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Heavy oil recovery by steam-driven hydrocarbon slugs from linear porous packs

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ABSTRACT

This work is principally concerned with an experimental study of oil recovery from a porous pack by the injection of a light hydrocarbon slug, followed by a steam slug, which is in turn driven by a conventional water-flood. The experiments involved fluid displacements in two glass bead packs having a rectangular internal cross-section of 4·45 × 9·53 cm and 122 cm length, overlain and underlain by 45·7 cm thick sandpacks to simulate the adjacent formations, and insulated on the sides.

The sandpack initially contained a residual oil saturation or a high initial oil saturation, corresponding to the irreducible water saturation. Drakeol 33 and Drakeol 35 (viscosities of 152 and 209 cp at 25°C respectively) were employed as the inplace oils, while iso-octane, Soltrol C, Soltrol 170, Kendex 0837, Drakeol 9, and Drakeol 15 and three mixtures of Soltrol C and Drakeol 33, Kendex 0837 and Drakeol 9, and Drakeol 9 and Drakeol 33 (viscosities of 0·5, 1·3, 2·0, 11·3, 23·4, 49·4, 6·4, 17·4, 73·3 cp at 25°C respectively) were used as the light hydrocarbon slug materials. Light hydrocarbon slug sizes of about 5, 10 and 25% were employed, while the steam slug size ranged from 19 to 66% PV, with an average of 35·7% PV. The steam average temperature was 169°C and the steam injection rate ranged from 3·4 to 45·7 m/day.

It was found that the light hydrocarbon slug injected prior to the steam slug in a sandpack initially containing a residual oil saturation improved the oil recovery as compared to a straight steam slug run. In view of the prevailing adverse mobility ratio, the light hydrocarbon mixes with the original inplace oil and helps to lower its viscosity. This viscosity is further reduced by the heat from the injected steam slug, leading to an improvement in the mobility ratio, and hence an improvement in the displacement efficiency. A large proportion of the light hydrocarbon slug is recovered by the steam distillation effects. It is concluded that from the recovery ratio (volume of oil recovered divided by hydrocarbon slug volume) point of view, it is advantageous to use a low viscosity light hydrocarbon slug, and a small slug size. The optimum slug size depends on the inplace oil, as well as the steam slug size, for a given steam temperature.

The temperature profiles and the heat loss rate measurement indicated that the combination light hydrocarbon slug–steam slug process utilises the maximum amount of heat injected, hence increasing the thermal efficiency of the process. The injected water effectively recovers the heat contained in the hot porous medium, transporting it farther downstream; however, the recovery of the heat contained in the adjacent fomations is low.

INTRODUCTION

Combination miscible–thermal methods have been employed in some instances for oil recovery. The authors' previous work (Alikhan & Farouq Ali 1971) described such a recovery method, where a light hydrocarbon slug was injected into an oil-bearing porous pack, followed by a slug of hot water, and finally by cold water. It was shown that the process is highly effective, particularly when the porous pack initially contains a residual oil saturation. The present investigation employs a similar approach, with the difference that the hot water slug is replaced by a steam slug. Experiments were carried out in porous packs. Use of a steam slug in place of hot water led to an increase in total oil recovery, partly because of the steam distillation of the light hydrocarbon slug.

The present investigation was undertaken in order to study the process involving the injection of a light hydrocarbon slug, followed by a steam slug, in turn driven by a cold water-flood, as a means of recovering light and relatively viscous oils from a sandpack containing residual oil or connate water saturation.

Specifically, the effects of the following variables on net oil recovery, hydrocarbon slug recovery, total hydrocarbon recovery, and the recovery ratio were investigated: light hydrocarbon slug size, type of light hydrocarbon, initial oil saturation, temperature distribution in the porous pack and in the adjacent formations, and heat losses.

It was intended to compare the results of this process with the previous results for a similar process where a hot water slug was injected instead of a steam slug.

APPARATUS AND EXPERIMENTAL PROCEDURE

Apparatus

Table 1 gives the properties of the two porous packs used in this study. Each consisted of a rectangular cross-section flanged steel tube, provided with two connections for the pressure transducers on one side, and with fifteen connections for thermocouples on the other side. The tubes were mounted verticaly, and packed under water with glass beads of 130 mesh size. The tubes were fitted with a sintered bronze plate at each end to ensure strictly linear flow within, and placed horizontally over a wooden box with dimensions of 10·2 × 45·7 × 116·8 cm, filled with fine-grained sand to represent the underlying formations. A similar box was placed over the tube to represent the overlying formations. For Runs 9–36, the whole system (sandpack and the adjacent formations) was installed in a vertical position. The system was carefully insulated with fibre-glass sheets to prevent heat losses from the two exposed sides of the glass bead pack.

Figure 1 shows a schematic diagram of the apparatus used in this study. Seventeen thermocouples were used to measure the temperature distribution within the sandpack, as well as the injected and produced fluid temperatures. Nineteen more thermocouples were fitted at selected points in both the overlying and the underlying formations to measure temperature changes during the process. An automatic switching system was used to record the temperatures. This system consisted of a scanner, thermocouple digital thermometer, printer/punch controller, and a printer. The scanner was capable of scanning up to ten points per second. Five heat flux transducers were placed on top of the sandpack (three touching the overlying formation and two touching the underlying formation) to measure the instantaneous heat loss rate to the adjacent formations. A digital millivoltmeter was employed for

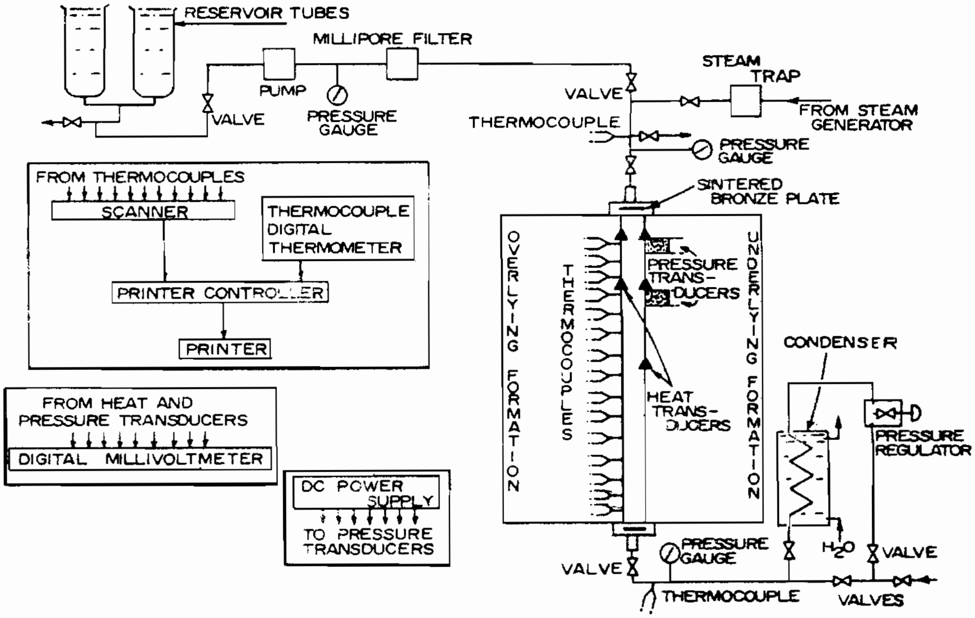

Fig. 1. Schematic diagram of experimental apparatus.

these measurements and its readings were converted by applying a constant multiplier and a thermal correction coefficient supplied for each transducer. The transducers touching the overlying formation were located at 5·1, 25·4 and 61 cm distances from the sandpack inlet, whereas two transducers touching the underlying formation were 5·1 and 27·9 cm from the sandpack inlet. Two pressure transducers, designed for high temperature (to 149°C) and with a pressure range of 0 to 21·3 atm were installed in the tube contacting the porous medium to measure pressure at two points located at 7·6 and 30·5 cm from the sandpack inlet. A nitrogen controlled pressure regulator was used at the outlet to exert the required back pressure for maintaining a constant fluid flow rate. A steam trap was used to prevent the steam condensate from entering into the formation with the injected steam. The effluent from the sandpack passed through a cold water condenser in order to condense any vapour produced in the effluent during the runs.

Table 2 and Fig. 2 give the properties of the fluids used in the present study. Mineral oils Drakeol 35, Drakeol 33, and Soltrol 170 were employed as the test oils, while Drakeol 15, Drakeol 9, Kendex 0837, Soltrol 170, Soltrol C, iso-octane, and three mixtures of these oils were used as the light hydrocarbon slug materials. Toluene, isopropyl alcohol, and water were used for cleaning the sandpack after each run.

Experimental procedure

The sandpack was first saturated with the desired test oil by displacement, after which it was water-flooded (if desired) until a water-oil ratio (WOR) of approximately 100:1 was reached. Next, the desired light hydrocarbon slug was injected at a constant rate. This was then followed by the desired volume of steam slug (at an average pressure of

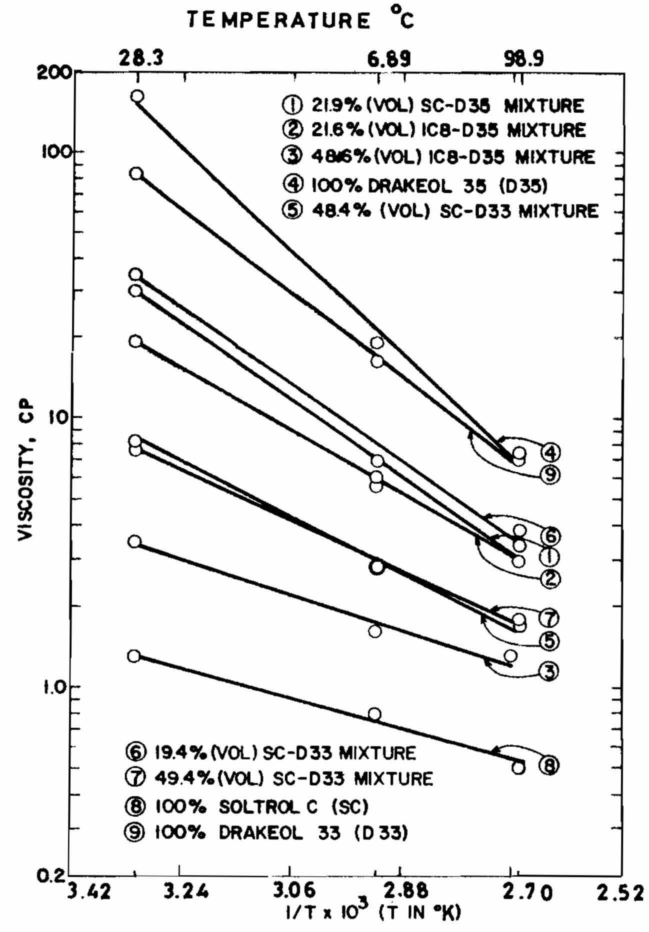

Fig. 2. Viscosity variation with temperature.

approximately 6·8 atm). The steam slug size ranged from 19 to 66% PV with an average slug size of 35·7% PV; the steam temperature ranged from 144 to 175°C. Cold water was then injected to drive the steam slug downstream and the run was terminated when a WOR of 100 : 1 was reached. The sandpack and the adjacent formation temperatures, heat loss rate, and the pressures at two points within the sandpack were measured every 5 to 10 min during the first half of the run, and later every 15 to 20 min. The refractive index of each sample collected was measured to determine the amount of light hydrocarbon recovered along with the original inplace oil.

DISCUSSION OF RESULTS

Table 3 summarizes results of the experiments carried out. Also given are results of the authors' previous experiments employing hot water for comparable conditions. Volumes are given in pore volumes as well as in cc. The various recovery indices used in Table 3, and in the following discussion, are defined below the table. The residual oil saturations obtained ranged from 18·02 to 25·91% PV for Soltrol 170, 28·91 to 41·00%

PV for Drakeol 33, and 30·18 to 38·43% PV for Drakeol 35 (in some runs the sandpack was not water-flooded). Iso-octane, Soltrol C, Soltrol 170, Kendex 0837, Drakeol 9, Drakeol 15, and three other mixtures of Soltrol C and Drakeol 33, Kendex 0837 and Drakeol 9, and Drakeol 9 and Drakeol 35 (M1, M2, and M3, see Table 2), with viscosities of 0·5, 1·3, 2·0, 11·3, 23·4, 49·4, 6·5, 17·4, and 73·3 cp, respectively, at 25°C were used as the light hydrocarbon slugs. The average slug sizes used were about 5, 10, and 25% PV. The steam slug size ranged from 19·27 to 56·68% PV. The steam temperature ranged from 144 to 175°C, with an average of 169°C. The system pressure was approximately constant at 6·8 atm. The steam advance rate varied from 3·4 to 45·7 m/day. Cold water was then injected in order to drive the steam slug and any fluids which had banked up toward the outlet. About 0·7 to 3·5 pore volumes of water were injected.

Displacement of oil by light hydrocarbon, steam and water

The displacement of oil by the proposed process involves a number of effects. The hydrocarbon slug is dispersed rapidly into the oil phase in view of the unfavourable mobility ratio involved. The increase in the oleic phase volume (assuming that initially the oil saturation is residual) leads to the development of an oil bank, at the rear of which there is an extensive transition zone containing the oil and the hydrocarbon in varying proportions. Effectively, this creates a grades oil viscosity zone, which is desirable in displacements at unfavourable mobility ratios (Sancevic 1961; Slobod & Thomas 1963). Steam injection, at this stage, causes further reduction in the oil viscosity close to the inlet end, and leads to oil displacement by a number of mechanisms which were discussed in detail by other authors. An important effect involved in the steam displacement phase of the process is steam distillation of the light hydrocarbon. The distilled fractions are carried farther downstream, where they help lower the viscosity of the cold inplace oil, thus increasing its mobility. On the whole, oil is efficiently displaced by the steam front and, at the same time, its production is facilitated at the outlet end. In the final phase of the process, water is injected to displace the inplace fluids. Water essentially leads to the transformation of the steam slug into a hot water bank. At the same time, the heat contained in the hot porous matrix near the inlet end is transported downstream. A fraction of the heat conducted into the adjacent formations is also recovered. As a result, the overall heat utilization efficiency of the process is improved.

In addition to the effects considered above, gravity segregation of the fluids and temperature variation of the relative permeabilities would affect the overall process.

Figures 3–6 show typical curves for an experimental run (Run 10). Fig. 3 shows the instantaneous and cumulative production curves for the inplace oil (Drakeol 35) and the hydrocarbon slug (Soltrol C), Fig. 4 shows the temperature distribution within the sandpack at various times during the run, Fig. 5 shows the temperature distribution in the adjacent formations, and Fig. 6 depicts the heat loss rates to the adjacent formations. In the last two figures (Figs 5 and 6) the cooling of the adjacent formations and the feedback of heat during cold water injection are clearly evident.

Overall oil recovery efficiency of the process

In considering oil recovery by the combination process, it is instructive to consider

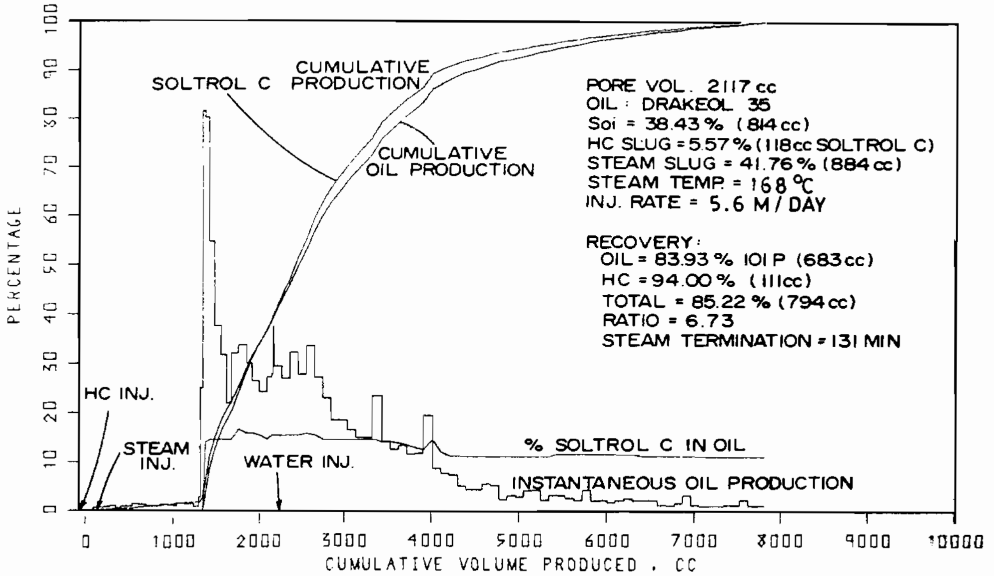

Fig. 3. Production history for Run 10.

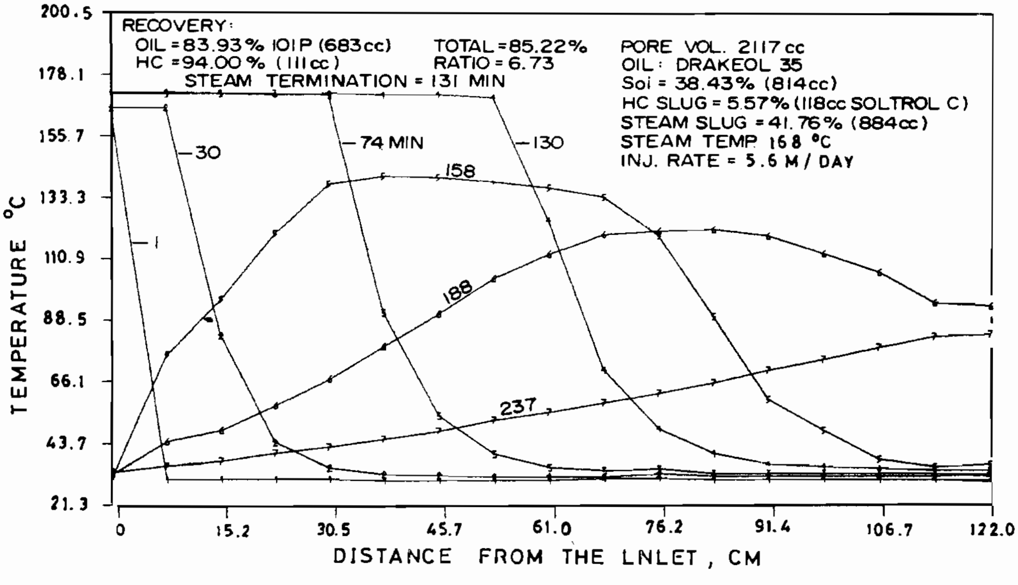

Fig. 4. Temperature profiles in the formation for Run 10.

recovery by straight steam injection into a sandpack containing either a low residual oil saturation, or a high initial oil saturation (corresponding to the irreducible water saturation). Table 4 lists several selected runs for this condition, for iso-octane, Soltrol C, Soltrol 170, Drakeol 33, and Drakeol 35 as the inplace hydrocarbons, i.e. the hydrocarbons used as slugs as well as the inplace oils. From this table it can generally be seen that, first, the steam-flood residual oil saturation increases with the inplace oil viscosity because the water-flood efficiency decreases with an increase in oil viscosity

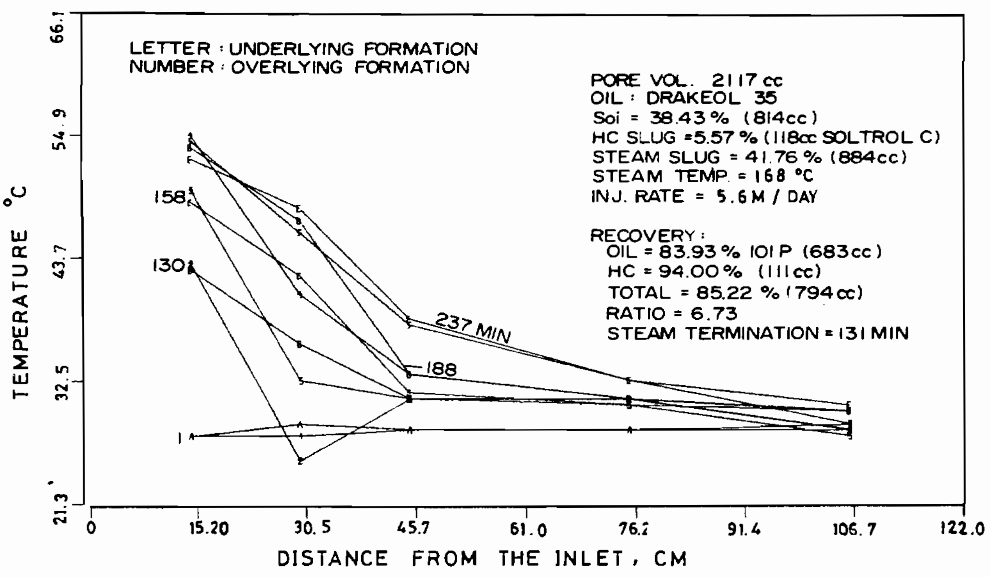

Fig. 5. Temperature profiles in the surroundings for Run 10.

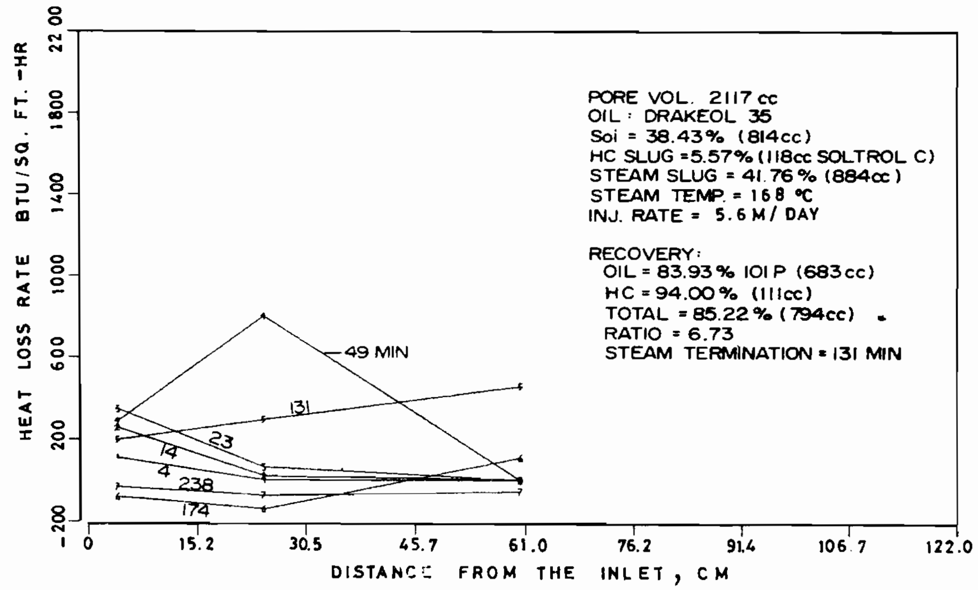

Fig. 6. Heat loss rate to the surroundings for Run 10.

for a given throughput; and secondly, the steam-flood residual oil saturation is approximately the same for either a low residual oil saturation, or a high oil saturation initially present in the sandpack. For example, in the case of iso-octane as the inplace oil, the steam-flood residual oil saturations are 5·6 and 6·6% PV for Runs 1 and 8, respectively; for Soltrol C, 12·8 and 11·2% PV for Runs 4 and 7, respectively, and so forth for the other oils. Consequently, these steam residual oil saturation values could be looked upon as the minimum values which will be obtained if the sandpack contained only these materials. These values could also serve as a basis for comparison of the oil recoveries for the combination process, and are of particular interest in the case of light hydrocarbon slug injection. For instance, in the case of iso-octane as the inplace oil, the steam-flood residual oil saturations were between 5·6 and 6·6% PV for low and high initial oil saturation, respectively. So if an iso-octane slug were used, the minimum steam-flood residual oil saturations will be expected to be higher than the minimum saturation attainable with iso-octane alone as the inplace oil. For example, in Run 12 where the inplace oil was Drakeol 33 and a 10% PV iso-octane slug was used, the steam-flood residual oil saturation was 15·5% PV. Another example is that of Soltrol 170 as the inplace oil, in Runs 20–24, 26–28, and 36, where using different sizes and types of light hydrocarbon slugs, the steam-flood residual oil saturations were 16·2, 8·3, 11·6, 14·7, 16·3, 18·2, 15·8, 18·5 and 10·2% PV, respectively. All of these values are of the same order of magnitude as the steam-flood residual oil saturation value obtained for Soltrol 170 alone, with no light hydrocarbon slug injection, as in Run 20. A similar observation can be made in the case of Drakeol 33 as the inplace oil. It could be concluded that the overall oil recovery efficiency of the combination process is high. This is seen by the comparison of the observed steam-flood residual oil saturation with that for the light hydrocarbon slug material alone as the inplace oil in the sandpack subjected to a steam-flood.

It should be noted that in the various runs listed in Table 3, the amount of steam injected, the steam injection rate, and the steam temperature are somewhat different. Thus to place all these runs on a common basis, the above variations were considered in order to adjust the recovery and/or the light hydrocarbon slug size used in each run. Since it was assumed that the recovery will depend on the amount of heat utilised in each run, the fraction of heat utilised, ε, was calculated as a function of time, on the basis of Marx and Langenheim's equation (Farouq Ali 1970). Next, in a given run, the amount of the total heat injected H_0 was multiplied by ε. A base value of ε was selected for the straight steam slug runs, and all other runs were then reduced to that datum by a multiplying factor F. The factor F is defined as the net amount of heat utilised in a run divided by that value for the straight steam slug run. This factor was then multiplied by the light hydrocarbon slug size, HC, to obtain the modified slug size, FHC. This slug size takes into account the differences occurring in the steam injection phase of each run. In the cases where selected runs were grouped together to study the effect of the light hydrocarbon slug viscosity on the recovery, an average modified slug value (FHC^*) was used. All other runs in that group were referred to it through a factor, F^*. The factor F^* is defined as the modified light hydrocarbon slug value of a run divided by the average modified value, FHC^*. The total oil recovery was then divided by F^* in order to obtain comparable values of oil recoveries, R^*, that consider the variations in the modified slug sizes. While the above procedure placed all the runs on a common base as far as the heat utilised is concerned, the general trends were the same as those observed without the compensating factor.

Effect of light hydrocarbon slug viscosity on oil recovery

Runs 3, 9, 12, 13, 16, 19, 20, 22–24, 26–28, and 31–35 give recoveries for Drakeol 35 and 10% PV slug of different types of light hydrocarbons, with the sandpack initially containing a high oil saturation; Drakeol 33 and 10% PV slug of different types of light hydrocarbon and the sandpack initially containing a residual oil saturation; and

Soltrol 170 and 10% PV slug of different light hydrocarbon types and again the sandpack initially containing a residual oil saturation.

Figure 7 shows the percent recovery (light hydrocarbon, net inplace oil, total oil, and modified total oil recovery as well as the steam-flood residual oil saturation) as functions of the light hydrocarbon slug viscosity for Drakol 33. Similar trends were observed for the other two oils. It is seen that the steam-flood residual oil saturation is independent of the light hydrocarbon slug viscosity, and the oil recovery tends to increase slightly with the light hydrocarbon slug viscosity. The light hydrocarbon slug recovery decreases at first with the slug viscosity and then increases somewhat. Essentially, it follows that in the case of viscous oils (such as Drakeol 33 or 35) in the sandpack, the light hydrocarbon slug has a relatively small effect on the oil recovery. For a light hydrocarbon slug, the hydrocarbon recovery is high because the slug material is more easily steam distilled. For a higher slug viscosity, the hydrocarbon recovery tends to be higher, because the mobility ratio at the slug inplace oil interface is somewhat less adverse. This explains the speculated minimum in the light hydrocarbon recovery curve in Fig. 7.

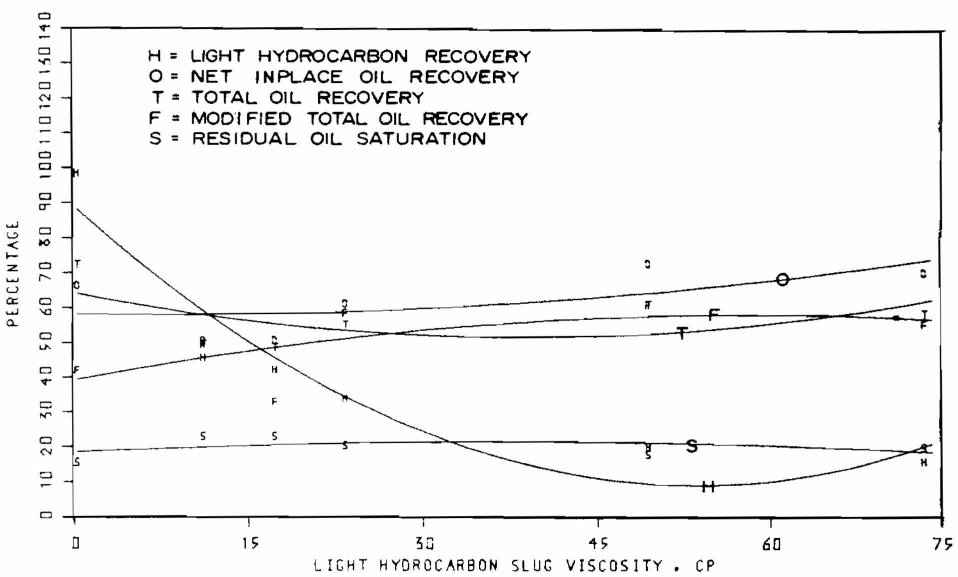

Fig. 7. Effect of light hydrocarbon slug (10% PV) type on recovery in Drakeol 33 ($S_{oi} = S_{or}$) and steam slug runs.

Effect of the light hydrocarbon slug size on oil recovery

Results of Runs 2, 3, 6, 11–15, 17, 18, 20, 22, 25, and 36 provide an insight into the effect of a particular light hydrocarbon slug size on oil recovery, for a given oil and a given initial oil saturation. Fig. 8 shows the recovery and the residual oil saturation curves for one particular case: iso-octane slug, with Drakeol 33 in the sandpack at a high initial oil saturation. As in the other cases, it is seen that the steam-flood residual oil saturation increases with the slug size, and there is a small decrease in the net and total oil recoveries. The overall behaviour shows the net effect of several competing phenomena. Generally, it may be expected that as the light hydrocarbon slug size increases, the total oil recovery should increase and hence the steam residual oil saturation should decrease. It could also be expected that the light hydrocarbon recovery will increase as well. Up to a certain point, this is the case, and the light hydrocarbon slug is effective in increasing the oil recovery and the light hydrocarbon material itself is produced efficiently by the injected steam. However, beyond a certain slug size, which for Fig. 8 seems to be 15–20% PV, the light hydrocarbon slug is not efficiently produced and, as a result, the total oil recovery as well as the slug material recovery, seem to decrease for the larger slug sizes. Therefore, the optimum light hydrocarbon slug size that will help to increase the oil recovery, while, at the same time, ensuring a high slug recovery by the injected steam would depend on the steam slug size. For instance, for a large steam slug size, a larger light hydrocarbon slug could be produced back, resulting in a high light hydrocarbon recovery. Table 3 (Runs 6, 11 and 15) shows that the steam-flood residual oil saturation was always higher than the base value (for a straight steam-flood) of 8·4% in Run 6.

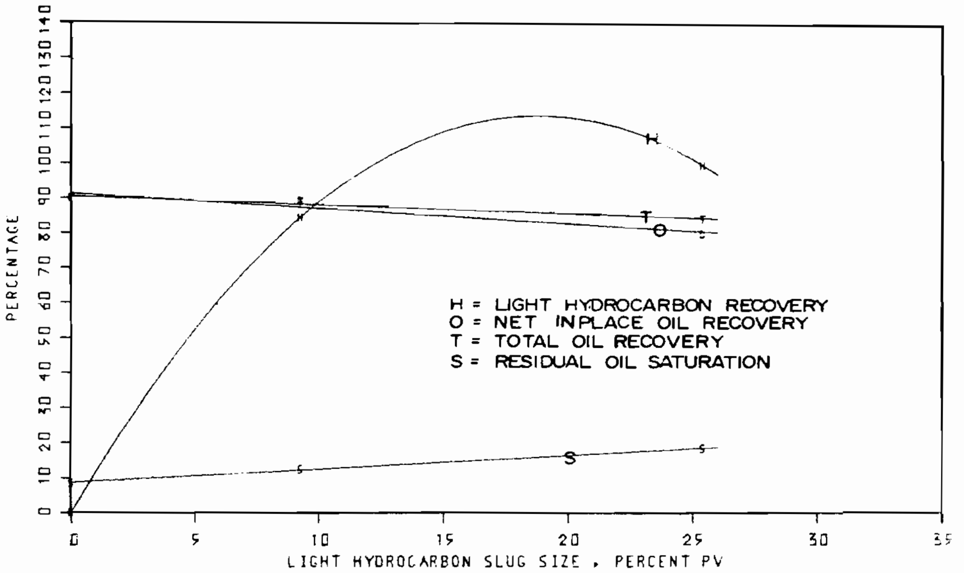

Fig. 8. Effect of light hydrocarbon (iso-octane) slug size on recovery in Drakeol 33 ($S_{oi} = 1 - S_{wr}$) and steam slug runs.

Effect of the initial oil saturation on oil recovery

From Table 3, it can be concluded that in the case of an initially high oil saturation ($S_{oi} = 1 - S_{wr}$) in the sandpack, the injected light hydrocarbon was not effective. In fact, the recovery was lower in several cases as compared to the recovery without any light hydrocarbon slug injection. (When Soltrol C was used as the light hydrocarbon slug there was a slight increase in the total recovery for the larger slug size of 25% PV.) It should be noted also that, in this case, the steam-flood residual oil saturations were higher than those obtained with no light hydrocarbon used. For example, in Runs 11 and 15, the steam-flood residual oil saturations were 12·5 and 18·4% PV, respectively, for the iso-octane slugs, as compared to the value of 8·4% PV for the straight steam slug (Run 6). Similar observations were made when Soltrol C was used instead of iso-octane as the light hydrocarbon slug. Therefore, it can be concluded, once again, that the injection of a light hydrocarbon slug in this case did not help increase the oil recovery.

In contrast to the above results, consider Runs 2, 9, 12, 20, 22, 25 and 36 in Table 3. Fig. 9 shows the results for Drakeol 33 for a residual oil saturation initially in the sandpack. It is noticeable that there is a definite decrease in the steam-flood residual oil saturation and an increase in oil recovery with an increase in the hydrocarbon slug size up to a 10–15% slug size, beyond which the trends reverse. The light hydrocarbon recovery shows a behaviour similar to that of the previous case. The increase in recovery and the decrease in the steam-flood residual oil saturation is even more evident in Table 3, where the steam-flood residual oil saturation for no light hydrocarbon slug is 24·9% PV, and contrasts with the values of 7·3, 15·5, and 12·4% PV for Runs 2, 12 and 25, respectively. Thus, on the basis of these and other results in Table 3, it can be concluded that the light hydrocarbon slug was effective in the case of an initially residual oil saturation rather than the high initial oil saturation. The reason for an increase in oil recovery in the case of an initially residual oil saturation is that initially the relative permeability to water is high while the relative permeability to oil is zero. As a result, if steam alone is injected, it will displace water more efficiently and the contact with oil will be inefficient and, consequently, oil production will be small. However, when a light hydrocarbon slug is injected prior to the steam injection, the relative permeability to oil will increase because of an increase in the oil saturation and thermal expansion. When steam is injected, the displaced oil banks up the oil ahead. In

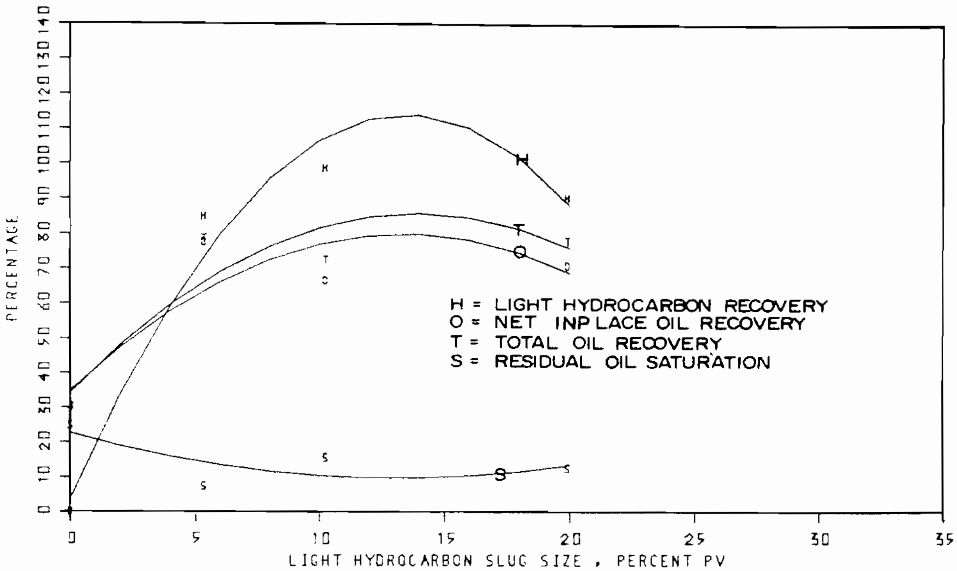

Fig. 9. Effect of light hydrocarbon (iso-octane) slug size on recovery in Drakeol 33 ($S_{oi} = S_{or}$) and steam slug runs.

this manner, the injected steam is more fully utilised to displace oil than in the case where no oil bank is present and the relative permeability to oil is initially zero. On the other hand, in the runs where the initial oil saturation is high ($S_{oi} = 1 - S_{wr}$), the steam is quite effective in displacing the oil because of the high relative permeability to oil initially present. Comparison of Runs 11 and 12 shows that for Drakeol 33 in the sandpack and a 10% PV iso-octane slug, for different initial oil saturations, the recovery was higher in the case of high initial oil saturation rather than that in the case of a low initial residual oil saturation. Steam residual oil saturations of 12·4 and 15·5% PV for Runs 11 and 12, respctively, were obtained. This showed that the recovery would be higher in the case of high initial oil saturations than for residual oil saturation initially in the sandpack if steam alone is injected.

Effect of the light hydrocarbon slug size and viscosity on the recovery ratio

As defined in Table 3, the recovery ratio is the amount of total oil recovered, divided by the amount of light hydrocarbon slug injected. On the basis of the experimental results, it could be concluded that as the light hydrocarbon slug viscosity increases, the recovery ratio decreases for Drakeol 35 for an initially high oil saturation. This was also the case for Soltrol 170 with a low initial oil saturation. For the Drakeol 33, with a low initial residual oil saturation, the recovery ratio tends to decrease with an increase in light hydrocarbon slug viscosity up to a viscosity of about 40 cp, beyond which the recovery ratio shows an increasing trend. The recovery ratio can be looked upon as an economic index, and is the net outcome of the interactions between different variables, and as such it is difficult to explain its variation with the increase in the light hydrocarbon slug viscosity. The effect of the light hydrocarbon slug size is more clearly seen in the case of Drakeol 33 and Soltrol 170 as the inplace oils, and iso-octane as the light hydrocarbon slug. Fig. 10 shows that, in both cases, the recovery ratio decreases

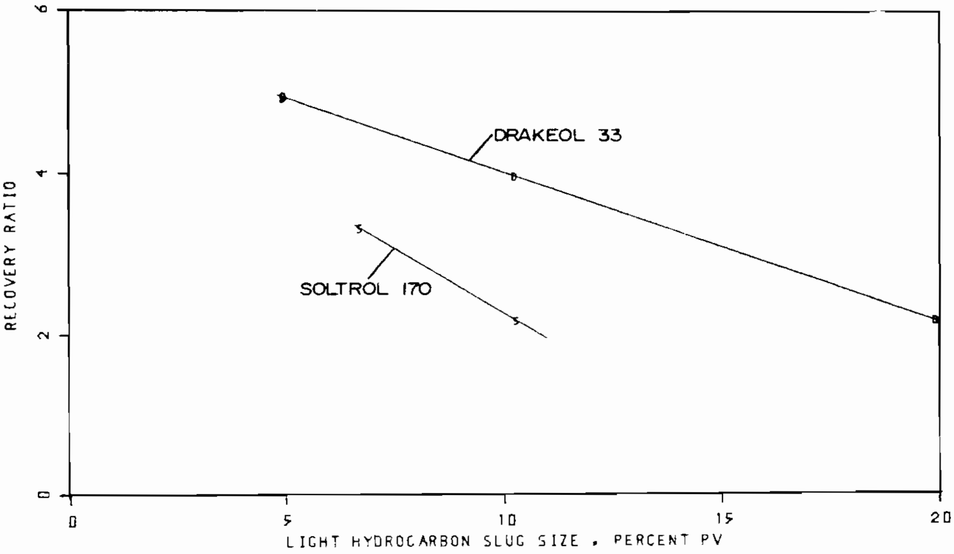

Fig. 10. Effect of light hydrocarbon (iso-octane) slug size on recovery ratio in Drakeol 33 and Soltrol 170 and steam slug runs.

as the light hydrocarbon slug size increases. Based upon the definition of the recovery ratio, such behaviour is expected. It is conjectured that it is advantageous, from the recovery ratio point of view, to use a low light hydrocarbon slug viscosity and small slug sizes.

COMPARISON OF THE STEAM-DRIVEN HYDROCARBON SLUG RUNS WITH HOT WATER-DRIVEN HYDROCARBON SLUG RUNS

Table 3 lists selected runs from the authors' previous work where hot water-driven light hydrocarbon slugs rather than steam-driven light hydrocarbon slugs were used. It is possible to compare selected runs, these being Runs 1–3, 5, 6, 9, 11–13 and 25 with comparable runs of the previous work. It is readily seen that, in each case, the recovery ratio is higher and the steam-flood residual oil saturation is lower when a steam slug was used instead of a hot water slug. As in the present work, it was found that the recovery tends to increase as the light hydrocarbon slug size increases and for a certain slug size, the recovery tends to attain a plateau, beyond which with any increase in the slug size, the increase in recovery is very small. On the other hand, the light hydrocarbon slug viscosity in the case of hot water-driven slugs had a greater effect than in the present case of steam-driven slugs. In the case of hot water, the percent oil recovery increased up to a certain point and then decreased. It is significant that, as in the present case, the hot water-driven slugs were effective in water-flooded sandpacks as compared to a sandpack containing a high initial oil saturation. This is the most striking similarity of the two processes.

CONCLUSIONS

Based upon the conditions of the present investigation, the following conclusions are derived:

1. In a straight steam slug displacement, the steam-flood residual oil saturation increases with an increase in the inplace oil viscosity, due to the low efficiency of the preceding water-flood. This saturation was approximately the same for either a low or high initial oil saturation in the sandpack.
2. In the case of a *high* initial oil saturation in the sandpack, the injected light hydrocarbon slug had little effect on oil recovery; in fact, the recoveries were often lower as compared to straight steam slug injection. On the other hand, the light hydrocarbon injection was highly effective in the case where the sandpack initially contained a *residual* oil saturation, as compared to straight steam slug injection. The magnitudes of the above results were different, however, the general trend being the same when the slug sizes were modified to account for the differences in the amounts and rates of steam injected in each run.
3. It is concluded that from the recovery ratio point of view, it is advantageous to use a low viscosity light hydrocarbon slug and a small slug size. The optimum slug size depends on the inplace oil, as well as the steam slug size, for a given steam temperature.
4. As also observed in the authors' previous work, employing a hot water slug instead of a steam slug in the present study, oil recovery was found to depend on the inplace oil viscosity, and the overall recovery efficiency of the combination process is high. Furthermore, it was found that the recovery ratio is higher and the steam residual

oil saturation is lower, when a steam slug is used rather than a hot water slug. In both cases, the recovery tends to attain a plateau after which there is no significant increase in recovery with an increase in the light hydrocarbon slug size. The most significant similarity of the two processes is that they are more effective in water-flooded sandpacks.

5. The temperature profiles and the heat loss rate measurement indicated that the combination, light hydrocarbon slug–steam slug process utilises the maximum amount of heat injected, hence increasing the efficiency of the process. The injected water effectively recovers the heat contained in the hot porous pack, transporting it farther downstream; however, the recovery of the heat contained in the adjacent formation is low.

REFERENCES

Alikhan, A.A. & Farouq Ali, S.M. 1971. Oil recovery by hydrocarbon slugs driven by a hot water bank. Soc. Petrol. Eng. J. **11:** 342–50.

Farouq Ali, S.M. 1970. Oil recovery by steam injection, p. 70. Producers Publishing Company, Inc., Bradford, Pennsylvania, USA.

Sancevic, Z. 1961. Effect of adverse mobility ratios and graded viscosity zones on viscous fingering in miscible displacement. Master's thesis, The Pennsylvania State University, University Park, USA.

Slobod, R.L. & Thomas, R.A. 1963. Effect of transverse diffusion on fingering in miscible phase displacement. Soc. Petrol. Eng. J. **3:** 9–13.

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Table 1. Properties of the porous packs used

Property	Sandpack 1*	Sandpack 2†
Length, cm	10·2	10·2
Width, cm	0·79	0·79
Thickness, cm	0·37	0·37
Pore volume, cc	2117	2281
Porosity, %PV	40·21	43·32
Permeability, darcies	8·225	7·720

Packing: Unconsolidated glass beads of 130 mesh size with a distribution of 0–15% of 120 and 85–100% of 170 mesh size.

* Sandpack 1 was used for Runs 1–12.

† Sandpack 2 was used for Runs 13–36.

Table 2. Properties and classification of the fluids used

Fluid	Molfraction	Molecular weight g/g-mole	ρ g/cc	μ cp	Boiling point range (°C)
Water	1·0000	18	0·9980*	1·00	100
IC8	1·0000	114	0·6868	0·47*	94–118†
SC	1·0000	170	0·7501	1·33	184–202†
S170	1·0000	198	0·7702	1·97	218–238†
Kendex 0837	1·0000	287	0·8444	11·25	314–370‡
D9	1·0000	389§	0·8454	23·43	322–466§
C1	0·0678	280	0·8300		322–364
C2	0·5596	380	0·8400		374–410
C3	0·3726	420	0·8550		419–466
D15	1·0000	428	0·8626	49·40	327–494
C1	0·0680	300	0·8400		327–375
C2	0·5540	415	0·8600		384–437
C3	0·3780	450	0·8750		448–494
D33	1·0000	469	0·8706	152·00	357–499
C1	0·0729	290	0·8400		357–409
C2	0·5238	460	0·8700		431–466
C3	0·4033	500	0·8900		472–499
D35	1·0000	474	0·8776	208·58	364–501
C1	0·0747	300	0·8400		364–424
C2	0·5491	465	0·8700		433–466
C3	0·3762	505	0·8900		473–501
M1	1·0000	211	0·8178	6·46	184–499
C1	0·7554	128	0·7501	1·33	184–202
C2	0·0178	290	0·8400		357–409
C3	0·1281	460	0·8700		431–466
C4	0·0987	500	0·8900		472–501
M2	1·0000	341	0·8441	17·37	314–466
C1	0·4713	287	0·8444	11·25	314–370
C2	0·0359	280	0·8300		322–364
C3	0·2959	380	0·8400		374–410
C4	0·1970	420	0·8550		419–466
M3	1·0000	400	0·8644	73·29	322–501
C1	0·0586	280	0·8300		322–364
C2	0·4835	380	0·8400		374–410
C3	0·3219	420	0·8550		419–466
C4	0·0102	300	0·8400		364–424
C5	0·0747	465	0·8700		433–466
C6	0·0512	505	0·8900		473–501

* All densities (in parentheses) and viscosities were measured in the laboratory except those for the Drakeol fractions. These were estimated and their molfractions were calculated.

† Philips Petroleum Company, Bartlesville, Oklahoma.

‡ Kendall Refining Company, Bradford, Pennsylvania.

§ Molecular weight and average normal boiling point temperatures for Drakeol 9, 15, 33 and 35 were provided by the Pennsylvania Refining Company, Butler, Pennsylvania.

Note: M1 = 49·4% SC in D33 mixture; M2 = 39·7% Kendex 0837 in D9 mixture; M3 = 84·4% D9 in D35 mixture; IC8 = Iso-octane; SC = Soltrol C; S170 = Soltrol 170; D9 = Drakeol 9; D15 = Drakeol 15; D33 = Drakeol 33; D35 = Drakeol 35. C1–C6 fractions of the test oils used.

Table 3. Summary of the experimental data obtained

	Test Oil		Waterflood		Steam Slug			H.C. Slug								Authors' previous work		
Run	Type	S_{oi} %PV	Rec. %	S_{or} %PV	Size %PV	°C	Rate m/day	Type	Size %PV	CW rate m/day	HC* %	Test† Oil %	Total‡ %	Ratio§	$S_{or_{st}}$‖ %PV	Time min.	Run	Rec. ratio	$S_{or_{hw}}$‖
1	IC8	70·85	77·57	15·90	33·82	144·4	45·67	—	—	24·16	—	64·93	64·93	—	5·57	90·5	17	—	10·71
		(1500)	(1164)	(337)	(716)		(55·08)			(29·83)		(218·50)	(218·50)		(118·0)	(13)			(181)
2	D33	86·73	66·67	28·91	33·82	144·4	22·83	IC8	5·34	26·22	84·91	77·46	78·62	5·04	7·32	230·0	15	3·96	12·84
		(1836)	(1224)	(612)	(716)		(27·54)		(113)	(31·62)	(95·95)	(474·05)	(570·00)		(155·0)	(26)			(217)
3	D35	94·00			19·27	169·9	3·07	—	—	49·99	—	87·09	87·09	—	12·14	235·5	20	—	25·15
		(1990)			(408)		(3·71)			(60·29)		(1733·0)	(1733·0)		(257·0)	(110)			(425)
4	SC	73·45	76·59	17·19	34·53	164·9	8·42	—	—	20·66	—	25·82	25·82	—	12·75	219·1	7	—	30·89
		(1555)	(1191)	(364)	(731)		(10·15)			(24·92)		(94·0)	(94·0)		(270·0)	(72)			(522)
5	D35	85·40	64·66	30·18	20·78	165·3	3·41	—	—	44·52	—	46·79	46·79	—	16·06	210·9	5	—	34·14
		(1808)	(1169)	(639)	(440)		(4·11)			(53·69)		(299·0)	(299·0)		(340·0)	(107)			(577)
6	D33	80·92			21·59	152·9	5·65	—	—	38·03		89·98	89·98	—	8·41	124·8			
		(1776)			(457)		(6·82)			(45·86)		(1598)	(1598)		(178·0)	(67)			
7	SC	72·51			31·84	158·4	9·78	—	—	46·33	—	84·63	84·63	—	11·15	70·9			
		(1535)			(674)		(11·80)			(55·87)		(1299)	(1299)		(236·0)	(21)			
8	IC8	68·54			21·20	158·4	14·89	—	—	48·99	—	90·42	90·42	—	6·57	66·9	4	—	18·05
		(1451)			(449)		(17·96)			(59·07)		(1312)	(1312)		(139·0)	(28)			(305)
9¶	D33	97·92	63·58	35·66	41·00	167·6	6·45	—	—	42·47	—	30·20	30·20	—	24·89	260·5			
		(2073)	(1318)	(1755)	(850)		(7·78)	—	—	(51·22)		(228)	(228)		(527·0)	(97)			
10	D35	93·01	58·68	38·43	41·76	168·1	5·59	SC	5·57	45·15	94·09	83·93	85·22	6·73	6·50	261·0			
		(1969)	(1156)	(814)	(884)		(6·75)		(118)	(54·44)	(111·00)	(682·8)	(793·8)		(137·7)	(131)			
11**	D33	92·00			52·29	169·9	8·58	IC8	9·26	44·82	84·54	87·98	87·66	9·59	12·49	217·0	2	6·47	36·75
		(1948)			(1102)		(10·36)		(196)	(54·06)	(165·71)	(1714)	(1880)		(264·5)	(106)			(621)
12**	D33	92·00	50·31	41·00	56·68	168·1	7·95	IC8	10·25	42·22	98·70	74·09	79·01	3·95	15·48	245·0	3	2·77	8·76
		(1948)	(980)	(868)	(1200)		(9·60)		(217)	(50·92)	(214·2)	(643·1)	(857·3)		(327·7)	(125)			(148)
13	D35	87·35			34·77)	168·7	13·15	IC8	9·34	48·16	106·95	81·29	83·77	8·67	15·69	160·0	21	6·25	31·95
		(1993)			(973)		(15·86)		(213)	(58·08)	(227·8)	(1619·7)	(1847·5)		(358·0)	(50)			(540)
14	D35	89·41			38·54	168·5	10·72	IC8	24·99	30·37	106·46	77·53	83·85	3·84	18·48	252·0			
		(2040)			(879)		(12·93)		(570)	(36·63)	(606·84)	(1581·2)	(2188)		(421·5)	(68)			
15	D33	90·31			35·55	170·2	10·47	IC8	25·38	34·69	99·74	79·73	84·12	3·83	18·37	225·0			
		(2060)			(811)		(12·67)		(579)	(41·84)	(577·5)	(1642·5)	(2220)		(419·0)	(64)			
16	D35	90·12			31·65	168·7	6·57	SC	10·26	40·62	102·60	81·37	83·48	8·17	16·58	220·0			
		(2056)			(722)		(7·93)		(234)	(48·99)	(238·8)	(1672·7)	(1911·5)			(91)			
17	D33	89·62			40·16	170·6	8·63	SC	10·04	34·06	106·03	80·01	82·63	8·20	17·31	245·0			
		(2044)			(916)		(10·41)		(229)	(41·08)	(242·81)	(1635·59)	(1878·4)		(394·9)	(88)			
18	D33	89·63			40·00	172·9	9·45	SC	25·12	37·73	95·49	82·97	85·72	3·92	16·39	238·0			
		(2046)			(912)		(11·40)		(573)	(45·50)	(547·18)	(1696·41)	(2243·59)		(373·9)	(80)			
19	D35	89·07			30·56	170·4	5·38	D9	10·13	41·86	81·36	83·81	83·56	8·19	16·30	214·0			
		(2032)			(697)		(6·49)		(231)	(50·48)	(187·93)	(1702·87)	(1890·8)		(371·9)	(108)			

20	S170	80·03 (1826)	71·95 (1314)	22·44 (519)	29·29 (668)	172·2	6·25 (7·54)	—	—	41·96 (50·60)	—	27·76 (142·1)	27·76 (142·1)	—	16·21 (369·7)	181·0 (89)			
21	S170	77·99 (1779)	76·89 (1368)	18·02 (411)	32·84 (749)	175·2	7·48 (9·02)	M1	10·17 (232)	39·94 (48·17)	31·74 (73·65)	92·67 (380·95)	70·69 (454·6)	1·96	8·26 (188·5)	196·0 (83)			
22	S170	83·43 (1903)	71·73 (1365)	23·58 (538)	43·05 (982)	172·7	8·52 (10·28)	IC8	10·30 (235)	48·39 (58·36)	59·37 (139·52)	68·58 (368·88)	65·78 (508·4)	2·16	11·60 (264·5)	185·0 (96)			
23	S170	83·34 (1901)	72·43 (1377)	22·98 (524)	42·88 (978)	174·6	6·78 (9·29)	S170	10·21 (233)	37·43 (45·14)	—		55·86 (423)	1·82	14·65 (334·2)	225·0 (105)			
24	S170	83·78 (1911)	72·04 (1377)	23·42 (534)	44·50 (1015)	172·6	9·96 (12·01)	D9	9·91 (226)	37·41 (45·12)	15·80 (35·72)	66·08 (353·08)	51·14 (388·8)	1·72	16·29 (371·5)	210·0 (84)			
25	D33	89·48 (2041)	60·28 (1230)	35·54 (811)	65·54 (1495)	173·6	11·87 (14·32)	IC8	19·90 (454)	32·53 (39·23)	90·07 (408·92)	70·70 (573·18)	77·65 (982·1)	2·16	12·39 (282·6)	228·0 (105)	13	1·65	11·42 (193)
26	S170	84·26 (1922)	69·56 (1337)	25·65 (585)	36·08 (823)	173·7	9·41 (11·35)	Kendex 0837	10·04 (229)	41·70 (50·29)	12·77 (29·23)	63·26 (370·07)	49·05 (399·3)	1·74	18·18 (414·7)	161·0 (72)			
27	S170	84·39 (1925)	70·16 (1351)	25·19 (575)	40·29 (919)	171·0	8·40 (10·13)	M1	10·26 (234)	35·73 (43·09)	22·64 (52·98)	68·90 (395·82)	55·51 (448·8)	1·92	15·77 (359·7)	178·0 (92)			
28	S170	84·61 (1930)	70·10 (1353)	25·30 (577)	32·32 (737)	171·8	6·93 (8·36)	D15	10·11 (231)	24·78 (29·88)	14·78 (34·07)	60·90 (351·43)	47·73 (385·5)	1·67	18·51 (422·1)	216·0 (90)			
29	S170	84·13 (1919)	69·20 (1328)	25·91 (591)	—	34·1	—	IC8	10·08 (230)	—	6·87 (15·80)	25·87 (152·90)	20·55 (168·7)	0·73	28·59 (652·2)	79·0 (0)			
30	S170	84·04 (1917)	69·93 (1341)	25·27 (577)		34·1	—	D15	10·13 (231)	39·82 (48·08)	0·47 (1·08)	24·76 (142·72)	17·81 (143·8)	0·62	29·10 (663·7)	129·0 (0)			
31	D33	89·87 (2050)	60·93 (1249)	35·12 (801)	29·16 (665)	174·8	4·61 (5·57)	D9	10·07 (230)	41·52 (49·81)	33·72 (77·41)	61·16 (489·89)	55·05 (567·3)	2·47	20·31 (463·3)	229·0 (120)			
32	D33	90·18 (2057)	60·67 (1248)	35·47 (809)	29·64 (676)	173·0	5·60 (6·76)	D15	10·04 (229)	41·83 (50·45)	19·95 45·69)	72·44 (586·01)	60·86 (631·7)	2·76	17·81 (406·3)	211·0 (101)			
33	D33	89·70 (2046)	60·46 (1237)	35·47 (809)	29·55 (674)	173·6	5·35 (6·46)	Kendex 0837	10·14 (231)	44·20 (53·31)	45·57 (105·44)	50·56 (409·06)	49·45 (514·5)	2·22	23·06 (525·9)	206·0 (104)			
34	D33	89·00 (2030)	60·99 (1238)	34·72 (792)	44·29 (1010)	172·4	7·98 (9·63)	M2	10·09 (230)	43·88 (52·92)	42·11 (96·90)	50·58 (400·8)	48·61 (496·8)	2·16	23·03 (525·3)	194·0 (106)			
35	D33	90·09 (2055)	58·73 (1207)	37·18 (848)	30·27 (691)	174·7	6·23 (7·52)	M3	10·17 (232)	42·03 (50·69)	15·68 (36·37)	70·00 (593·63)	58·33 (630·0)	2·72	19·73 (450·0)	200·0 (93)			
36	S170	85·40 (1948)	69·92 (1362)	25·69 (586)	40·07 (914)	174·6	9·52 (11·48)	IC8	6·72 (153)	47·39 (57·14)	61·22 (93·79)	70·63 (413·81)	68·68 (507·60)	3·31	10·15 (231·5)	150·0 (80)			

* (Hydrocarbon slug volume produced) × 100/(Hydrocarbon slug volume injected).

† (Total hydrocarbon produced − Hydrocarbon slug volume produced) × 100/(Initial oil inplace).

‡ (Total hydrocarbon produced) × 100/(Initial oil inplace + Hydrocarbon slug volume injected).

§ (Total hydrocarbon produced)/(Hydrocarbon slug volume injected).

‖ (Initial oil in place + Volume of slug material injected − Total oil produced) × 100/(Pore volume).

¶ Sandpack was put in vertical position. Difficulty in closing the steam trap valve, hence steam slug size was approximate.

** S_{oi} modified because of setting in the sand due to steam injection in the vertical position.

Note: Runs 1–12 Sandpack 1 (pore vol. = 2117cc), Runs 13–36 Sandpack 2 (pore vol. = 2281cc); M1 = 49·4% SC in D33 mixture; M2 = 39·7% Kendex 0837 in D9 mixture; M3 = 84·4% D9 in D35 mixture; IC8 = iso-octane; Sc = Soltrol C; S170 = Soltrol 170; D9 = Drakeol 9; D15 = Drakeol 15; D33 = Drakeol 33; D35 = Drakeol 35; HC = light hydrocarbon.

Figures in parentheses are actual volumes in cc, actual rates in cc/min, and the duration of steam injection in min.

Table 4. Experimental data for the studies of the effect of inplace oil type and initial oil saturation on straight steam injection

Run	μ cp	$\frac{\text{Oil}}{S_{oi}}$ %PV	Type	Rec %*	S_{orst}† %PV
1	0·5	15·9	IC8	64·9	5·6
8	0·5	68·5	IC8	90·4	6·6
4	1·3	17·2	SC	25·8	12·8
7	1·3	72·5	SC	84·6	11·2
20	2·0	22·4	S170	27·8	16·2
9	152	35·7	D33	30·2	24·9
6	152	80·9	D33	90·0	8·4
5	209	30·2	D35	46·8	16·1
3	209	94·0	D35	87·1	12·1

* (Total hydrocarbon produced – Hydrocarbon slug volume produced) × 100/(Initial oil in place).

† (Initial oil in place + Volume of slug material injected – Total oil produced) × 100/(Pore volume).

Note: IC8 = Iso-octane; SC = Soltrol C; S170 = Soltrol 170; D33 = Drakeol 33; D35 = Drakeol 35.

استخراج الزيت الثقيل بواسطة الزيت الخفيف والبخار

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خلاصة

يعني هذا البحث باستخراج الزيت الثقيل من وسط مسامي بواسطة حقن كميات معينة من الزيت الخفيف متبوعة بكميات من البخار ، ثم دفع هذا الخليط بالماء .

أجريت التجارب عندما كان الوسط المسامي مشبعا بنسب عالية من الزيت الثقيل تارة ، ونسب قليلة جدا تارة أخرى . وقد استعمل نوعان من الزيت المعدني الثقيل بدرجة لزوجة ١٥٢ و ٢٠٩ (cp) عند درجة حرارة ٢٥° م ، وعدة أنواع من الزيت المعدني الخفيف بدرجة لزوجة تتراوح بين ٠,٥ و ٧٣,٣ (cp) عند درجة حرارة ٢٥° م ، وكان حجم الزيت الخفيف المستخدم حوالي ٥٪ و ١٠٪ و ٢٥٪ من الحجم المسامي المختبر .

وقد حقن البخار بنسبة ٣٦٪ من الحجم المسامي عند درجة حرارة ١٦٩° م . واظهرت النتائج ان الحقن بالزيت الخفيف قبل البخار قد زاد في الانتاج في الحالات التي يتواجد فيها الزيت الثقيل بنسب قليلة .

ان التباين الكبير بين حركة الزيت الخفيف وحركة الزيت الثقيل يزيد من سرعة المزج بينهما ، مما يقلل من درجة لزوجة الخليط ، وتستمر درجة لزوجة الخليط في الانخفاض بواسطة حرارة البخار ، مما يزيد الحركة بين الزيتين فتتحسن بذلك كفاءة ازاحة الزيت الثقيل .

لقد وجد أنه من الأفضل استخدام نسب أقل من الزيت الخفيف ذي اللزوجة المنخفضة ، وان الحجم الأمثل لهذا الزيت يعتمد على نوع الزيت الثقيل ، وكذلك على كمية البخار ودرجة حرارته . كما وجد ان هذه الطريقة تستخدم أكبر كمية من الحرارة المحقونة ، وأن الماء المحقون ينتزع الحرارة من الحبيبات الصخرية التي مر خلالها البخار ، وينقلها إلى المقدمة لتسخن مزيدا من الزيت الثقيل .