FLUID FLOW THROUGH POROUS MEDIA. PART III. AIR PERMEABILITY OF CONSOLIDATED SANDS PARTLY SATURATED WITH WATER*

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ABSTRACT An apparatus suitable for measuring gas permeabilities of consolidated sands, partly saturated with liquids is described The maximum rates of flow of air beyond which the observed permeabilities tend to diminish were found for seven samples of dry consolidated oilwell sands from Assam oil fields. Air permeabilities of these core samples at different degrees of water saturation were obtained keeping the rate of flow of air within the above limit. When the relative air permeabilities were plotted against the corresponding water saturations the curves obtained with the different core samples could be divided into two types In the first type the air permeability was constant within the limits of experimental error until the liquid saturation exceeded a certain value (5—15%) beyond which the permeability diminished, and finally became zero as the liquid saturation approached 100%. With the second type of curve the permeability began to diminish as the liquid saturation increased from zero. The remaining portions of the curve were similar to those of the first type

INTRODUCTION

In the first and second parts of this series (Sengupta and Mg. Thein Nyun, 1942, 1943) measurements on the use of gases for measuring true permeabilities of porous media, and the relations between porosity, permeability and average grain size of a number of oilsands obtained from Burma were reported. In these measurements the cores were extracted with chloroform and then thoroughly dried before measuring their permeabilities. In all technical problems associated with flow of fluids through porous media the latter are almost always partially saturated with one or more fluids. For example, oilsands may contain, in addition to crude oil, either water or natural gas or both. It is desirable in such cases to investigate conditions of flow of one fluid through consolidated sands partly saturated with another fluid. In the present paper results on flow of air through cores partially saturated with water have been reported.

The permeabilities K_a were calculated using the relation:—

$$K_a = \frac{2V \cdot p \cdot \eta \cdot L}{(p_2^2 - p_1^2)A}$$

where V in the volumes of air in *c. c.* flowing per second at atmospheric pressure through the cylindrical core of length L *cm.* and area A sq. *cm.*, p_2 is the pressure of the inflowing and p_1 that of the outflowing air, p the atmospheric pressure all expressed in atmospheres and η the viscosity of air in centipoises (0.0189 *c.p.* at 25°C the temperature of measurements).

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The permeabilities of the partly saturated cores were expressed as fractions of the permeabilities of the dry cores and the liquid saturations were expressed in percentages, those of the completely saturated cores being taken as 100%.

EXPERIMENTAL

The apparatus used for the present measurements is shown in Figure 1.

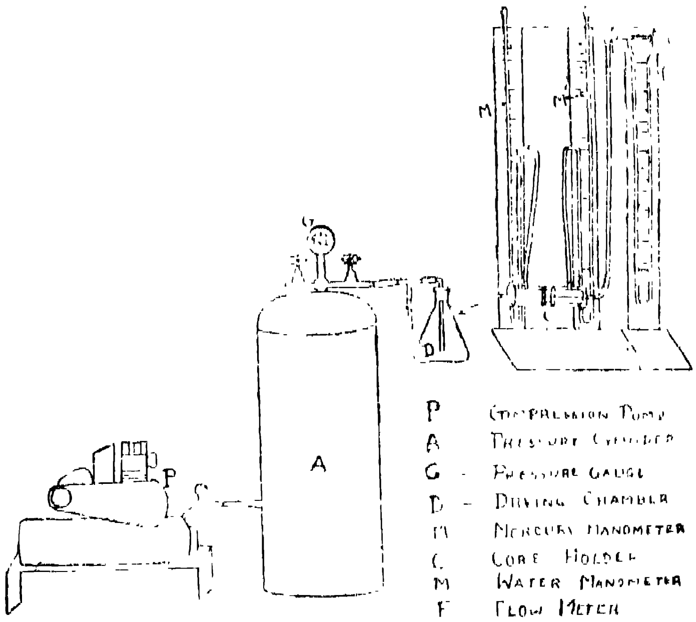


FIG. 1

It is different from that described in Part I of the series. The core holder is very similar to that used by Muscat (1937) and others except that the cores were sealed in brass cylinders and held in position in the core holder by rubber washers. The brass cylinders were removed from the core holders from time to time and weighed to determine the relative saturations. Air was taken from a pressure cylinder and dried by passing through a chamber containing fused calcium chloride. The pressure of the inflowing air was obtained from a mercury manometer and that of the outflowing air from a water manometer. The rate of flow of air was measured with a capillary flow-meter previously calibrated using a gas burette.

The core samples were first cut to the proper size, extracted with chloroform and thoroughly dried. Each core was then sealed in position with sealing wax in a brass ring. The brass rings containing the cores were weighed when dry and again when completely saturated with water, the difference giving the weight of the liquid filling the pores.

It was shown in Part I of this series that the measured permeability diminishes when the rate of flow of the gas exceeds a certain limit. Similar measurements were also made with the seven core samples used in the present measurements and the limiting rates of flow below which the measured permeability remained constant were ascertained. In measurements with partially saturated cores the rates of flow of air were kept within this limit.

RESULTS AND DISCUSSION

The rates of flow at different pressure gradients through several core samples are given in Figure 2 and in Tables I and II.

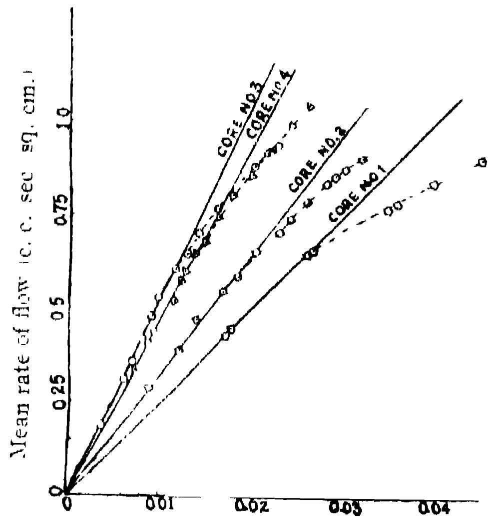


FIG. 2

TABLE I

Core No. 6 Length—2.00 cm. Area of cross section—9.26 sq. cm.

Pressure gradient (atm./cm.)	Rate of flow (c.c./sec., sq. cm.	Permeability (millidarcy).	Percentage deviation from permeability at zero rate of flow.
0.0241	0.1315	103	-0.5
0.0362	0.1974	103	-0.5
0.0483	0.2650	104	+0.5
0.0602	0.3348	105	+1.5
0.0729	0.4025	104	+0.5
0.0849	0.4581	102	-1.5
0.0960	0.5183	101	-2.4
0.1094	0.5776	100	-3.4
0.1213	0.6250	97.4	-5.9
0.1339	0.6712	95.3	-8.0
0.1457	0.7191	93.3	-9.9

Permeability at zero rate of flow from graphical extrapolation—103.5 millidarcy.

TABLE II

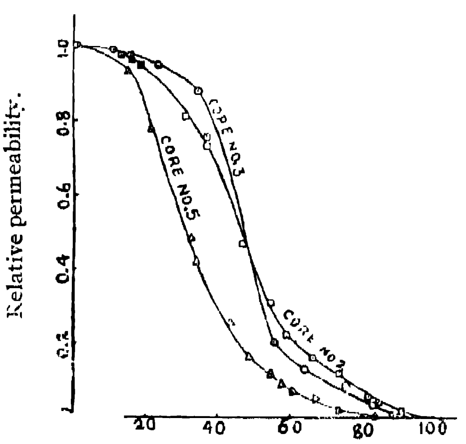
Core No. 3 Length—1.90 cm. Area of cross section—0.95 sq. cm.

Pressure gradient (atm./cm.)	Rate of flow (c.c./sec./sq. cm.)	Permeability (millidarcy).	Percentage deviation from permeability at zero rate of flow.
0.00352	0.102	1030	+2.5
0.00612	0.317	980	−2.5
0.00705	0.366	980	−2.5
0.00802	0.418	981	−2.4
0.00890	0.482	1020	+1.5
0.00975	0.531	1035	+3.0
0.01280	0.641	[illegible]	−0.5
0.01413	0.714	956	−4.9
0.01613	0.779	903	−10.1
0.02027	0.891	834	−17.0
0.02164	0.930	803	−20.1
0.02305	0.940	771	−23.3

Permeability at zero rate of flow from graphical extrapolation—1005 millidarcy.

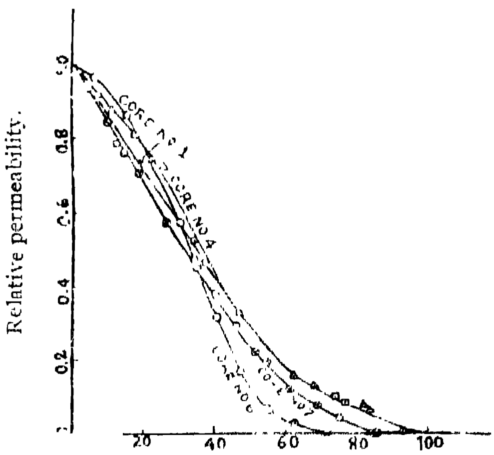
The permeability remains constant (within a maximum error of ±2.5%) until the rate of flow exceeds a value of 0.5—0.6 c.c./sec./sq. cm. Similar results were also obtained by Carlson and Eastman (1940). In the measurements reported below the rates of flow were kept below 0.5 c.c. per sec. per sq. cm.

Air permeability at different degrees of water saturation are shown in Figures 3 and 4 and Tables III and IV.



Percent water saturation.

FIG. 3



Percent water saturation.

FIG. 4

TABLE III

Core No. 7 Length—1.95 cm. Area of cross section—9.58 sq. cm.

Percentage water saturation	Permeability (millidarcy)	Relative permeability
95.8	0	-
89.6	0	--
83.9	0	—
76.0	3.8	0.045
69.0	6.9	0.083
61.0	10.2	0.122
55.0	17.2	0.206
51.1	18.2	0.218
46.3	25.2	0.302
39.7	32.2	0.386
34.6	38.4	0.460
30.2	47.3	0.566
25.8	49.1	0.581
18.9	60.9	0.730
14.6	64.9	0.768
10.1	72.6	0.859
0.0	83.5	1.00

TABLE IV

Core No. 5 Length 2.00 cm. Area of cross section 9.26 sq. cm

Percentage water saturation	Permeability (millidarcy)	Relative permeability
83.9	0	—
74.0	1.75	0.0215
67.3	4.05	0.0498
61.5	5.67	0.0698
58.1	7.43	0.0914
55.3	9.06	0.1167
49.2	12.86	0.1582
43.8	21.05	0.2589
33.4	34.08	0.4193
32.7	39.59	0.4871
21.2	63.39	0.7798
14.9	76.72	0.9439
1.0	81.28	1.00
0.0	81.28	1.00
—	—	—
--	-	—
—	—	—

While curves plotted in Figure 3 approach zero liquid saturation asymptotically those plotted in Figure 4 make an angle at zero liquid saturation. Otherwise the curves are all alike in shape. The slopes at the point of zero liquid saturation do not seem to depend on the permeability of the cores. Again, some cores attain zero air permeability long before complete liquid saturation is obtained while others approach zero permeability as the liquid saturation approaches 100%; cores showing the former behaviour generally have lower permeabilities.

Krutter (1941) made measurements similar to those reported in this paper. The author is not aware of any other work of similar nature although the simultaneous flow of two or three fluids through loose as well as consolidated sands was studied by Wyckoff, and others. (Wyckoff and Botset, 1936; Leverett, 1938, Botset, 1939 ; Leverett and Lewis, 1940). Wyckoff and others made measurements using very highly permeable cores and obtained curves which resembled in some respect those reported in Figure 3. Krutter found that different core samples produced curves of different shapes although his average curve was similar to those of Wyckoff and others. The reason why different cores would show different permeability/liquid saturation curves does not appear to be very clear.

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