Equilibrium Revaporization of Retrograde Condensate By Dry Gas Injection

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ABSTRACT

This paper presents results of a laboratory study of retrograde condensate recovery by revaporization into dry injection gas. Flow tests were performed in 10.6-ft long sand packs at 100F and 1,500 psi. In three runs methane revaporized the liquid from a n-pentane-methane mixture in the presence of immobile water. Two of these tests were water-wet, and the third was totally oil-wet. In the three runs n-pentane recovery was complete after 2.5 hydrocarbon PV of injection. There was no significant performance difference between the two wettability extremes.

In a fourth experiment, a methane-hydrogen sulfide mixture revaporized a synthetic light, sour condensate. No water saturation was present. Equilibrium compositions and volumetric data were obtained for the four-component condensate. The heavy component, n-heptane, was removed after 6 PV production. Comparison of the effluent fluid compositions with known equilibrium data shows that the flowing fluid was equilibrium vapor and that the mixing zone between equilibrium vapor and dry injection gas was short. Data indicated that complete recovery of retrograde liquid occurred after it was contacted by a sufficient quantity of dry gas.

INTRODUCTION

When pressure declines below the fluid dew point in a gas condensate reservoir, a liquid phase forms. In this process, referred to as retrograde condensation, the quantity of liquid formed is frequently small enough that the liquid is not a flowing phase. To prevent loss of valuable retrograde liquids, the process of dry gas cycling has been employed for several years as a more or less standard practice. In this procedure the reservoir pressure is maintained above the fluid dew point so that the liquid components may be produced as vapor and then separated at the surface.

Although full pressure maintenance by gas cycling seems ideal in terms of preventing liquid loss, several factors can reduce the attractiveness of such an operation. From a study of a condensate reservoir in Alberta, Canada, Havlena et al.[1] concluded that cycling under conditions of declining pressure leads to economic advantages and to a high recovery of hydrocarbon liquids. This study considered effects of volumetric sweep efficiency, retrograde behavior of the original wet gas and revaporization characteristics of the retrograde liquid when contacted by dry gas.

The first major work concerning revaporization of liquid in a gas condensate system is that of Standing et al.[2] Calculations based upon the PVT behavior of a recombined gas condensate fluid indicated that all retrograde liquid can be recovered if it is contacted by a sufficient quantity of dry gas. The paper considered the effect of variable permeability upon the recovery of retrograde liquid. Standing et al. concluded that recovery of heavier components in the retrograde liquid is greatest if reservoir pressure is allowed to decline below the dew point prior to dry gas injection.

Since the work of Standing et al., several laboratory studies have been reported which show that recovery of hydrocarbon liquids by vaporization into dry injected gas can contribute to increased recovery above that obtained by ordinary production practices. Vaporization from retrograde condensate,[3] conventional oil[4-7] and volatile oil[8] reservoirs has been considered. There is little work that deals with revaporization recovery from condensate reservoirs.

This study demonstrates that vapor-liquid equilibrium exists when a dry gas is injected into a porous medium containing retrograde condensate; investigates the effect of wettability on revaporization of retrograde condensate; and provides an indication of the amount of dry gas necessary to

[1]References given at end of paper.

recover the heavy components from a condensate that contains a large concentration of hydrogen sulfide.

To demonstrate the equilibrium operation of and evaluate the effect of wettability upon the revaporization process, dry gas injection tests were performed in long, unconsolidated sand packs. The tests were run at both totally water-wet and oil-wet conditions in the presence of immobile water using a simple binary hydrocarbon fluid. Although distribution of fluids in the pore space of the oil-wet pack is not the same as in an oil-wet reservoir, the arrangement is such that laboratory revaporization is inherently more difficult. Therefore, an equivalence in performance between the two laboratory wettability extremes would indicate no extra difficulty in revaporizing condensate from an oil-wet reservoir. To observe the liquid recovery performance for a fluid system that more nearly represents an actual sour gas condensate, a similar injection test (without immobile water saturation) was run using a four-component sour fluid. A phase behavior study of the four-component fluid in a windowed cell provided necessary PVT data for this experiment.

REVAPORIZATION PROCESS

To establish a conceptual basis for this experimental study, a brief description follows of the revaporization recovery of retrograde liquid.

Fig. 1 shows a linear porous medium flow system containing gas condensate at a pressure below the fluid dew point. Fig. 1a indicates the initial condition of the system, including the presence of connate water in addition to retrograde liquid and equilibrium vapor saturations. The porous medium is considered homogeneous, and in the following discussion perfect sweep efficiency is assumed.

Fig. 1b indicates the system behavior when dry gas is injected. Consider the small linear element at the inlet. As dry gas enters it displaces the original equilibrium vapor. Immediately upon contact between dry gas and the retrograde liquid in this volume element, the two phases will seek to establish physical equilibrium (mixing between injected and in-place gas is neglected for the

(a) INITIAL CONDITION-CONDENSATE SYSTEM BELOW DEW POINT

(b) DRY GAS INJECTION

FIG. 1 — GAS CONDENSATE SYSTEM SUBJECTED TO DRY GAS INJECTION.

moment). To achieve equilibrium, chemical species will transfer countercurrently between phases with intermediate and heavy components moving into the vapor and some light components moving into the liquid. As a result of this mass transfer process, the relative amount of liquid decreases. The rich vapor thus formed will be displaced by entering dry gas, and eventually the volume element is depleted of liquid. At this point only dry gas flows through the element and the next linear element down-stream is subjected to the same process. In this manner the contact zone moves through the system and the liquid is removed. Only equilibrium vapor is produced from the system until the liquid is depleted to just up-stream of the exit end. In revaporization experiments operated at constant temperature, negligible pressure drop, and with a binary fluid system the composition of the produced fluid will remain constant over nearly all the production history. Only wet-gas systems are considered in this study, and the possibility of liquid being displaced by the injected gas may be neglected since it is assumed that the liquid saturation is below the level where liquid is a flowing phase.

The above description of the revaporization process assumes that physical equilibrium exists at all points in the flow system where vapor and liquid are present. This assumption is widely supported in the literature. Studies of nitrogen revaporizing n-hexane, n-heptane and condensate by Oxford and Huntington[3] showed that departure from equilibrium did not occur until the space velocity reached a rate which greatly exceeds actual field injection rates. More recently, Raimondi and Torcaso[9] found that interphase mass transfer between two immiscible liquids takes place under equilibrium conditions at velocities as high as 500 ft/day in unconsolidated sand. Therefore, equilibrium is reached within a very short distance. The calculation method of Standing et al.[2] also was based on the conceptual model outlined above, and reportedly was verified by experiments.

Since equilibrium apparently is reached quickly between dry injection gas and the in-place liquid, any experimentally measured departure from the equilibrium vapor composition in the exiting fluid would be a measure of the extent of mixing between injection gas and equilibrium vapor. Such a departure would only be seen near the end of a run when the transition zone arrives at the outlet of the flow system.

EXPERIMENTAL

EQUIPMENT

Unconsolidated sand packs were chosen for the revaporization flow tests because their high permeability minimizes pressure drop, and because a simulated sour condensate could not be contained in a consolidated core arrangement (Fig. 2). The sand packs, composed of No. 16 AGS Ottawa sand contained in a stainless steel tube, measured 10.625
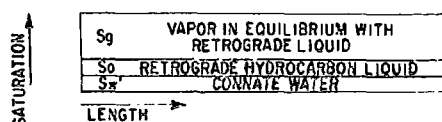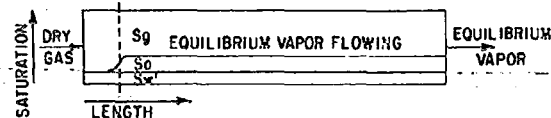
ft long by 1.939 in. in diameter. About ½ in. of 20-30 mesh sand was placed at each end to aid flow distribution. Dry gas displaced from a calibrated transfer cell was injected at constant rate. Calibrated gauges provided inlet and outlet pressure readings for the sand pack. The effluent from the pack was collected in a receiver fitted with a floating piston; water discharged from the back side of the piston passed through a backpressure regulator and was collected in a graduated lucite cylinder. Readings from this cylinder and the calibrated transfer cell were used in following the volumetric balance. The backpressure regulator on the down-stream side of the effluent receiver established the pressure level for the flow system. The sand pack, pressure gauges, effluent receiver and backpressure regulator were enclosed in a cabinet maintained at 100F.

Fig. 2 indicates a sampling valve located between the pack outlet and the effluent receiver. This is a specially designed valve that allows flow in either closed or open position, and that traps a very small volume sample (on the order of microliters).[10]

PROCEDURES

In three runs, mixtures of methane and n-pentane comprised the in-place hydrocarbon for which fluid properties and phase behavior of the pure binary are well established.[11] Methane was the injection gas and immobile water was present. The fourth revaporization run was made using a simulated sour condensate and involved large concentrations of hydrogen sulfide. Because of the possible severe chemical attack on the equipment if water were present together with H_2S, no immobile water saturation was present in the sand pack; hydraulic oil was used in the effluent receiver and the intermediate transfer cell was eliminated. The sour fluid experiment was attempted in a consolidated sandstone core but the run failed due to chemical attack on the epoxy resin core coating.

The general flow test procedure consisted of establishing an immobile water saturation (except for the sour fluid run), saturating the pack with a single-phase gaseous hydrocarbon mixture, depressuring the system to establish a retrograde

FIG. 2 — EXPERIMENTAL EQUIPMENT.

hydrocarbon liquid saturation and injecting the dry gas. All runs were made at nominal conditions of 100F, 1,500 psig and 2 ft/day fluid velocity. Fluid analyses were obtained by gas chromatography.[10]

For the n-pentane-methane revaporization tests, composition of the single-phase binary mixture was nominally specified as 10 mol percent pentane which yields about 6.5 volume percent liquid at 1,500 psia (differential depletion). In saturating the sand pack, several pore volumes of the single-phase (2,500 psig) charge mixture were passed through the pack until analyses of the input and effluent fluids matched. Depressurization to the operating level was done gradually over an 8-hour interval, and the volume and composition of the depressurization effluent were measured. These data, in conjunction with the known amount of material in place prior to depressuring, established the over-all fluid composition in the pack and permitted an estimate of the amount of retrograde condensate present at the start of gas injection.

During methane injection the effluent sample receiver was periodically replaced. The entire produced fluid volume was compressed to 2,500 psig and agitated to assure homogeneity. Determining the effluent's composition and volume, together with knowledge of the pressure and temperature, allowed calculation of the amount of pentane removed from the pack. The Standing-Katz[12] compressibility factors were used in the material balance calculations. Intermediate to the receiver changes, the effluent composition was followed by analysis of samples removed in the sample valve.

One methane-pentane run was made in a totally oil-wet sand pack. To render the sand oil-wet, it was treated with a 2 percent volumetric solution of silicone in alcohol. Sand and solution were mixed in a 1:1 volumetric ratio in a blender and evaporated at 200F. The batches were cured at 130F and stored under nitrogen until packed in the stainless steel tube.

The simulated sour condensate was composed of methane, hydrogen sulfide, n-pentane and n-heptane. The synthetic condensate was composed so that the quantity of liquid formed at laboratory test conditions would be about the same as that yielded by a known light, sour condensate. The dry injection gas was a methane-hydrogen sulfide mixture. An auxiliary volumetric and phase composition study for the sour charge fluid provided PVT data for the revaporization run. Table 1 gives the analysis and volumetric data for the simulated condensate, and Table 2 gives measured compositions of the equilibrium phases and calculated K-values at 100F obtained during the differential depletion test (although the 1,511-psia compositions are the main data of interest in Table 2, all depletion data are included for completeness). The analysis includes small concentrations of nitrogen, carbon dioxide and ethane which entered as impurities in the hydrocarbons used in making up the mixture. The
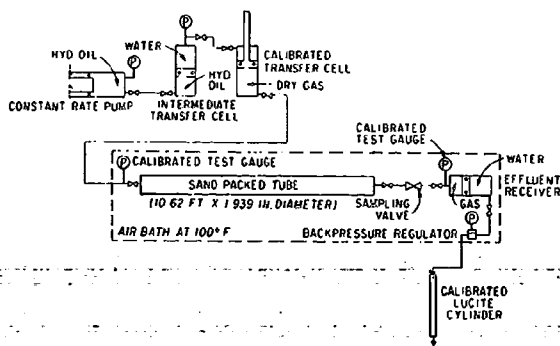
run with this synthetic condensate was operated according to the general procedures outlined above. Recovery of the n-pentane and n-heptane was followed as a measure of the liquid revaporization. As an aid in determining the amount of single-phase material in the pack before depressurization, the compressibility factors were determined for the mixture above the dew point (Table 1). The material balance calculations for the injection test utilized an improved compressibility factor correlation for gases containing substantial amounts of hydrogen sulfide.[13]

EXPERIMENTAL RESULTS

Table 3 summarizes the parameters for the four revaporization flow tests. Runs 1 through 3 involved the simple methane-pentane fluid system; Runs 1 and 2 were water-wet and Run 3 was oil-wet. Run 4 was the revaporization of the simulated light, sour condensate.

WATER-WET REVAPORIZATION TESTS

The only substantial difference between Runs 1 and 2 was the magnitude of the immobile water saturation in the sand pack. Figs. 3 and 4 give the pentane recovery performance and effluent fluid composition as a function of HCPV dry methane injected.

Run 1 was a shakedown run and led to experimental improvements for Run 2 where the material balance was more satisfactory. In Run 1 the apparent over-all pentane recovery of 93 percent was attained after 2.5 HCPV methane were injected. At the end of the run the pack was depressured to atmospheric through a cold trap. No liquid condensed

in the trap during depressurization nor during a follow-up purge with methane, indicating that all the pentane had left the system during the revaporization run. The 7 percent pentane unaccounted for is considered lost in sampling.

Improved sample handling in Run 2 resulted in a better pentane balance (99 percent recovery). Comparing the effluent compositions between the two runs shows that Run 2 pentane was consistently higher (Table 4); the second point in Run 1 is particularly suspect (Fig. 3). Because of uncertainties in compressibility factors and effluent volumes, the 99 percent recovery in Run 2 is considered to be excellent.

In the second run and all others following, small in-line effluent samples were taken by means of the sampling valve. Although these analyses scatter (Fig. 4) prior to arrival of the mixing zone, these periodic incremental checks are of great value in determining the arrival and size of the mixing zone.

TABLE 1 — ANALYSIS OF AND VOLUMETRIC DATA AT 100F FOR A METHANE, HYDROGEN SULFIDE, n-PENTANE, n-HEPTANE MIXTURE

Component	Mol percent
Nitrogen	.44
Methane	76.33
Carbon dioxide	.25
Ethane	.10
Hydrogen sulfide	16.40
n-Pentane	3.70
n-Heptane	2.78

Constant Composition Mixture			Differential Depletion of Mixture	
Pressure (psia)	Mixture Compressibility Factor	Volume Percent Liquid	Pressure (psia)	Volume Percent Liquid
3047	.7024		2386	.50
2837	.6917		2351	1.78
2646	.6758		2291	3.41
2543	.6712		2216	4.76
2442	.6672		2124	5.65
2400 (DP)	.6646	0	2040	6.20
2390		.29	1797	7.2
2365		1.30	1511	7.3
2315		2.80	1053	6.3
2250		4.16	533	4.7
2040		5.55	227	3.4
1543		4.70		
1040		2.76		

TABLE 2 — EXPERIMENTAL EQUILIBRIUM PHASE COMPOSITIONS AND CALCULATED K-VALUES AT 100F FOR SIMULATED GAS CONDENSATE

See Table 1 for initial mixture composition.

Component	Vapor Sample 1	Liquid Sample 1	Vapor Sample 2	Liquid Sample 2	K_1	K_2
2,040 psia						
N_2	.468	.169	.470		2.77	2.78*
C_1	79.637	47.811	79.615		1.666	1.665
CO_2	.241	.203	.264		1.19	1.30
C_2	.093	.117	.086		.79	.74
H_2S	15.622	23.541	15.651		.664	.665
nC_5	2.561	12.789	2.548		.200	.199
nC_7	1.378	15.370	1.366		.0897	.0889
1,511 psia						
N_2	.480	.099	.480		4.85	4.85*
C_1	81.763	35.755	81.407		2.287	2.277
CO_2	.207	.166	.223		1.25	1.34
C_2	.088	.117	.089		.75	.76
H_2S	14.989	24.609	15.335		.609	.623
nC_5	1.841	18.200	1.828		.101	.100
nC_7	.632	21.054	.638		.0300	.0303
1,053 psia						
N_2	.473	.061	.469		7.75	7.69*
C_1	81.549	25.865	81.496		3.153	3.151
CO_2	.209	.137	.211		1.53	1.54
C_2	.084	.104	.085		0.81	0.82
H_2S	15.788	23.230	15.823		0.680	0.681
nC_5	1.535	23.423	1.543		0.0655	0.0659
nC_7	.362	27.180	.373		0.0133	0.0137
533 psia						
N_2	.447	.028	.445	.028	16.0	15.9
C_1	79.195	14.202	78.906	13.906	5.576	5.674
CO_2	.246	.075	.244	.074	3.3	3.3
C_2	.104	.076	.104	.076	1.37	1.37
H_2S	17.798	16.864	18.109	16.987	1.055	1.066
nC_5	1.870	30.976	1.858	31.021	.0604	.0599
nC_7	.340	37.779	.333	37.907	.0090	.0088
227 psia						
N_2	.415	.008	.418	.009	52.0	46.0
C_1	75.603	5.944	75.335	6.147	12.72	12.26
CO_2	.208	.033	.233	.034	6.3	6.9
C_2	.103	.039	.123	.042	2.6	2.9
H_2S	19.950	9.332	20.233	9.480	2.138	2.134
nC_5	3.147	36.342	3.125	36.223	0.0866	0.0863
nC_7	.575	48.302	.533	48.066	0.0119	0.0111

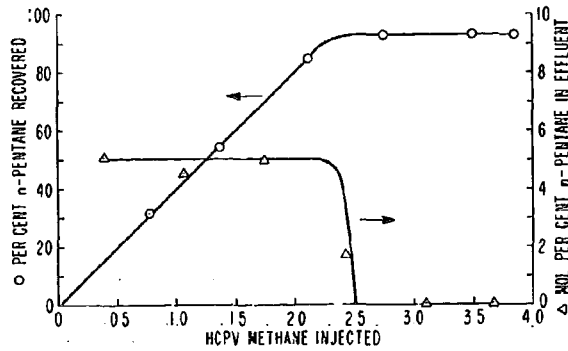*K_2 calculated using Vapor Sample 2 and Liquid Sample 1.

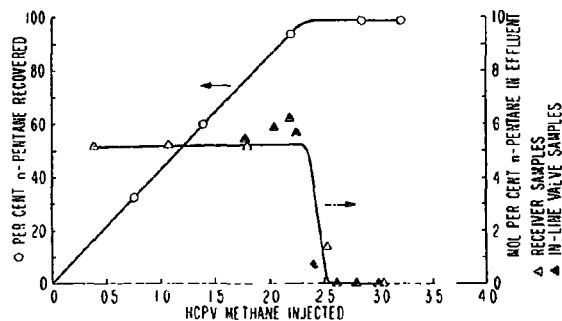FIG. 3 — REVAPORIZATION RUN 1 WITH METHANE-PENTANE SYSTEM IN WATER-WET SAND PACK (S_w = 45.2 PERCENT).

FIG. 4 — REVAPORIZATION RUN 2 WITH METHANE-PENTANE SYSTEM IN WATER-WET SAND PACK (S_w = 21.4 PERCENT).

TABLE 4 — COMPARISON OF EFFLUENT COMPOSITIONS WITH KNOWN EQUILIBRIUM VALUES (TEMPERATURE: 100F)

Experiments Using Methane-Pentane Fluid System

n-Pentane (mol fraction)

Run	Average Pressure (psia)	Measured Vapor Composition At 1,522 psia*	Sage & Lacey Vapor Composition[11]	Run Effluent Average*
1	1528	.0531	.0598	.0503
2	1530	.0531	.0598	.0518
3	1525	.0531	.0597	.0517

*Balance of composition is primarily methane with small amounts (less than 1 mol percent) of N_2, CO_2 and C_2H_6.

Experiment With Simulated Sour Condensate Fluid

Analysis (mol percent)

Run	Average Pressure (psia)	Component	Equilibrium* Vapor at 1,511 psia	Run Effluent (1,535 psia**)
4	1535	N_2	.48	.54
		CH_4	81.585	80.59
		CO_2	.215	.24
		C_2H_6	.088	.09
		H_2S	15.162	15.95
		$n-C_5H_{12}$	1.835	1.91
		$n-C_7H_{16}$	.635	.68

*Data obtained during the differential depletion test (Table 1
**Average of first two effluent receiver analyses.

TABLE 3 — SUMMARY OF REVAPORIZATION TEST PARAMETERS

	Run	Pack Properties				Run Parameters			Fluid Compositions (mol percent)			
		Absolute Permeability (darcys)	Pore Volume at 1,500 psi (cc)	Water Saturation of 1,500 psi	HCPV at 1,500 psi (cc)	Average Pressure (psia)	Advance Rate (HCPV Basis) ft/day	Initial Volume Percent Liquid in Hydrocarbon*	Component	Charge Mixture	In Place at Start of Injection	Inject Gas
Water-Wet Runs	1	3.09	2134	.452	1169	1528	2.08	6.50	N_2	.60	.58	.56
									CH_4	89.07	87.11	99.08
									CO_2	.24	.25	.23
									C_2H_6	.12	.11	.13
									nC_5H_{12}	9.97	11.95	—
									Pressure	2515	1520	
	2	3.09	2134	.214	1678	1530	2.16	6.50	N_2	.52	.51	.56
									CH_4	89.13	87.29	99.08
									CO_2	.12	.11	.23
									C_2H_6	.12	.13	.13
									nC_5H_{12}	10.11	11.95	—
									Pressure	2513	1517	—
Oil-Wet Run	3	4.20	2196	.196	1776	1525	2.10	6.50	N_2	.52	.50	.56
									CH_4	89.19	87.34	99.08
									CO_2	.14	.14	.23
									C_2H_6	.12	.12	.13
									nC_5H_{12}	10.03	11.90	—
									Pressure	2515	1513	—
Run With Simulated Condensate	4	4.20	2196	0	2196	1535	1.95	7.2	N_2	.51	.48	.57*
									CH_4	75.72	71.95	63.16
									CO_2	.23	.22	.20
									C_2H_6	.10	.10	.08
									H_2S	16.73	18.09	35.99
									nC_5H_{12}	3.74	4.81	—
									nC_7H_{16}	2.97	4.35	—
									Pressure	2525	1535	—

*The initial liquid volume percent is based on the volume percent liquid obtained in differential depletion tests at comparable pressure.
**This is the composition of the third batch of driving gas which was injected between 2.5 and 6.0 PV. Compositions of the other three batches of driving gas were about the same.

The early in-line samples probably scatter because of saturated liquid droplets entering the valve.

OIL-WET REVAPORIZATION TEST

Fig. 5 presents the results of Run 3 that was made in a completely oil-wet sand pack. This run was operated at a water saturation and displacement rate essentially the same as Run 2, and thus allows a comparison of the two wettability extremes as they affect the revaporization process. The apparent over-all pentane recovery from Run 3 was 98.1 percent. As in Run 1, the oil-wet system afterwards was depressured to atmospheric through a cold trap; no liquid condensed which indicated complete removal of pentane during the injection test. The in-line incremental sample analyses also scatter, but again are helpful in defining the arrival and size of the mixing zone.

REVAPORIZATION OF SIMULATED SOUR CONDENSATE FLUID

Run 4 was made with the simulated sour consensate fluid described in Tables 1 and 2. Since the differential depletion test consumed the original mixture, it was necessary to synthesize more of this fluid for the flow test. Comparing Tables 1 and 3 indicates that a fairly good match was achieved. Differential depletion data indicate that the retrograde liquid saturation at the start of dry gas injection was about 7.2 volume percent.

Fig. 6 presents the results of Run 4 in terms of the n-pentane and n-heptane recovery. The amounts of these components in the produced fluid are also plotted. Great care was exercised in handling the effluent receivers for Run 4. Since the compressibility factor correlation[13] cannot be used at pressures much above 1,500 psia, the effluent volumes were not allowed to exceed this pressure level and were maintained as single-phase by immersing in a 130F air bath. The volume was adjusted to keep the pressure near 1,500 psia. This established the PVT datum from which the material balance was calculated. At the time of sampling, the receivers were compressed to 2,000 psig and agitated to assure homogeneity of the samples.

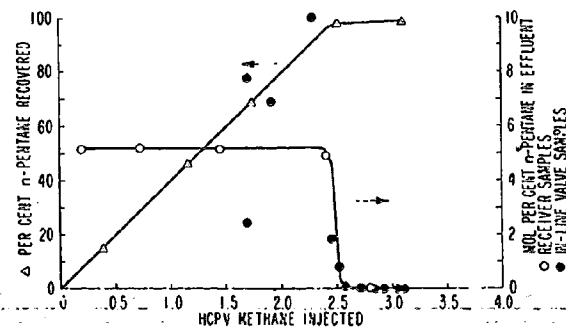As was also the case in Runs 1 through 3, the over-all pressure drop across the sand was about

10 psi, which is negligibly small compared with the system pressure level.

Because of the fluid's reactivity toward the rubber O-rings in Run 4, small leaks developed from time to time in the injection gas transfer cell. This fact, in conjunction with the long duration of the run (38 days), caused a much larger volumetric balance discrepancy than resulted in the methane-pentane experiments. However, the final difference between input and output volumes was only 0.14 PV. Part of this volumetric difference was also due to occasional leaks around the effluent receiver O-rings and to drifts in the back-pressure. Results of Run 4 are plotted on a produced-volume basis.

Following Run 4 the system was blown down through a cold trap. Again, no liquid was collected, verifying that the pack had been depleted of liquid. The calculated recoveries were 100.08 percent for n-pentane and 94.7 percent for n-heptane.

DISCUSSION OF RESULTS

EQUILIBRIUM OPERATIONS

Examination of the four test runs (Figs. 3 through 6) indicates that, as expected, the flow system produced equilibrium vapor until the retrograde liquid essentially was removed.

In Runs 1 through 3 with the binary hydrocarbon system, the effluent fluid compositions remained essentially constant, resulting in a linear recovery performance of the n-pentane until the transition zone reached the end of the pack. The effluent fluid compositions (Table 4) are within 3 percent of the average equilibrium vapor composition measured for the fluid system at 1,522 psia and 100F. Table 4 also shows the equilibrium vapor compositions reported by Sage and Lacey[11] for the pure binary system. The larger differences of the effluent from Sage and Lacey values (13 percent) are attributed to the presence of about 1 mol percent impurities (N_2, CO_2, C_2H_6) in the present fluid system. The composition consistency between runs (Run 1 was lower due to sampling differences), the essentially constant effluent compositions and

FIG. 5 — REVAPORIZATION RUN 3 WITH METHANE-PENTANE SYSTEM IN OIL-WET SAND PACK (S_w = 19.6 PERCENT).
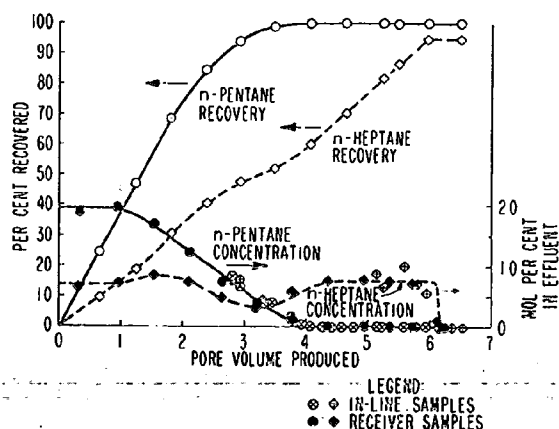
FIG. 6 — REVAPORIZATION RUN 4 WITH SIMULATED SOUR-CONDENSATE FLUID.

their agreement with the measured equilibrium vapor composition at comparable pressure demonstrate that the flowing fluid was equilibrium vapor.

In the simulated sour-condensate experiment (Run 4), the early effluent fluid compositions agreed well with equilibrium vapor compositions obtained in the auxiliary phase behavior study for the quaternary system. Table 4 compares the average composition of the first two effluent batches from Run 4 with a known equilibrium composition at comparable pressure. The two fluid compositions agree favorably.

Examination of Fig. 6 shows that the change from the initial vapor composition occurs earlier and more gradually in the four-component fluid than in the simple binary fluid tests. The more gradual decline in n-pentane concentration, beginning after about 1 PV in Run 4, results from a gradual shift in the equilibrium composition that occurs because the over-all mixture composition is changing. The H_2S concentration after 1 PV injection was substantially increased because of higher concentration in the injection gas. The over-all composition change causes a change in the single-phase pressure of the fluid system, and thus the convergence pressure to which the equilibrium K-values of the components are related also changes.

Thus, the fact that a four-component system is being revaporized and that large composition changes (particularly hydrogen sulfide) occur generally result in the gradual and complicated vapor composition changes.

EFFECT OF WETTABILITY UPON REVAPORIZATION OF RETROGRADE LIQUID

Distribution of the immobile water in the oil-wet test (Run 3) is quite different from that in the water-wet tests (Runs 1 and 2). In the oil-wet case the entire sand surface was rendered water repellent prior to saturation with water. After saturation with water, and then partial desaturation by displacement with pentane to achieve a low water saturation value, the remaining immobile water would be expected to exist as discrete globules in the center of the pores with little, if any, water in the smaller interstices. This is a direct contrast with the commonly accepted concept of fluid distribution in oil-wet reservoirs wherein the connate water is thought to occupy the smaller pores (as in the water-wet case). Therefore, the oil-wet laboratory pack posed a much more severe test of the revaporization recovery process than would an oil-wet reservoir. This is true since the position of the water globules in the artificially oil-wet pack offers more resistance to the flow of the hydrocarbon phases.

Fig. 7 provides a comparison of the pentane recovery performances between the two comparable methane-pentane runs of opposite wettability, and also includes the data from Run 1 at higher water saturation. The approach to total recovery in the oil-wet case is about the same as in the water-wet test, i.e., total recovery is approached at 2.5 PV in Run 2 and about 2.6 PV in Run 3. Perhaps the

most significant difference between Runs 2 and [3] evident in Fig. 7 is between the slopes of the linear portions of the recovery curves. The difference is attributed to uncertainty in determinations of the sand pack pore volume. A repeat measurement of this value following Run 3 suggests that the uncertainty in pore volume was about [ ] percent. The uncertainty range arising from [ ] percent PV uncertainty is given for several of the points plotted in Fig. 7. The overlap between the uncertainty bands for Runs 2 and 3 indicates that the two performance curves are not significant different.

It is concluded that arrangement of the fluids [in] the pore space does not affect equilibrium revaporization at the flow rates employed. Since the laboratory test presented a much more stringent fluid distribution than would an oil-wet reservoir, revaporization recovery should be no more difficult in the latter than in a water-wet reservoir.

DRY GAS REQUIREMENTS FOR COMPLETE REVAPORIZATION

For the simple binary fluid experiments (Figs. 3 through 5) the liquid was depleted by methane gas injection after about 2.5 PV. The effluent n-pentane concentration curves indicate that the mixing zone was very short — probably no longer than 0.25 PV or about 2.5 ft in the sand pack.

Run 4 with the simulated sour condensate fluid provides a more realistic estimate of the dry gas requirements for complete recovery of acid retrograde liquids. The n-pentane was recovered after 4 PV production. The total liquid recovery, as indicated by n-heptane removal, was at about 6 PV. The simulated sour condensate fluid used in Run 4 was not altogether representative of actual reservoir condensates, especially in the properties of the heavy components. Reservoir fluids containing significant amounts of heavy components could require substantially more dry gas for revaporization than the fluid in Run 4. On the other hand, the gas requirements in Run 4 could be conservative with respect to some reservoir situations since the experimental temperature was about 100F lower than typical condensate reservoirs, and
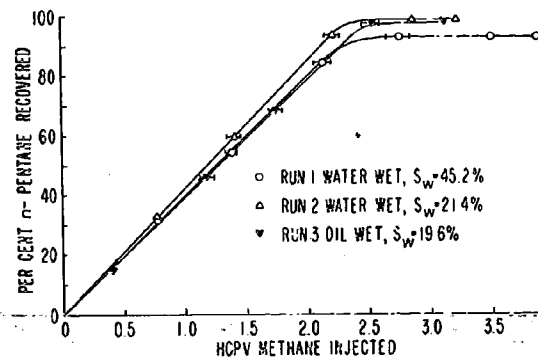
FIG. 7 — COMPARISON OF PENTANE RECOVERY PERFORMANCE.

equilibrium K-values for intermediate and heavy hydrocarbons depend strongly on temperature.

The only comparative information available in the literature concerning dry gas requirements is that reported by Standing *et al.*[2] who used an actual condensate. For their fluid system, 3 PV of dry gas were required to vaporize the liquid phase. This is not a completely comparable situation with the present experiment since Standing's revaporization was at 1,310 psia and 195F. At these conditions the equilibrium K-values for n-pentane, hexane and octane are two to three times the values at the conditions of Run 4. Also, for convergence pressures of 4,000 psi and above, the decane K-value at Standing's conditions is three to four times that at Run 4 conditions.[14] Therefore, the difference in gas requirements in Standing's work as compared with Run 4 may be attributed to the difference in equilibrium compositions.

Generally, the dry gas volume required to revaporize retrograde liquid would be expected to depend on the specific reservoir conditions and also on the nature of the condensate system, i.e., the relative amounts of heavy components present. The sweep efficiency of the injected gas also has a major influence on the amount of gas cycling necessary for adequate contact of the liquid.

CONCLUSIONS

1. When dry gas is injected into a porous medium containing wet gas below the dew point, a part or all of the retrograde liquid is revaporized and the flowing fluid is the vapor in equilibrium with the liquid. Dry injection gas becomes saturated within a short distance after first contact with the liquid.

2. The quantity of dry gas required for complete recovery of retrograde liquid by contact is influenced by the heaviest components of the liquid. In an experiment with a simulated sour condensate fluid, the required dry gas volume was 6 PV. However, the amount required in an actual reservoir situation depends on the temperature and pressure conditions, the nature of the condensate fluid and sweep efficiency in the fluid injection process.

3. The fluid arrangement in the pore space has no effect on the equilibrium revaporization of retrograde liquid at the flow rate employed, indicating that reservoir wettability is not a factor in the revaporization recovery of retrograde liquids.

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