EXPERIMENTAL STUDY OF THE INVASION OF OIL INTO A WATER-WET SAND.¹

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INTRODUCTION.

Since the successful prediction of commercial deposits of petroleum in porous strata depends to a large extent on a knowledge of the several factors which influence and control its segregation and accumulation in such strata, it seems profitable to devote some time to the study of those factors which are known or at least thought to exert such an influence. The purpose of this paper is to present in a preliminary way the results of a number of experiments which were arranged and performed with the object of determining what relations exist between the physical properties manifested by crude oil, water, and sand, in contact—and the process of accumulation of oil in sands of various textures and porosities.

ACKNOWLEDGMENTS.

A number of published works on soils were consulted in the hope of finding definite information concerning the behavior of liquids in porous soil at and near the surface. The following books were found of especial interest and deserve mention: "Phys-

¹ Presented before the Society of Economic Geologists, Amherst Meeting, Dec. 29, 1921. Introduced by Roswell H. Johnson.

ical Properties of the Soil"—Robert Warington; "The Soil"—Sir A. D. Hall; "Soils"—E. W. Hilgard.

The writer is also greatly indebted to Roswell H. Johnson, professor of oil and gas production, and to Dr. Gebhard Stegeman, assistant professor of physical chemistry at the University of Pittsburgh, for valuable suggestions during experimental investigations and for the use of apparatus in the determination of porosity, surface tension and viscosity.

APPARATUS AND CONDITIONS OF EXPERIMENTATION.

The apparatus used for the experiments consisted of a glass percolator, slightly cone-shaped, with top and bottom diameters of 4.6 inches (11.7 cm.) and 2.9 inches (7.4 cm.) respectively and a height of 7.4 inches (18.8 cm.). A second percolator of similar dimensions was used in connection with rubber tubing as a container from which to introduce the invading liquid into the sands previously arranged as desired in the original percolator.

A dividing sheet of thin cardboard was cut to fit the percolator on a diameter and with this in place the interior of the percolator was divided into two compartments into which different grades of dry sands could be poured without intermixing. The cardboard was then withdrawn leaving the different sands arranged vertically in place with a definite line of contact between them.

The experiments were all carried out at room temperature and with a pressure on the liquid in the sand of approximately a 1.4 foot head of water.

MATERIALS USED.

The physical properties of the sands and liquids used for experimentation are recorded in Tables I., II. and III. on the following page. The sands are designated by small letters, and the oils by numbers. The only quality of water used was that which is shown in Table III.—a sodium chloride brine having a specific gravity of 1.100. The sands used were white quartz beach sands.

EXPERIMENTS.

The first group of experiments was performed to show the effect of invasion of oil-saturated sands or strata by water. The dry sands were arranged with a sand of medium-sized grains (*c*—Table I.) on top and bottom and sands of relatively coarse and fine grains arranged vertically near the center.

After the sands were completely saturated with oil a connection was made with a container of water (chloride brine—Table III.), invasion of the oil-saturated sands being induced by elevating the container.

Various combinations of sands were used together with the three grades of oil shown in Table II. In each case the invading water entered the relatively coarser-grained sand more easily than the relatively finer-grained sand regardless of the porosities of the two sands.

When the difference in grain sizes of the two sands at the center of the percolator was relatively large (as sands *a* and *d*, *b* and *e*, *c* and *f*—Table I.) the oil retained in the finer of the sands remained there indefinitely, that is, there was no dispersion after the invading action ceased. If, however, the difference in sizes of grains was comparatively small (as sands *b* and *c*, *d* and *e*—Table I.) the oil in the finer sand either moved out with the

TABLE I.
SANDS USED FOR EXPERIMENTATION.

Sand Designation Mark.	Diameters of Grains in Millimeters.		Total Porosity Percentage of Volume of Sand.
	Maximum.	Minimum.	
<i>a</i>	0.833	0.589	38
<i>b</i>	0.589	0.295	37
<i>c</i>	0.295	0.147	38
<i>d</i>	0.147	0.104	39
<i>e</i>	0.104	0.074	40
<i>f</i>	0.074		37

TABLE II
OILS USED FOR EXPERIMENTATION.

Oil Designation Mark.	Source of Oil.	Color.	Gravity 60° F. (15.6° C.).		Viscosity "Saybolt" at 100° F. (37.8° C.).	Viscosity "Engler" at 100° F. (37.8° C.).	Surface Tension Dynes per Cm. at 86° F. (30° C.).
			Specific.	Baumé.			
1.....	Pennsylvania...	Black	0.8178	41.2	40.4	1.33	25.32
2.....	Oklahoma.....	Black	0.8745	30.1	95.2	2.67	25.45
3.....	Texas.....	Black	0.9265	21.1	2863.0	76.44	26.96

TABLE III
WATER USED FOR EXPERIMENTATION.

Liquid.	Specific Gravity at 60° F. (15.6° C.).	Viscosity Coefficient in C.G.S. Units 68° F. (20° C.).	Surface Tension Dynes per Cm. at 86° F. (30° C.).
Water + NaCl.....	1.100	0.0100	74.9

oil from the coarser sand—but at a slower rate—or was displaced soon after the oil had been removed from the coarser sand. In such cases the finer grained of the two sands always retained more oil by adhesion, that is, the displacement was not as complete in the finer sand as in the coarser.

When an oil of high viscosity (Oil 3—Table II.) was used the adhesion to the sand grains was so great that the slight pressure available with the type of apparatus used was not sufficient to effect anything like complete displacement from even a relatively coarse sand. The experiments of this group with this oil may be regarded as unsuccessful except in so far as they tend to show the effect of adhesion on movements of viscous oils.

The second group of experiments shows the effect of invasion of water-saturated sands by oil. The sands were arranged as in the previous experiments and saturated with water (chloride brine—Table III.).

After complete saturation with water a connection was made with a container of oil and invasion induced by elevating the container. In each case the oil entered the coarser of the two sands leaving the finer sand saturated with water—regardless of the relative porosities of the two sands. When heavy oils of high viscosity were used (Oil 3—Table II.) the same results were obtained although the time factor was very much larger than for a light oil of low viscosity (Oil 1—Table II.).

In studying the effects of surface tension on accumulation some secondary experiments were performed with capillary tubes and with small glass tubing filled with sand. The inner walls of a capillary tube are wet with a thin film of oil by passing oil through the bore and then draining for thirty or forty minutes. If now one end is immersed in a beaker of water there will be no rise above the level of the water outside. On the contrary if a capillary tube is first wet with water and then immersed in oil the rise of oil within is practically normal. To demonstrate this effect in a sandstone reservoir a glass tube was filled with a slightly oil-wet sand and one end of it held in water. There was no rise of the water within whereas the dry sand in a tube acts as a very good capillary or rather series of capillaries.

CONCLUSIONS.

It has been shown experimentally that water invading an oil-saturated sand body containing a relatively coarse-grained and a relatively fine-grained sand will (within certain limits) displace the oil from the coarse sand and not from the fine sand. It has also been demonstrated that oil invading a similar sand body, but water-saturated, will displace the water from the coarse sand and not from the fine sand. There is no dispersion after the experiment in the latter case, nor in either case if the difference in grain size of the two sands—and therefore the difference in size of pores—is greater than a certain limiting value which has not been determined.

From these considerations it would appear that whether oil is

found in coarser- or finer-grained sands or strata than the adjacent strata—assuming the rocks to be water “wet”—depends on whether the oil has accumulated by displacing water or whether the oil is the residual fraction retained in the finer-grained portion of the reservoir after the displacement or removal of that in the more open portion by invading water. Commercial deposits of oil usually occur in the more open portions of a water “wet” sand, that is, in those portions of a reservoir in which the pore spaces are larger than the surrounding ones, provided there are irregularities in the sand body. We would infer, then, that such deposits are the result of oil displacing water from a more open part of a sand body. That this view is in accord with the anticlinal theory and its hydraulic modifications is attested by the carefully performed experiments of Mills² in which oil was made to displace water from the relatively coarse tops of domes and their analogies—but not from the fine-grained “cap” sands above, by the action of relatively weak hydraulic currents.

The relative viscosities of oil and water, oil, especially the heavier grades, being more viscous, tend to effect a segregation of oil in the larger pores whenever the motion of the two liquids is from larger to smaller pores. This is true because the resistance of small pores to viscous oil is much greater than that offered by the larger pores, while at the same time the resistance of small pores to water is much less than their resistance to the more viscous oil.

Adhesion of oil to a sand particle is a function of the attraction of the molecules of the substance composing the grain for the molecules of oil. When this attraction is greater than the internal molecular attraction of the liquid, the substance is wet by the oil and adhesion becomes greater in proportion to the magnitude of excess attraction. Since all mineral oils wet the sand or reservoir material we have assumed that the attraction between the molecules of the two substances at their surface of separation is

² Mills, R. A., “Experimental Studies of Subsurface Relationships in Oil and Gas Fields,” *ECONOMIC GEOLOGY*, vol. XV., no. 5, pp. 398-421, 1920.

greater than the molecular attraction within the oil. The rôle of adhesion is to retain as much oil as possible in contact with the sand surfaces. When adhesion is relatively small, as with most light oils of low viscosity, the actual amount which a sand surface is able to retain when the liquid is subjected to a displacement force is small compared to the amount retained under similar conditions when the adhesion is great. Since viscosity is the result of internal molecular attraction or friction, while adhesion is the attraction or friction at the surface of contact with sand particles, it is seen that both work toward the same end to oppose any force which tends to remove the oil from contact with itself or with sand grains. This is why water flooding methods for recovery of oil are much less effective with moderately viscous oils than with the light so-called non-viscous varieties. For since adhesion becomes more pronounced with higher viscosity we have both factors assuming important magnitudes as we pass from less viscous to more viscous oils.

Before discussing the effect of the difference in surface tension between oil and water on the accumulation of oil it is well to lay stress on a point recently brought out by Johnson.³ A great many writers in dealing with capillarity have apparently assumed that the surface tension of water to gas and oil to gas is a measure of the surface tension between water and oil. This is undoubtedly an error, for it can be shown mathematically that the upper limiting value of the surface tension between oil and water is less than 46 dynes per centimeter, while the lower limiting value is zero. The capillary tube experiments previously described seem to indicate that the surface tension between water and an oily surface is zero, or at least very slight, for there was no rise of water within the tube when the walls were wet with only a thin film of oil. The contact in this case is necessarily a water-oil one, because the oil from the bore of the tube spreads out over the surface of the water within, eliminating entirely the water-gas contact.

³ Johnson, Roswell H., "The Time Factor in the Accumulation of Oil and Gas," *Bulletin A. A. P. G.*, vol. 5, no. 4, pp. 475-481, 1921.

On the contrary in the water-wet tube immersed in oil there is an oil-gas contact always present—since water does not spread out forming a film on oil—and the rise of oil within is normal, as previously noted.

In the first group of experiments conducted with oil-saturated sands with water as the invader, we should have expected, if surface tension or capillary attraction were a controlling factor, to find water displacing oil from the fine-grained sands more easily than from the coarser sands. The reason why this is not the case becomes more intelligible after a consideration of the foregoing capillary tube experiments—for it is evident that the pores of the finer sand being wet with oil have no more capillary attraction for water than have the larger pores of the coarser sand. It follows then that relative viscosity and adhesion are the important factors in such cases for the small pores offer much more resistance to movements of liquid than do the larger ones—the resistance offered by any one uniform series of openings being proportional to the viscosity and adhesion of the liquid passing through them.

If the smaller oil-wet pores of a partially exhausted oil sand offered more capillary attraction for water than the larger oil-wet pores, water flooding methods would be very much more effective than they have proved to be—for we would have simply to introduce water into the pay sand and allow it to exchange places with the oil in the finer portions of the reservoir by differential capillary attraction. This action evidently does not take place.

The theory has been brought forward by McCoy⁴ that the accumulation of oil, especially the migration of oil from fine bituminous shales to adjacent reservoir rocks, is effected mainly by capillary forces. With this view the writer cannot agree because experimental evidence seems to emphasize that any series of openings of capillary dimensions wet with only the thinnest film of oil have no preferential attraction for water. Since clays and

⁴ McCoy, A. W., "Notes on Principles of Oil Accumulation," *Journal of Geology*, vol. 27, pp. 252-262, 1919.

shales are more compressible than sandstones, it is mainly through pressure and the resulting reduction in volume of pore space of the bituminous shales that oil is forced out of them and into the adjacent reservoir rocks.

SUMMARY.

An experimental study of the theory of invasion was undertaken which shows that the larger pores contain the invading fluid whether this is oil that invades a water-wet sand or water that invades an oil-wet sand. This reduces the supposed rôle of differential capillarity in the distribution of oil and water in rocks, as related to their porosity. The results of a few additional experiments with capillary tubes are also discussed.

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