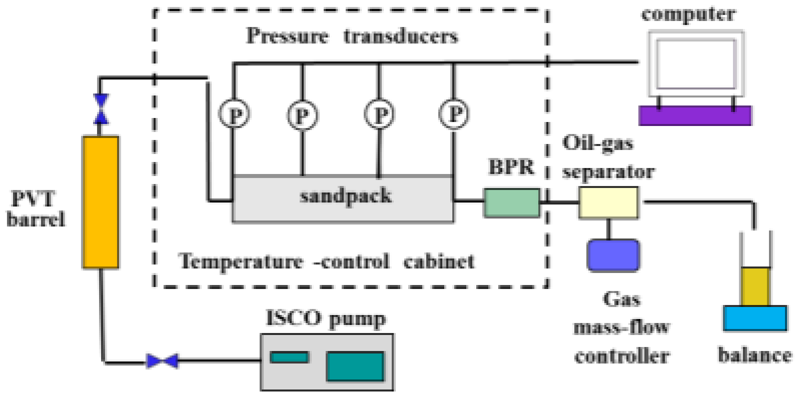

Fig.1 Schematic diagram of one-dimensional depletion experiment

Injection system was composed of an ISCO pump and a Pressure-Volume-Temperature (PVT) barrel. Live oil was prepared in the PVT barrel and injected into the sand-packed model by pump. A heating muff was wrapped around the PVT barrel to keep the live oil at reservoir temperature.

Multifunction displacement system mainly included sand-packed model, temperature-control cabinet and back-pressure regulator (BPR). Sand-packed model has a length of 60.00cm and an inner diameter of 2.54cm, on which two pressure detecting points are distributed evenly. BPR connected to a nitrogen cylinder was used to control the pressure at the outlet of sand-packed model with an open error of less than 0.01MPa. Sand-packed model and BPR were placed in the temperature-control cabinet, which could be set to a given temperature with an accuracy of 0.1℃.

Data acquisition system recorded the pressures and the temperature of the cabinet in real-time by pressure transducers and thermocouples that were connected to a computer.

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Production system was mainly made up of oil-gas separator, gas mass-flow meter and balance. Produced fluid was separated into liquid phase and gas phase in the oil-gas separator, and then oil and gas were measured respectively by balance and gas mass-flow meter.

2.3 Procedures

(1) Live oil was prepared in the PVT barrel according to experimental conditions. (2) Sand-packed model was prepared with proper permeability and porosities, and then was saturated with the prepared brine after evacuated for 4 hours. The pore volume and permeability were measured and calculated. (3) The back pressure was set to 8.5MPa. The sand-packed model was saturated with live oil at the rate of 0.1mL/min until no more water was produced, and then irreducible water saturation and initial oil saturation were calculated. (4) The saturated sand-packed model was placed at reservoir temperature (53.7℃) for 24 hours for phase equilibrium. Then back pressure was reduced gradually at a constant pressure depletion rate with oil production and gas production recorded. (5) When the average pressure of sand-packed model declined to zero and no gas or oil was produced, stop experiment.

III. RESULTS AND DISCUSSION

3.1 The effect of oil viscosity on foamy oil

Using the dead oil samples prepared before, five pressure depletion experiments were conducted to investigate the effect of oil viscosity on foamy oil. The experimental parameters are given in TABLE I. Figure 2 shows the relationships between oil recovery and average pressure at different oil viscosities.

TABLE I. Experimental parameters at different oil viscosities

NO.	Live oil viscosity (mPa·s)	Porosity (%)	Permeability (mD)	Initial oil saturation (%)	Solution gas-oil ratio (Sm^3/m^3)	Pressure depletion rate (KPa/min)
1	75	37.60	9976	88.63	16	25
2	210	37.91	10150	88.56	16	25
3	1030	39.12	10680	89.23	16	25
4	3350	38.83	10345	88.72	16	25
5	8120	38.64	10300	88.67	16	25

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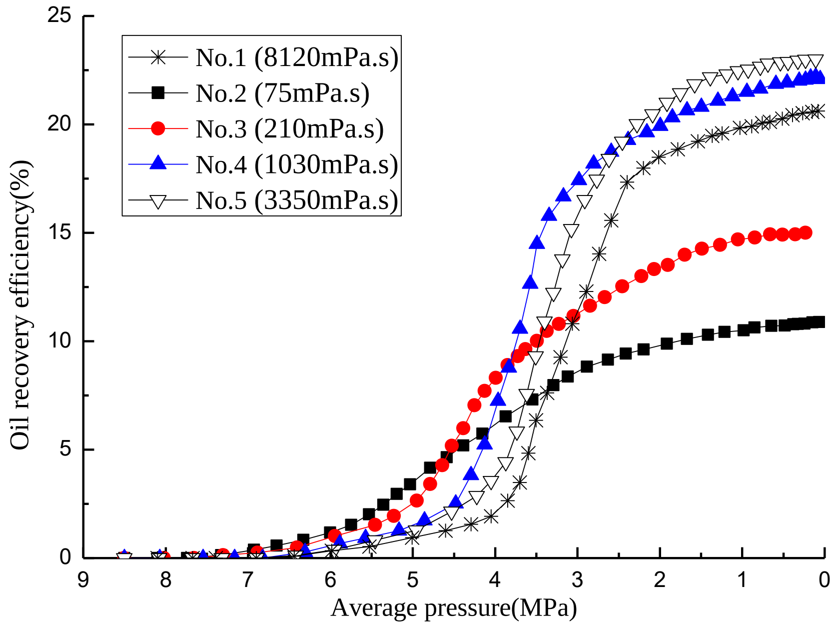

Fig.2 Oil recovery at different oil viscosities

As can be seen from the Fig.2, for the three experiments with high viscosity oil of 1030mPa·s, 3350mPa·s and 8120mPa·s, oil recovery is much bigger than the other two experiments with lower viscosity oil, and the increase pattern displays S curve of slow-fast-slow for oil recovery that increases rapidly in the middle section. Previous studies[9] found the depletion process could be divided into three stages, namely elastic expansion stage, foamy oil flow stage and oil-gas two-phase flow stage, which was believed to be a typical feature of depletion development with foamy oil. Based on the results, the foamy oil features also can be observed in the three oil recovery curves. However, for the experiments with oil of 75mPa·s and 210mPa·s, oil recovery increases gradually with the decrease of average pressure without a sharply rising section, which indicates foamy oil flow does not evolve at such low oil viscosity. So it can be perceived that oil viscosity has a significant influence on foamy oil that greatly promotes the production of oil in depletion development.

As is known to all, foamy oil is a special state of solution gas-oil mixture with large quantity of micro-bubbles dispersed in oil stably. The growth and coalescence of bubble is slowed in high viscosity oil because of huge resistance. But if the oil viscosity is too low, it is not sufficient to trap the liberated gas in micro-bubbles and the solution gas would soon flow out in continuous phase. Stability of foamy oil declines due to the decrease of oil viscosity, resulting in the difficulty in forming foamy oil flow. So in order to make use of foamy oil to enhance oil recovery of heavy oil reservoir, oil viscosity can't be too small. It is believed that the lowest live oil viscosity at which foamy oil forms should exceed 210mPa·s according to the results of this study.

3.2 The effect of solution gas-oil ratio on foamy oil

With the live oil of different solution gas-oil ratios, six pressure depletion experiments were carried out

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to study the effect of solution gas-oil ratio on foamy oil. The experimental parameters are illustrated in TABLE II. Fig.3 shows the oil recovery under different solution gas-oil ratios.

TABLE II. Experimental parameters at different solution gas-oil ratios

NO.	Live oil viscosity (mPa·s)	Porosity (%)	Permeability (mD)	Initial oil saturation (%)	Solution gas-oil ratio (Sm^3/m^3)	Pressure depletion rate (KPa/min)
1	8120	39.26	10675	88.96	2.5	25
2	8120	38.71	10560	88.53	5	25
3	8120	38.23	10035	88.02	10	25
4	8120	38.64	10300	88.67	16	25
5	8120	38.26	9895	87.89	26	25
6	8120	38.18	9955	88.27	35	25

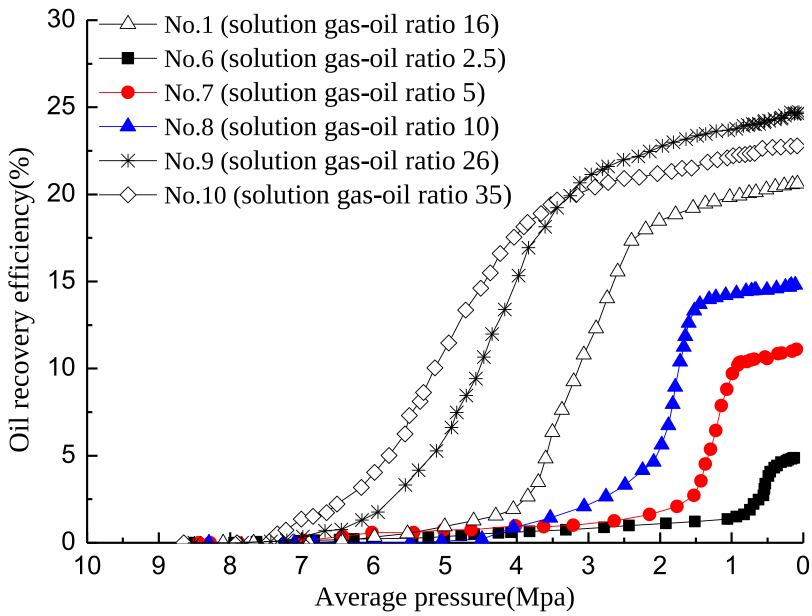

Fig.3 Oil recovery at different solution gas-oil ratios

It can be observed from fig.3 that in the case of solution gas-oil ratio being 2.5 Sm3/m3, the oil recovery is as low as conventional depletion test, which indicates there is no foamy oil flow at such low solution gas-oil ratio. As solution gas-oil ratio increases from 5 Sm3/m3 to 26 Sm3/m3, oil recovery increases gradually; but when solution gas-oil ratio increases to 35 Sm3/m3, the oil recovery declines slightly. All the oil recovery curves present obvious foamy oil features except the experiment of solution gas-oil ratio being 2.5 Sm3/m3. Meanwhile, the starting-point pressure, i.e. bubble point pressure, at which oil recovery begins to rise rapidly increases with the increase of solution gas-oil ratio.

Since the driving energy of depletion development is the elastic energy generated by the expand of solution gas, and the more solution gas dissolved, the bigger the driving energy, therefore oil recovery first

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increases with the increase of solution gas-oil ratio. But if excess amount of solution gas is dissolved in oil, it is easy for dispersed micro-bubbles to coalesce and form continues gas phase. Once the state of solution gas turns from dispersed micro-bubbles into continues gas phase, gas channeling will occur and oil mobility will be reduced dramatically. As can be seen from the fig.3, foamy oil flow stage is shortened and oil recovery decreases slightly in the case of solution gas-oil ratio being 35 Sm3/m3. So, it can infer that there is optimal range of solution gas ratio for foamy oil flow. For the heavy oil used in the depletion experiments, when solution gas-oil ratio is between 5 Sm3/m3 and 26 Sm3/m3, foamy oil would form and play a positive role fully.

3.3 The effect of pressure depletion rate on foamy oil

The effect of pressure depletion rate on foamy oil was investigated by five sandpack experiments with different pressure depletion rates of 0.2KPa/min, 1.0KPa/min, 5.0KPa/min, 25KPa/min, and 100KPa/min. The experimental parameters are shown in TABLE III. Fig.4 demonstrates the change of oil recovery with average pressure.

TABLE III. Experimental parameters at different pressure depletion rates

NO.	Live oil viscosity (mPa·s)	Porosity (%)	Permeability (mD)	Initial oil saturation (%)	Solution gas-oil ratio (Sm^3/m^3)	Pressure depletion rate (KPa/min)
1	8120	38.26	10075	88.13	16	0.2
2	8120	37.93	9860	87.63	16	1.0
3	8120	38.06	9955	88.22	16	5.0
4	8120	38.64	10300	88.67	16	25
5	8120	38.44	10135	88.37	16	100

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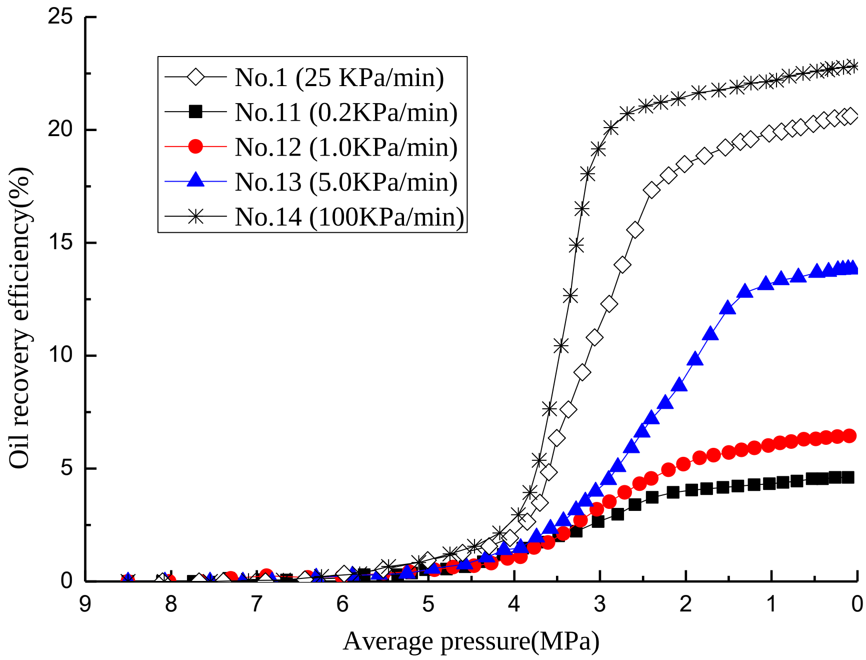

Fig.4 Oil recovery at different pressure depletion rates

As we can see from Fig.4, in the cases of pressure depletion rate being 0.2KPa/min and 1.0KPa/min, oil recovery increases slowly as average pressure decreases and the ultimate recovery, less than 10%, is about the same as the primary recovery of conventional depletion. Furthermore, the foamy oil characteristic that oil recovery rises sharply in the middle section is not observed from these two curves, which indicates foamy oil cannot form under such low pressure depletion rate conditions. While pressure depletion rate is 5KPa/min、25KPa/min、100KPa/min, oil recovery improves significantly compared with the first two tests, and there are typical foamy oil features on oil recovery curve that the curve shows as S with a sharp rise in middle section. All these characteristics suggest the formation of foamy oil in high pressure depletion rate condition. Moreover, the bigger the pressure depletion rate, the higher the oil recovery.

Since pressure depletion rate is proportional to solution gas liberation rate, low solution gas liberation rate under low pressure depletion rate means there is enough time for dispersed micro-bubbles to migrate and coalesce. As a result, solution gas flows out in continuous phase rather than foamy oil at low depletion rate. On the contrary, more micro-bubbles would be generated within the same period at higher pressure depletion rate, resulting in bigger expansion energy. This explains why oil recovery increases with the increase of pressure depletion rate. Therefore, it can be inferred that foamy oil flow tends to form at high depletion rate. According to the results, the lowest pressure depletion rate is believed to be about 5KPa/min for formation of foamy oil.

3.4 The effect of formation permeability on foamy oil

With different permeable sand-packed models prepared, five depletion experiments were conducted to

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study the effect of formation permeability on foamy oil. The experimental parameters are illustrated in TABLE IV. Fig.5 shows the curves of oil recovery and average pressure at different permeabilities.

TABLE IV. Experimental parameters at different formation permeabilities

NO.	Live oil viscosity (mPa·s)	Porosity (%)	Permeability (mD)	Initial oil saturation (%)	Solution gas-oil ratio (Sm^3/m^3)	Pressure depletion rate (KPa/min)
1	8120	35.07	1640	86.35	16	25
2	8120	36.23	3080	87.02	16	25
3	8120	37.68	5730	87.53	16	25
4	8120	38.64	10300	88.67	16	25
5	8120	40.18	14650	89.36	16	25

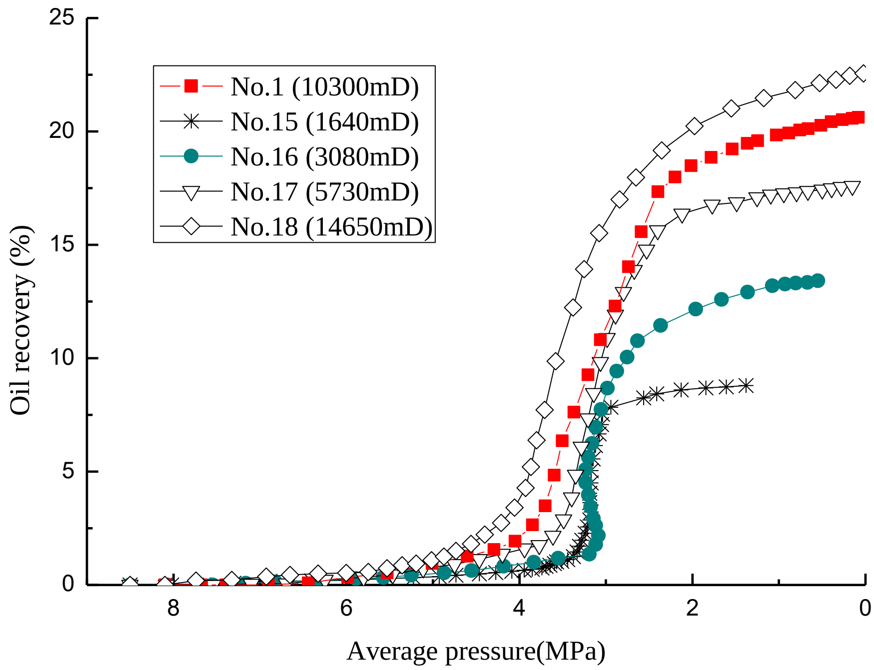

Fig.5 Oil recovery at different formation permeabilities

From the Fig.5, the foamy oil characteristic that the oil recovery curve shows S-shaped with a sharp rise in the middle section can be observed in cores of different permeability, and oil recovery increases gradually with the increase of permeability. This is mainly because in higher permeable cores flow resistance and Jamin effect are much lower and mobility of foamy oil is enhanced. Moreover, due to lower production rate in lower permeable cores, micro-bubbles of solution gas liberated from oil cannot be carried out in time, but be trapped and deposited in sandpacks, leading to coalescence of micro-bubbles and formation of gas channeling soon. As a result, the stage of foamy oil flow is shortened in cores of lower permeability, which also can be validated in Fig.5. Due to the combination of low oil mobility and short stage of foamy oil flow, the contribution of foamy oil to oil recovery in low permeable core is

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impaired.

Consequently, based on the experimental results, it can be concluded that reservoir permeability has a little impact on the formation of foamy oil, but influence foamy oil flow significantly. To make sure that foamy oil can take effect in depletion development, the formation permeability should be high enough, well over 3000mD.

IV. CONCLUSION

(1) The decrease of oil viscosity results in the decline of stability of foamy oil. It is difficult to form steady foamy oil flow in depletion when live oil viscosity is below about 200 mPa·s.

(2) As solution gas-oil ratio increases, oil recovery of foamy oil first increases and then decreases slightly. The optimal range of solution gas-oil ratio for foamy oil flow is 10-26 Sm3/m3.

(3) The oil recovery of depletion increases gradually with the increase of pressure depletion rate. The lowest pressure depletion rate for formation of foamy oil should be not less than 5 KPa/min.

(4) Lower formation permeability is not beneficial to foamy oil flow due to bigger flow resistance and shorter foamy oil flow stage. In order to make the most of foamy oil in depletion, formation permeability should be greater than 3000 mD preferably.

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