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An Experimental Study of Mobilization and Creeping Flow of Oil Slugs in a Water-Filled Capillary

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Abstract An experimental investigation was carried out on mobilization and very slow flow of oil slugs in a capillary tube. The pressure drop of the slug flow was measured at every stage of mobilizing and moving the oil slugs as a function of capillary number in the range of 4×10^{-7}–6×10^{-6}. The pressure drop across the oil slug experienced three stages: build-up, hold-up, and steady stages. During the build-up stage, the convex rear end of the slug was becoming concave into the oil slug and the convex front end of the slug moved ahead to form a new portion of the slug. At the hold-up stage, both the concave rear end and the front end continued to advance, and the initial contact line of the oil slug with the tube wall through a very thin water film was being shortened. At this stage, the pressure drop reached a maximum value and remained nearly constant. At the steady stage, after the oil slug was completely mobilized out of the original contact region, the differential pressure had a step-drop first, and then the oil slug flowed at a lower differential pressure depending on the flow rate. Numerous slug flow tests of this study showed that the hold-up pressure drop was always higher than the steady stage pressure drop. Results also showed that the measured extra pressure drop was significantly high compared to the pressure drop calculated from Poiseuille equation, which is still commonly used in network modeling of multiphase flow in porous media.

Keywords Slug flow · Capillary tube · Oil drop flow · Residual oil · Enhanced oil recovery

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1 Introduction

The mobilization and flow of oil slugs in water-filled capillaries is of interest in multiphase flow in porous media—for example, for waterflooding and enhanced oil recovery in the petroleum industry. A significant portion of oil remains in reservoirs after the waterflooding process (Melrose and Brandner 1974). Residual oil after waterflooding is thought to exist as isolated oil blobs held in place by the combination of capillary forces and the resistance of pore walls of the porous reservoirs (Morrow 1979). The blobs with diameters smaller than pore throats have been moved out through waterflooding process (Olbricht 1996), but the others exist in the form of oil slugs trapped in pores. There have been numerous studies of two-phase flow in capillary tubes or microchannels under high capillary numbers (*Ca*) that are several orders higher than the range of *Ca* encountered in flow through porous media in oil reservoirs. The pore-level mechanism for mobilizing a trapped oil slug has not been well understood.

Numerous studies have been reported on drop flow in capillaries. The name of drop flow is adopted when the diameter of a drop is comparable to the tube inner diameter. Hestroni et al. (1970) investigated the case of a small-spherical drop moving axially at an arbitrary radial location in the tube and found that the drop velocity U decreases as a quadratic in the dimensionless drop size k, where k is the ratio of the undeformed drop size to the tube size. Brenner (1971) employed the solution of Hestroni et al. (1970) in a reciprocal theorem for creeping motion to obtain extra pressure drop ΔP^+ due to the presence of drop in the bulk flow. He realized that the suspension flow is non-linear. Hyman and Skalak (1972) used finite difference method to handle a train of equally spaced drops flowing through a circular tube. Their work validated Brenner's claim that the pressure drop decreases as the bulk velocity V increases. Ho and Leal (1975) experimentally investigated a drop train by varying the dimensionless drop size k from 0.7 to 1.1. They measured the drop velocity U and extra pressure drop ΔP^+ against drop size k, bulk velocity V, and viscosity ratio σ and found that the dimensionless extra pressure drop, $\Delta P^+ R_t/\mu_d V$, decreases as capillary number Ca increases for $0.06 < Ca < 0.25$, where μ_d is the viscosity of the drop phase and R_t is the radius of the tube. The Capillary number $Ca = \mu V/\gamma$, where μ is the viscosity of the suspending phase and γ is the oil-water interfacial tension. Olbricht and Kung (1987) and Aul and Olbricht (1990) also conducted drop flow experiments under low Reynolds numbers, and focused on drop deformation, break-up, and coalescence.

In the case of the drop diameter greater than that of the tube, drop flow is called slug flow. Extensive experimental studies have been reported in the literature on slug (gas or liquid slug) flow in a capillary tube filled by a wetting liquid (Fairbrothers and Stubbs 1935; Taylor 1961; Goldsmith and Mason 1963; Schwartz et al. 1986; Chen 1986; Mostefa and Biesel 1988). The main focus of these studies was to determine the wetting film thickness between the slug and the tube walls as a function of capillary number. The general funding is that the film thickness increases with increasing slug velocity U, and the wetting film thickness approaches a constant value when slug velocity U is extremely low. Dong and Chatzis (2004) studied the relationship between the retention of wetting phase after a flow of gas or liquid slug and capillary Ca in a square capillary. They found that the retention of a wetting liquid in the corners strongly depended on the capillary number (*i.e.*, the retention of the liquid decreased with decreasing capillary number). For a capillary number less than 10^{-4}, the retention of a wetting liquid was found to be determined by the capillary forces, and the rate (or viscous) effect was negligible. Bretherton (1961) presented a theoretical analysis to calculate the wetting film thickness, and the pressure difference across the bubble is $3.58(3Ca)^{2/3}\gamma/R_t$, when capillary number Ca approaches zero. Mostefa and Biesel (1988) measured the pressure drop over a long air bubble in a capillary to study the influence of surfactant on the pressure difference. They found that the steady pressure drop was 20–60 times Bretherton's theoretical value.

Because of its relevance to oil recovery and other applications, many numerical studies of displacement of a wetting liquid in a capillary tube using a gas bubble or a long semi-infinite slug of gas have been carried out extensively (Shen and Udell 1985; Westborg and Hassager 1989; Martinez and Udell 1989, 1990; Ratulowski and Chang 1989, 1990; Tsai and Miksis 1994). While these numerical solutions demonstrated good agreement with the high-speed experimental results of Taylor (1961), apparently, no numerical method has been extended to describe the low-speed region ($Ca < 10^{-3}$) well because of the difficulty of adequately resolving the thin-film region.

A fundamental understanding of why the residual oil is difficult to recover compared to the mobile oil in a reservoir is critical for developing effective enhanced oil recovery (EOR) methods. To the authors' knowledge, no research has been reported to address the fundamental physics of mobilizing trapped oil slugs in pores.

In this study, experiments were carried out to mobilize trapped oil slugs in a capillary tube of 1.5 mm in diameter filled by water. Oil slug length varied from 2.0 to 101 mm, corresponding to dimensionless slug size k of 1.33–67.3. The displacement velocity ranged from 1.6×10^{-3} to 2.4×10^{-2} cm/s and the corresponding capillary number Ca changed from 4×10^{-7} to 6×10^{-6}. The differential pressure across the tube was measured at every stage of the displacement process. The mechanism of mobilizing a trapped oil slug in a straight capillary is studied by analyzing the measured differential pressure profiles under various displacement conditions.

2 Experimental

2.1 Experimental Setup

A schematic of the experimental setup is shown in Fig. 1. The central part of the apparatus is a uniform, circular glass tube of 1.0 m in length with an inner diameter of 1.5 mm (PYREX Brand Glass Tubing). Two Plexiglas chambers were employed to connect a pressure transducer, a constant flow rate syringe pump, and a syringe for oil slug introduction into the tube. A high-sensitive, super low-pressure transducer, DP103 (Validyne Engineering), was employed to measure the pressure difference across the glass tube. A pulse-free constant flow syringe pump (Sage Instrument model 341A) was used for water injection at a constant flow rate.

This experimental design includes the following considerations: (1) The tube is long enough to ensure that a set of measurements can be carried out at different flow rates; (2) The inner diameter of the tube is small enough that the gravitational force is negligible compared with the capillary force; (3) The inner diameter of the two Plexiglas chambers is so large compared to the inner diameter of the tube that the water in it can be virtually considered stagnant; as a result, the flow-induced pressure drop between the tube end and the access of the pressure transducer tubing in the chambers can be considered negligible; (4) DP103-26 (Validyne Engineering) is a super-low, highly sensitive pressure transducer with accuracy of $0.14\,\text{N/m}^2$, which can satisfy the measurement requirements in the experiment.

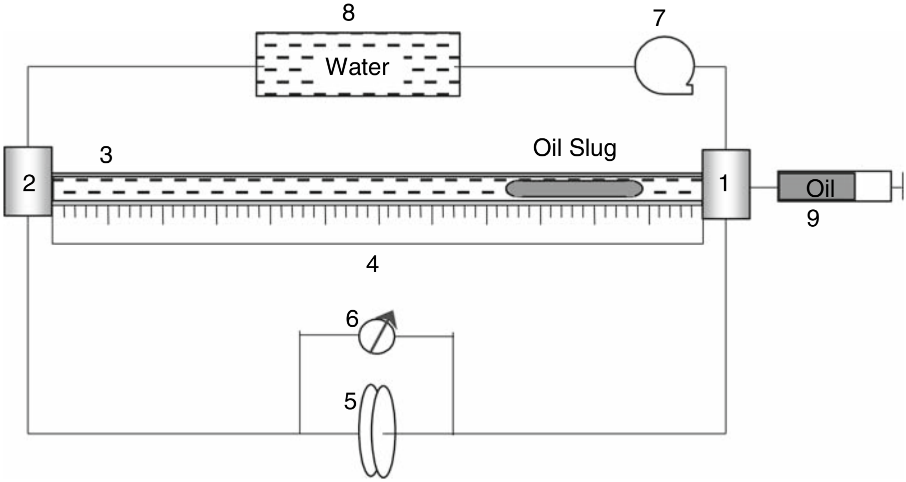

Fig. 1 Schematic of experimental setup for measuring differential pressure profiles under various displacement stages of mobilizing a trapped oil slug in a straight capillary. (1) and (2) Plexiglas chambers, (3) glass tube, (4) graduated base, (5) pressure transducer, (6) bypass valve, (7) pump, (8) water reservoir, (9) syringe

2.2 Materials

Standard oil S60 with viscosity conforming to ASTM Oil Standard (Cannon Instrument Company) and de-ionized (DI) water were employed for oil and water phases. At the test temperature, the oil–water interfacial tension, γ, was measured to be 40.0 mN/m using the pendant drop method. The viscosities of oil and water were 148.0 and 1.0 mPa.s, respectively. The respective densities of oil and water were 0.87 and 1.00 g/cm^3. All the experiments were conducted at room temperature (22 $\pm$ 0.5°C).

2.3 Procedure

The following procedure was used for the trapped oil mobilization and flow tests: (1) The glass tube was cleaned with Varsol, acetone and then DI water; (2) The whole setup was connected and saturated with DI water; (3) An oil slug was injected into the tube with a syringe; (4) The oil slug was left to age for a certain time period to reach the minimum film thickness (draining of the water film between slug and tube walls); (5) Water was injected at a constant rate to mobilize and induce flow of the oil slug. The contact angle of water at the inner tube surface was measured to be 59° using capillary-rise method. Therefore, the wettability of the inner tube surface was intermediate water-wet, which can be used to simulate the wettability of most sandstone oil reservoirs (Melrose and Brandner 1974; Treiber et al. 1972).

Morrow (1979) pointed out that the average velocity of the oil/water flow in oil reservoirs is about 1.27–2.54 cm/h, which corresponds to a flow velocity of 5.1–10.2 cm/h in pores if the porosity of the reservoirs is 25%. In this study, the bulk velocity was varied from 5.66 to 84.88 cm/h and the corresponding capillary number changed from 4×10^{-7} to 6×10^{-6} to ensure that the experiments simulated the conditions in different parts of the reservoirs with respect to well locations. For analysis, a series of oil slugs with dimensionless lengths between 1.33 and 67.3 was tested, and the differential pressure across the tube at a given injection rate for each slug was recorded.

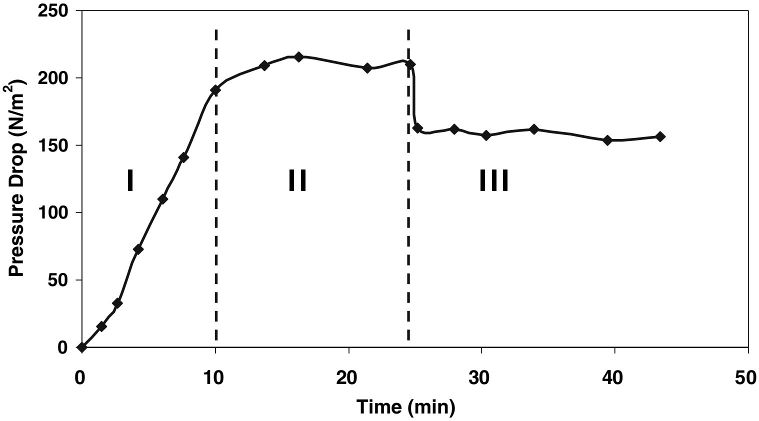

Fig. 2 A schematic pressure profile for mobilizing a trapped oil slug in a glass capillary by injecting water. (I) Build-up stage, (II) Hold-up stage, (III) Steady slow stage

3 Results and Discussion

3.1 Pressure Drop Profile for Mobilizing Trapped Oil Slugs

Measurements revealed that all the trapped oil slugs produced similar pressure drop profiles, when they were mobilized by means of constant rate water injection. Figure 2 shows a typical pressure drop profile for a trapped oil slug dislodged by constant rate water flow. The whole pressure profile can be divided into three stages: I—Build-up stage, II—Hold-up stage, and III—Steady flow stage.

Before the injection of water, the output of the pressure transducers is zero. Both ends of the slug assume the same shape, as shown in Fig. 3a.

The build-up stage is defined as the stage at which the pressure difference across the oil slug keeps increasing due to the water injection while the slug, as a whole, does not move (the contact line of the trailing end of the slug does not move), with both ends adjusting to balance the external pressure variations. In Fig. 2, stage I is the period of time when the pressure increases nearly linearly with time. The shapes of the two ends of the slug at a moment of this stage are shown in Fig. 3b. The slope of the pressure drop versus time curve of this stage becomes steeper as the injection rate increases. In fact, the shape of the advancing end and the receding end continued to change gradually in response to the external pressure change (i.e. the convex rear end of the slug was becoming concave into the oil slug and the convex front end of the slug was moved ahead to form a new portion of the slug).

When the imposed differential pressure increased to a certain value, the rear contact line with the tube wall of oil slug began to move, and the pressure drop continued to rise slightly to a certain value. This is the start of the hold-up stage, which is defined as the stage in which the oil slug moves with a fixed bulk flow rate under a nearly constant differential pressure. As shown in Fig. 3c, both the leading and trailing menisci resemble nearly hemisphere bending toward the flow direction. The hold-up stage lasts for the time period it takes for the oil slug to travel an entire slug length.

The steady flow stage is viewed as the stage in which the oil slug is displaced at a constant rate, surprisingly, under a lower pressure drop, which is defined as steady differential pressure

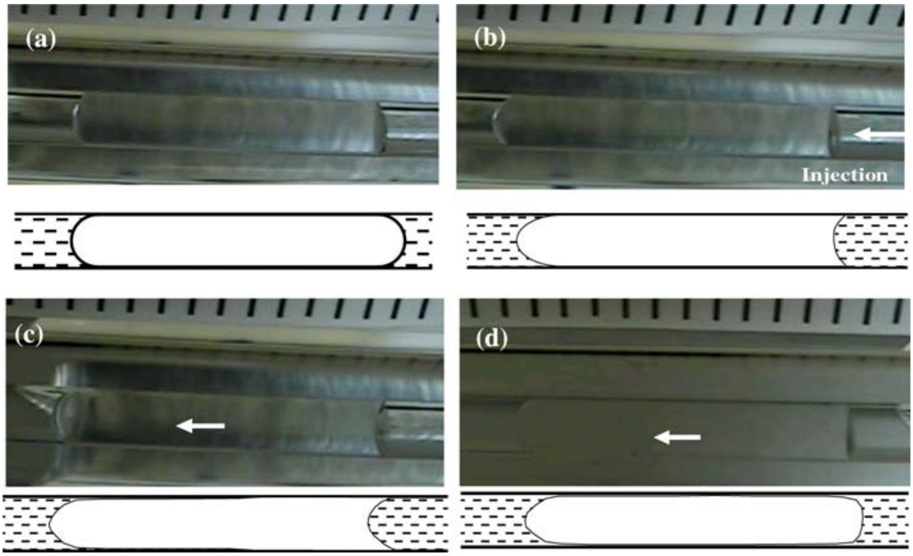

Fig. 3 Slug shapes during the process of mobilization (for each stage, the upper part is a picture and the lower part is the corresponding depiction). **a** Stationary stage, **b** Build-up Stage, **c** Hold-up Stage and **d** Steady Stage

(SDP). During this stage, the oil slug takes on a bullet shape with a sharper leading end and a blunt trailing end, as shown in Fig. 4d.

The variations of the pressure drop directly reflect that of the resistance of the capillary wall to the oil slug during mobilization. The variations of the resistance of a uniform capillary to slugs during mobilization, to the authors' knowledge, have not been mentioned in the literature.

3.2 Hold-Up Pressure Drop

A series of differential pressure curves for mobilizing trapped oil slugs of various lengths was measured at different injection rates. The mobilization of all slugs produced similar differential pressure profiles. There existed some noises in the differential pressure measurements. These noises are thought to be caused by the unsteady drainage of the water film, the inner tube surface roughness, etc. In the figures displayed thereafter, curves of averaged pressure drop data are plotted. Figure 4a–d shows the respective differential pressure curves for mobilizing oil slugs of 5.5, 14.0, 24.0, and 33.5 mm long at different injection rates.

All the pressure drop curves in Fig. 4 show that the hold-up differential pressure (HDP) is greater than the subsequent steady differential pressure. Since HDP stands for the resistance of capillary to trapped residual oil and SDP represents that to mobile oil, the higher HDP phenomenon illustrates that the trapped residual oil is more difficult to recover than the mobile oil in a reservoir.

At the hold-up stage, both the concave rear end and the convex front end kept advancing, and the initial contact line of the oil slug with the tube wall through a very thin water film was being shortened. At this stage, the pressure drop reached a maximum value and remained nearly constant. Pressure drop measurement and observation of oil slug shape at this stage revealed that the mobilization of a stationary oil slug, between which and the tube wall there

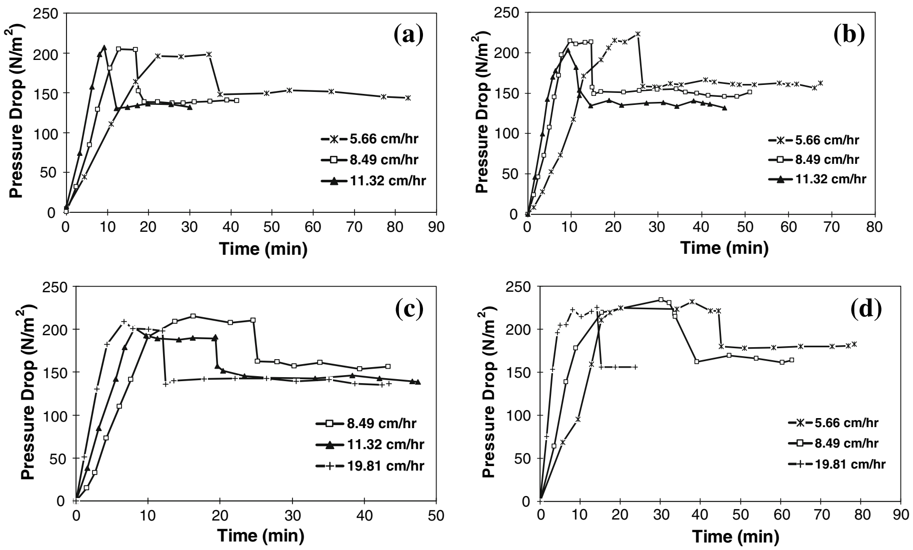

Fig. 4 Pressure drop profiles for mobilizing and flow oil slugs through a capillary tube occupied by water at different flow velocities. **a** 5.5 mm oil slug, **b** 14.0 mm oil slug, **c** 24.0 mm oil slug, **d** 33.5 mm oil slug

was an equilibrium water film, was realized by the combination of (1) deformation of the oil slug at the two ends, (2) internal flow within the oil slug, and (3) peeling-off of the contact surface of the oil slug from the thin water film at the rear end of the oil slug. There is no displacement of the oil of the immediate layer next to the original contact line with the tube wall.

Observation of the mobilization process of trapped oil slugs mobilized by water injection demonstrated that the trapped oil slugs are able to sustain a finite pressure drop, HDP. Smith and Crane (1930) experimentally found that a chain of alternate air and water bubbles in a hot chromic acid-treated glass tube is capable of sustaining a finite pressure. They named this phenomenon the Jamin effect in cylindrical tubes due to the contact angle hysteresis.

The HDP phenomenon is similar to the pressure sustenance phenomenon mentioned by Smith and Crane (1930) in their work. However, from the observation and analysis of the differential pressure profile of the mobilization of a trapped oil slug, it is more logical for one to attribute the HDP phenomenon to the tube wall resistance to the slug flow instead of the Jamin effect. This is supported by the following facts: (1) At the build-up stage, there is no displacement of the oil slug as a whole but the deformation of the two menisci; the degree of the deformation of the two menisci is determined by the values of differential pressure exerted; (2) If the water film between the oil slug and the tube wall does not reach the minimum thickness, the hold-up pressure may have a different and lower value; (3) For the same length oil slug, the steady flow pressure drop changes with the flow velocity because different flow velocities result in different water film thicknesses. In other words, one can observe different deformations of the oil slug in terms of apparent contact angles, such as advancing and receding angles, which are the major reasons of the Jamin effect, by changing the water film thickness or the displacement velocity. The key is the water film between the oil slug and the tube wall, which determines the resistance of the tube wall to the slug flow and, consequently, the deformation of the oil slug. In view of the above analysis, the Jamin

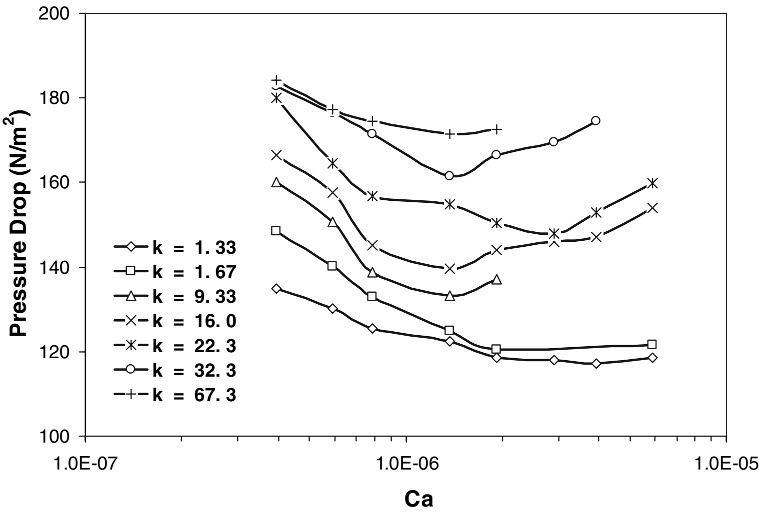

Fig. 5 The steady differential pressure versus capillary number for flowing oil slugs through a capillary tube occupied by water

effect is just an external expression of the resistance of the tube wall to or the viscous pressure drop of slug flow.

3.3 Steady Flow Pressure Drop

From Fig. 4, it is noticed that the steady differential pressure for flowing oil slugs of 5.5, 14.0, 24.0, and 33.5 mm decreases as the injection rate increases from 5.66 to 19.81 cm/h. In order to further probe this phenomenon, the SDPs are plotted against capillary number for oil slugs with dimensionless lengths between 1.33 and 67.3 in Fig. 5.

The change of the pressure drop with slug velocity is the result of competing effects of viscous flow, altered flow field, and water film thickening (Ho and Leal 1975; Martinez and Udell 1990). The first effect is the simple exchange of the suspending phase with the drop phase, which results in the increase of extra pressure drop. The second is the alteration of flow field due to the presence of the drop of another viscosity, which also increases the pressure drop. The third effect is that the drop deformation leads to decrease of the pressure drop. At low velocities, the third effect, the water film thickening effect, will dominate the slug flow behavior, so the pressure drop will decrease with flow rate. When the injection rate increases beyond a certain level, the first two effects will overcome the third one and govern the slug flow.

3.4 Analysis of Mobilization of a Trapped Oil Slug in a Capillary

The whole process of a trapped oil slug mobilized by water injection can be understood by integrating the effects of water film, drop deformation, and viscous flow. When a moving oil slug comes to a stop in a pore, the water film between oil slug and pore walls begins to drain under the influence of the oil/water interfacial tension. For a given oil–water system, the drainage rate depends on the length of the oil slug and the thickness of the water film. The drainage time needed to reach the minimum film thickness can be determined by measuring

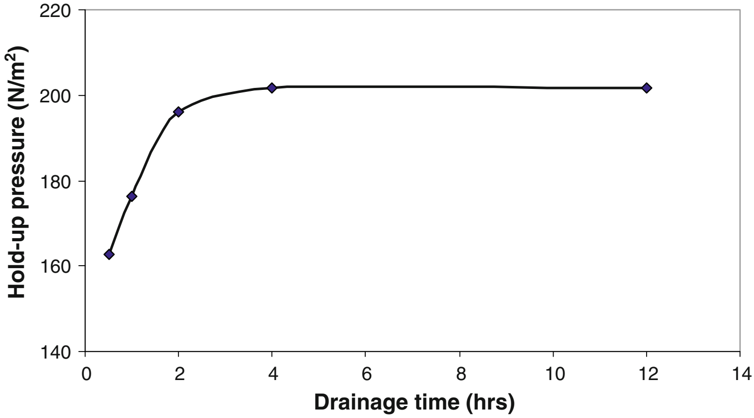

Fig. 6 Variation of the hold-up pressure drop for mobilizing a 10 mm oil slug at 5.66 cm/h with the water film drainage time

the differential pressure at the hold-up stage. The thinner the water film, the larger is the differential pressure. When the water film reaches its minimal value, the differential pressure at the hold-up stage stops increasing with the drainage time. As an example, Fig. 6 shows the variation of the differential pressure at the hold-up stage for a 10 mm long oil slug with different drainage times. It shows that a 10 mm long oil slug needs a drainage time of about 4 h to reach the minimum water film thickness. For this oil slug, when the drainage time is shorter than 4 h, the hold-up differential pressure needed to mobilize the slug increases with drainage time. This is because the water film thickness between the oil slug and the tube walls is thinner with a longer drainage time, resulting in a larger resistance to the slug flow. It was also observed that the deformation of the two menisci of the oil slug depended on the resistance or the hold-up pressure drop. A higher hold-up differential pressure brought more deformation of the slug, which corresponds to a higher resistance from the tube wall to the movement of the oil slug because of the thinner water film.

From our tests, it was found that if the water film did not drain to the minimum thickness, the differential pressure would not have the step-drop from the hold-up stage to the steady flow stage; it would decrease gradually to a stable level after reaching a maximum value. This means that the oil slug started to flow once the differential pressure reached a certain value without undergoing the hold-up stage. In the discussion of the subsequent sections, HDP is used for the hold-up differential pressure, with the minimum film thickness for the sake of simplicity.

Hirasaki (1991) pointed out that a stable water film develops between a stationary oil slug and the tube walls due to the disjoining pressure of the water film. When a driven pressure is exerted on a stationary oil slug, it will be delivered to one end of the oil slug, deforming its two menisci and causing the flow within the oil slug.

The movement of the slug was measured by the movement of the contact line of the trailing end. Since the water film at the initial stage does not flow, the oil slug acts as a plug with its radius fitting within the capillary as shown in Fig. 7. When the leading end of the oil slug advances further during the build-up stage, the newly formed water film should be much thicker than the stationary film; the leading end of the moving slug is like an extended finger with its contact line fixed at its original place; the trailing meniscus has reversed its original bending direction by the injection flow and moves like a syringe plunger; the oil at the older

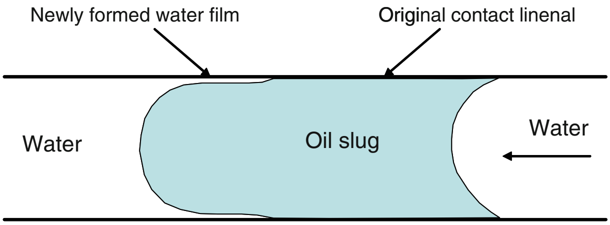

Fig. 7 Schematic of mobilization of oil slug under hold-up differential pressure in a capillary tube occupied by water

contact line is torn down from slug boundaries near the stationary film and joins the trailing meniscus; under the influence of oil–water interfacial tension, the oil on the trailing meniscus is gradually rolled into the moving slug. As a result of these movements, the length of the stationary water film is shortened until it becomes zero. That is why the hold-up differential pressure (HDP) stays over the time period it takes for an oil slug to travel an entire slug length.

The new region of the water film will be drained by the oil slug, owing to the presence of the oil–water interfacial tension. However, the oil slug moves so fast compared to the water film drainage so that the water film is still very thick when both menisci are released from their original positions. At this point (i.e., where the oil slug is released to the steady flow state), the pressure drop across the moving oil slug will drastically drop from HDP to SDP. At the steady state, the water film is in a dynamic equilibrium state and will thicken as the bulk flow rate increases (Bretherton 1961; Goldsmith and Mason 1963; Chen 1986; Dong and Chatzis 2004). The increase of the average velocity and the disturbed flow velocity field will result in the increase of SDP, but increased water film thickness will end up with a decrease of SDP (Ho and Leal 1975; Martinez and Udell 1990).

3.5 Extra Pressure Drop of Slug Flow in a Capillary

In dynamic network modeling of multiphase flow in porous media, viscous pressure drops in wetting and non-wetting phases in the form of slug flow are usually calculated by using Poiseulle's equation. Then, the total pressure drop across a segment of capillary that contains several fluid slugs is obtained by adding up all the viscous pressure drops across the individual slugs (Koplik and Lasseter 1984, 1985; Stark and Manga 2000; van Dijke and Sorbie 2002; Singh and Mohanty 2003; Hou 2007; Joekar-Niasar et al. 2008). In this section, the pressure drops calculated in the above manner are compared with the measured results. As shown in Fig. 8, the linear pressure drop across the tube is calculated as:

$$\Delta P_t = \Delta P_{w1} + \Delta P_o + \Delta P_{w2} \tag{1}$$

where ΔP_t is the sum of the calculated viscous pressure drops along the entire tube, ΔP_{w1}, ΔP_{w2}, and ΔP_o are the Poiseuille pressure loss caused by the left water slug, right water slug and oil slug, respectively. The pressure drop across each slug is calculated with the Poiseuille equation as follows:

$$\Delta P = \frac{8\mu V L}{R_t^2} \tag{2}$$

where R_t is the radius of the tube, μ the viscosity of the fluid, V the average velocity of the slug flow, and L the length of the corresponding slug.

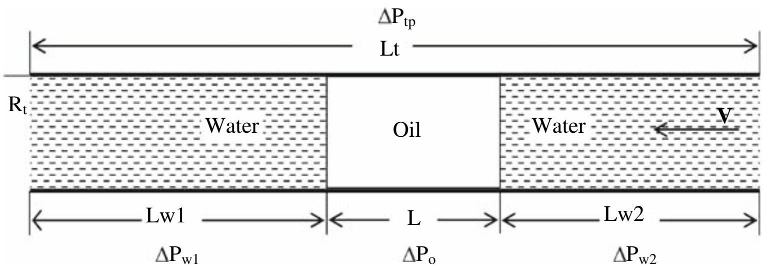

Fig. 8 Viscous pressure drop calculation of the slug flow using the Poiseuille equation

Table 1 Ratios of measured viscous pressure drop at the steady-state stage to the calculated value using Poiseuille equation for oil slugs of various lengths and at different flow velocities

Flow velocity (cm/h)	Oil slug length (mm)						
	2.0	5.5	14.0	24.0	33.5	48.5	101
5.66	476	375	239	168	139	103	53
8.49	306	236	150	106	84	66	34
11.32	219	168	103	73	60	48	25
19.81	124	90	57	40	34	26	14
27.73	85	62	42	30	24	19	10
41.88	56	–	–	20	15	13	–
56.59	41	–	–	15	12	10	–
84.88	28	20	–	10	8	–	–

From the above linear method, for example, the total viscous pressure drop is estimated to be 1.47 N/m_2 across a tube of 1.0 m in length and 1.5 mm in diameter containing a 24.0 mm long oil slug flowing with an average velocity of 8.5 cm/h. However, the measurement showed that the differential pressure was 157 N/m^2, 107 times the calculated value from the linear method. This indicates that the resistance of the capillary to and the viscous pressure drop of oil slug flow are significantly high compared to the pressure drop calculated for laminar flow.

The extra pressure of slug flow can be reflected by the ratio $\Delta P_m/\Delta P_t$, where ΔP_m is the measured pressure drop and ΔP_t is the estimated value from the Poiseuille equation for the same injection rate. Values of $\Delta P_m/\Delta P_t$ for flowing oil slugs are summarized in Table 1 and plotted against injection velocity in Fig. 9. From this figure, it is seen that oil–water flow with different sizes of oil slugs at the test velocity range possess very high extra pressure drop. This figure also shows that the smaller the oil slug, the higher the ratio and the more pronounced the extra pressure drop.

Although the above results of differential pressure in slug flow are obtained in a straight capillary, the complexity of slug flow through capillaries is obvious. No sound theories or mathematical models are available for predicting it at present. Understanding the mechanism of slug flow in capillaries is of significance in developing theories and models for predicting multiphase flow in porous media, such as the relative permeability curves in network models.

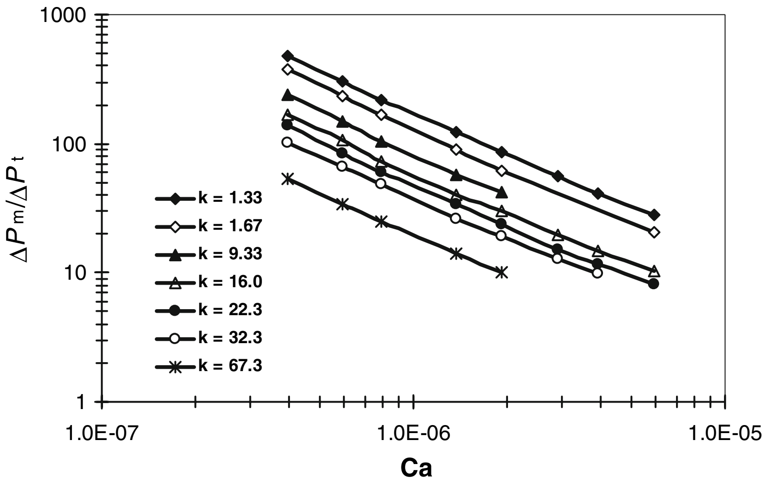

Fig. 9 Ratio of measured viscous pressure drop to the calculated value using Poiseuille equation for oil slugs of various dimensionless lengths and with different capillary numbers

4 Conclusions

Mobilization of trapped oil slugs in a circular capillary has been experimentally studied to investigate the relationship between pressure drop and flow rate. Based on this investigation, a number of conclusions, as discussed below, can be drawn.

When a trapped oil slug in a capillary is mobilized by constant water injection, the oil slug will experience three types of pressure drop: build-up, hold-up, and steady differential pressures. The hold-up pressure drop is always higher than the steady differential pressure. The measured hold-up pressure indicates that the resistance of the capillary to and the viscous pressure drop of oil slug flow are significantly high compared to the pressure drop calculated for laminar flow.

Pressure drop measurement and observation of oil slug shape at every stage revealed that the mobilization of a stationary oil slug is realized by the combination of (1) deformation of the oil slug at the two ends, (2) internal flow within the oil slug, and (3) peeling off of the contact surface of the oil slug from the thin water film at the rear end of the oil slug. There is no displacement of the oil of the immediate layer next to the original contact line relative the tube wall.

Oil–water flow with different sizes of oil slugs in a capillary showed a very high extra pressure drop. The smaller the oil slug, the more pronounced is the extra pressure drop.

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