Fluid Flow in Simulated Fractures

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Fractures in some petroleum reservoirs often play an important role in the production of fluid from the pay formation. In fact, in some cases the oil or gas could not be produced economically in the absence of fractures functioning as principal conduits for transporting the fluids from the reservoir to the well bore. On occasions, special well treatments designed to induce fractures, to widen fractures, and/or to extend existing fractures are employed in oil wells.

The flow of a fluid in fractures in the vicinity of the well bore may be of either a viscous or a turbulent type, depending upon the fluid properties and the conditions prevailing in the fractures. It is the purpose of this paper to present correlations of the fluid properties and conditions prevailing in simulated fractures so that engineering flow calculations for the single-phase flow of Newtonian fluids in actual fractures may be made more expediently than at present.

For present purposes a fracture is defined as a three-dimensional conduit; that is, it has length, width, and depth. The flow within the fracture is considered unidirectional and steady state and is treated similarly to the flow between two parallel plates. Any surface irregularity extending from the surface of a plate is designated as surface roughness. For the case of packed fractures, such as those filled with sand or similar granular material, the flow problem is considered analogous to that encountered in packed columns.

RELATED STUDIES

A survey of the literature reveals many studies that are related to, but not directly concerned with, fluid flow in fractures. An equation for viscous flow between parallel plates which may be used to simulate the geometry of a fracture may be written as

$$Q = \frac{\Delta P g_c b W_f^{\,3}}{12 \mu l_f} \qquad (1)$$

Lamb (*13*) states that Equation (1) is approximately valid even if the interval W_f between the two surfaces is variable, provided that the gradient dW_f/dl_f is small and, even if both surfaces are curved, provided that W_f is small compared with the radii of curvature.

Another means of describing fluid flow behavior in fractures is in terms of a Fanning-type friction-factor plot, in which the Reynolds number

$$Re = \frac{2 W_f U \rho}{\mu} \qquad (2)$$

is correlated with the friction factor

$$f = \frac{\Delta P g_c W_f}{l_f \rho U^2} \qquad (3)$$

Under conditions of viscous flow in fractures, it may be shown that the friction factor and Reynolds number have the relation

$$f = \frac{24}{Re} \qquad (4)$$

Davies and White (*7*) in experimenting with variable-width rectangular pipes as water conduits found that Equation (4) did not hold for Reynolds numbers above 1,800. The reported data covered a Reynolds number range of 60 to 4,500. Page et al. (*16*) in a study of temperature gradients in turbulent gas streams flowing between parallel glass plates reported flow data in the Reynolds number range of 7,000 to 60,000. The data and correlations of these two studies cover a sufficiently wide range of flow conditions to be adequate to describe the flow in most smooth-surface fracture systems.

The flow of a fluid in rough-surface conduits has been under study for a considerable period of time. However, very little of this work has dealt with conduits resembling fractures. Darcy (*6*) was one of the first to recognize that the nature of the wall of a pipe affected the flow. Bazin (*1*) continued the experiments of Darcy and developed empirical equations relating the flow to surface conditions of specific materials. Stanton (*18*) worked with two pipes of different size, the inner surfaces of which were threaded so that the surface-roughness-to-diameter ratio was the same, and from these experiments concluded that the Reynolds number concept held for flow in such rough-surface pipe. Although the friction factor and Reynolds number for flow in these two particular pipes agreed, the friction factor for a corresponding Reynolds number in a smooth-surface pipe was lower at large Reynolds number values. Schiller (*17*), in working with brass tubes threaded similarly to those used by Stanton, studied the flow behavior in the critical region of flow and concluded that the critical Reynolds number was independent of the surface roughness of the pipe. This conclusion, however, was based on a limited degree of surface roughness. Mises (*14*) in an attempt to correlate the existing published data introduced the term *relative roughness*, which is the ratio of the arithmetic mean elevation of surface roughness to the radius of the pipe. The resulting empirical correlations gave the resistance to flow as a function of both the Reynolds number and the relative roughness. Hopf (*10*) used rectangular conduits made from sheets of various smooth- and rough-surface materials to study the effect of surface roughness on flow behavior. For flow at sufficiently large Reynolds numbers, the following expression for the Fanning-type friction factor was offered:

$$f = 0.04\left(\frac{z}{r}\right)^{0.314} \qquad (5)$$

The most recent and exhaustive study is that of Nikuradse (*15*), who investigated the relative roughness effect of artificially roughened pipe surfaces. A coating of lacquer to which sand grains adhered served as the surface. For viscous flow in the rough-surface pipe, the equation for flow in smooth surface pipe was adequate, which expressed in terms of the Fanning-type friction factor is

$$f = \frac{16}{Re} \qquad (6)$$

[It should be noted that Equation (6) for circular conduits has the constant 16 and that Equation (4) for fractures has the constant 24.] For complete turbulence and sufficiently large Reynolds numbers, the friction factor proposed by Nikuradse for flow in rough-surface pipe is

$$f = \frac{1}{4\left(1.74 + 2\log\frac{r}{z}\right)^2} \qquad (7)$$

The above-reported studies of rough surfaces, although adequate for flow

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calculations involving large-diameter pipes, are not conclusive for use in calculations involving fractures with widths of the order of a millimeter or less.

Another condition that may affect fluid flow in some fracture systems, particularly in oil-production practice, is the presence of granular material such as sand, which may be placed there as a propping agent to maintain a fracture in an "open" condition under the existing high overbūrden pressures. In many respects a fracture packed with sand resembles a packed column; thus, the studies of flow through beds of solids have offered some information useful in a study of packed fractures. One of the first to treat the flow in a packed column as similar to the flow in a pipe was Blake (*2*), who proposed a modified Reynolds number in which D_p/ϵ replaced the diameter in pipe-flow calculations. Using this parameter, he found that the pressure loss through the packing was inversely proportional to ϵ^3. In similar studies Burke and Plummer (*3*) reported that at high rates of flow the resistance to flow was proportional to $(1 - \epsilon)/\epsilon^3$, and Kozeny (*12*) reported that at low rates of flow the resistance to flow was proportional to $(1 - \epsilon)^2/\epsilon^3$.

Carman (*4*) showed that at low rates of flow the Blake method of correlation led to the equation offered by Kozeny, namely,

$$\frac{\Delta P g_c}{l} = C_1 \frac{(1 - \epsilon)^2}{\epsilon^3} \frac{\mu U}{D_p^2} \quad (8)$$

Also, at high rates of flow the Blake method of correlation led to the equation reported by Burke and Plummer, which is

$$\frac{\Delta P g_c}{l} = C_2 \frac{(1 - \epsilon)}{\epsilon^3} \frac{\rho U^2}{D_p} \quad (9)$$

Later Ergun (*8*) showed that for all rates of flow, Equations (8) and (9) were additive. He proposed the equation

$$\frac{\Delta P g_c}{l} = 150 \frac{(1 - \epsilon)^2}{\epsilon^3} \frac{\mu U}{D_p^2} + 1.75 \frac{(1 - \epsilon)}{\epsilon^3} \frac{\rho U^2}{D_p} \quad (10)$$

from which the Blake-type friction factor is

$$f = 1.75 + 150 \frac{(1 - \epsilon)}{Re} \quad (11)$$

Equations (10) and (11) are valid for flow in columns packed with solids; however, for flow in a packed fracture where the particle diameter is of the same order of magnitude as the fracture, the validity of the equations has not been established.

Studies reported in the literature adequately cover the flow in conduits usually encountered; however, the use of the reported data to anticipate the flow behavior in a conduit resembling a fracture was considered questionable. Therefore, the study reported in this paper was undertaken to provide the necessary data so that the flow in fractures might be treated similarly to the flow in pipes or in packed columns, as the specific condition in the fracture required.

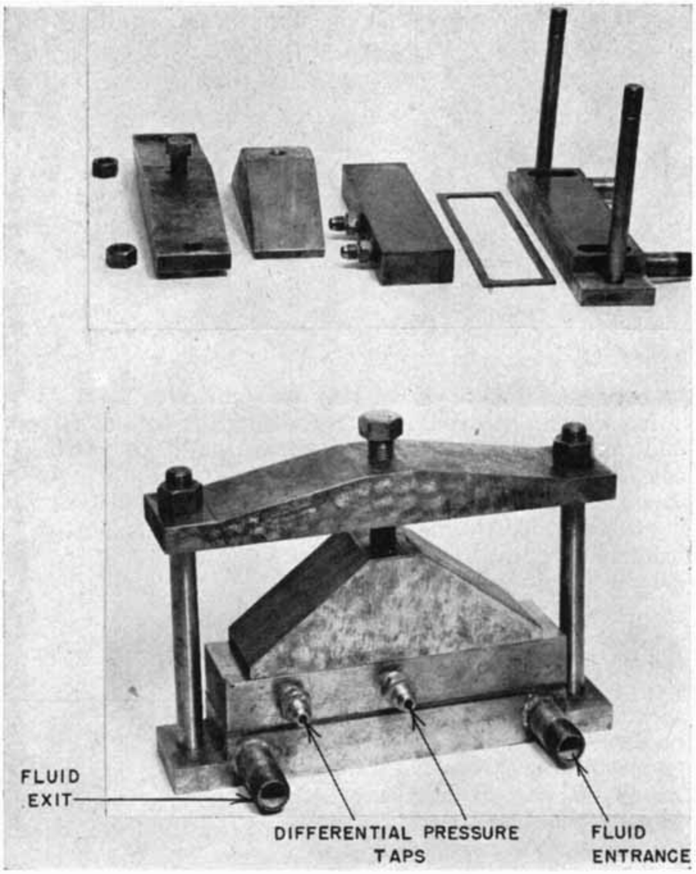

Fig. 1. Flow cell for rough-surface fracture only.

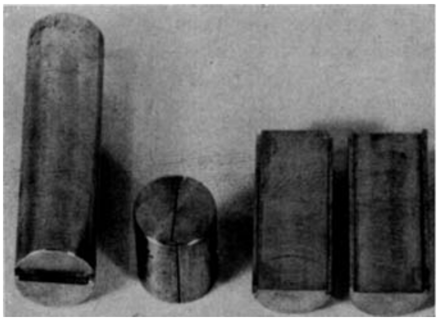

Fig. 2. Steel plugs for simulated fractures.

EXPERIMENTAL METHODS*

Fractures in oil reservoirs may vary widely in the characteristics that define the flow within the fractures. Inasmuch as it was necessary in this study to control the characteristics of the fracture as well as the other variables in the flow system, the fractures were formed in such a manner that all the pertinent variables might be controlled. The flow cell shown in Figure 1 was used for the study of flow in planar fractures. The surfaces which formed the boundaries of the flow cell were coated with a layer of shellac (1 part shellac, 1 part methyl alcohol) by submerging the surfaces in the liquid and then allowing the excess shellac to drain from the surface. Close-cut fractionized sand was sprinkled on the shellacked surface through a sieve screen. The sand grain size was predetermined experimentally by a three-dimensional measurement method (*11*) for each particular sand fraction. The shellac was allowed to dry for about 12 hr. before the surfaces were observed under a microscope for uniformity. For a surface to be used in the flow study, the sand grains covered 40 to 60% of the shellacked surface with no sand particle resting on top of another. Repeated micrometer measurements of the shellacked portion of the surface showed that the shellac film thickness was about 0.01 mm. Upon examination of the surfaces, it appeared that the sand grains were partially immersed in the shellac; for calculation purposes it was assumed that the grains rested on the steel surfaces.

Flow experiments for rough-surface fractures were for the most part performed with air as the fluid at room temperature and atmospheric pressure. Several "calibration runs" were made at the lower flow rates by

*Experimental data are available as document 4832 from the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., for $1.25 for photoprints or 35-mm. microfilm.

use of water, mineral oil, and Soltrol-C (a narrow-boiling-range petroleum fraction resembling kerosene). Flow rates were observed at various differential pressures over a 5.08-cm. test section of the fracture, which was 13.3 cm. in over-all length. The test section was 7.0 cm. from the fluid entrance to the fracture and 1.22 cm. from the exit. Flow data were obtained for fracture widths of 1.58 to 3.74 mm. and surface roughnesses of 0.167 to 0.247 mm. The resulting relative surface roughnesses (z/W_f) were 0.0446 to 0.156. The depth of the fracture in each case was 3.75 cm.

For the study of flow in packed fractures, flat-faced half sections of steel plugs from 2.56 to 7.63 cm. in length were spaced with thin steel plates of sheet metal (shim stock material) and the open section thus formed was packed with fractionized sand samples of predetermined particle diameter. The steel plugs are shown in Figure 2. The average particle diameter of the sand fraction was determined in the following manner. Sand particles of a particular fraction were counted (200 to 2,000) with the aid of a microscope and weighed to determine the number of particles per gram of sand. The particle volume per gram of sand was obtained by measuring the volume of water displaced by a given bulk volume (and weight) of sand in an ordinary burette. The particles were considered as spheres and the average particle diameter was calculated. The bulk volume of the sand was measured in the burette at the time the particle volume was measured. The porosity of the bulk sand was calculated from the particle volume and the bulk volume of the sand.

The fracture of known width was packed with the sand, and the steel plug was tapped to settle the sand in the fracture. The sand was wetted with the fluid to be used in the flow study with further tapping of the plug to ensure close packing of the sand within the fracture. During the packing of the fracture, and during the subsequent flow study, the downstream end of the fraction was "blocked" by a wire screen to retain the sand in the fracture.

The plug was placed in a Hassler-type flow cell for the flow study. After the completion of the flow experiments, the sand pack was removed and dried, and the sand particle volume determined. With the volume of the fracture known, the porosity of the sand pack was calculated.

Flow data were obtained for air, water, a mineral oil, and Soltrol-C in fractures of 0.356- to 1.47-mm. widths. The average particle diameter of the various sand packs varied from 0.111 to 0.803 mm. The resulting particle-diameter–to–fracture-width ratios were 0.084 to 0.78. In each case the fracture depth was 1.85 cm.

A limited amount of flow data on water and Soltrol-C were obtained in a radial flow system using sand packs between circular glass plates 27 cm. in diameter. The plates were oriented in a horizontal plane and fluid entry was through a 7-mm.-diameter hole in the center of one of the plates. The fracture was packed during the flowing of the fluid from the center to the circumference of the fracture. Sand packs having average particle diameters of 0.708 and 0.409 mm. were used in fractures of widths 0.80 and 1.4 mm., respectively The method of obtaining the porosities was the same as previously described.

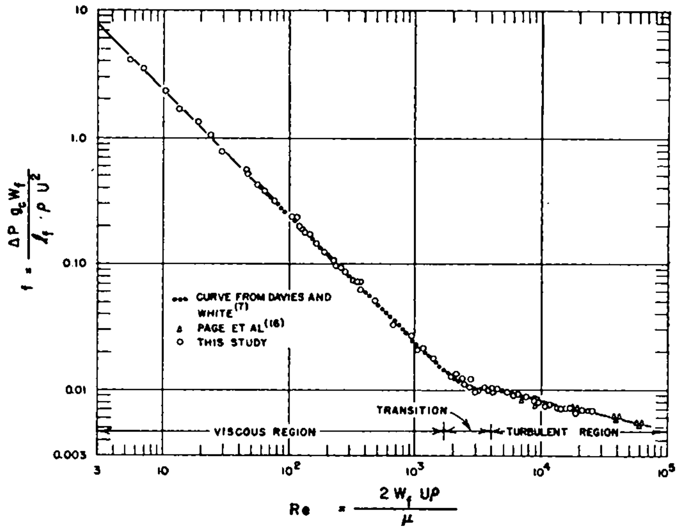

Fig. 3. Friction-factor–Reynolds-number relation for flow in smooth-surface fractures

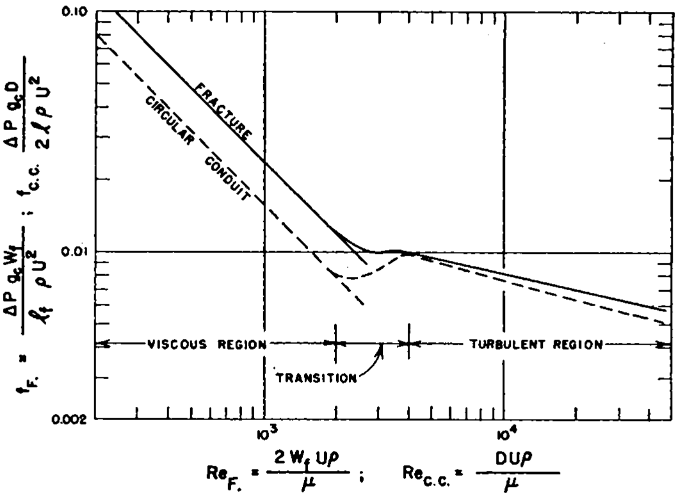

Fig. 4. Friction-factor–Reynolds-number relation for flow in smooth fractures and circular conduits.

DISCUSSION

Previously reported data (*7, 16*) are considered adequate for flow calculations involving fractures possessing smooth surfaces. These reported data are compared in Figure 3 with data obtained from this study. The agreement substantiates the conclusion of Davies and White (*7*) that there is departure from viscous flow at a Reynolds number of about 1,800 and that full turbulence is manifested at about 4,000 and above.

A comparison of flow in a fracture and a circular conduit is made in Figure 4. It is assumed here that the equivalent diameter of a fracture (for use in calculating the Reynolds number) approaches twice the width of the fracture if the depth is large in comparison with the width. For corresponding Reynolds numbers, the friction factors for flow in fractures are higher than for flow in circular conduits; however, at the lowest point where full turbulence is manifested in both systems (*Re* of about 4,000) the friction factors are approximately the same.

Figure 5 shows the friction factors calculated from experimental flow data obtained with rough surface fractures of various relative roughnesses. As was mentioned previously, 40 to 60% of each plate area forming the fracture was "covered" with the sand particles, which provided roughness to the fracture surface. This range of roughness was chosen because it is believed that when a rock is ruptured the roughness of each of the two surfaces forming the resulting fracture would be about the same.

In the viscous flow region the line calculated by Equation (4), which describes the friction factor f at different Reynolds numbers Re shows good agreement with the experimental flow data. In the Reynolds number range of 1,800 to 4,000 the flow is erratic and in some cases the calculated f values lie on the smooth-surface curve up to Reynolds numbers of about 3,000; in other cases the f values show an increase above a Reynolds number of 1,800. With the particular apparatus used in the flow studies, this behavior was probably due to the eddy currents caused by the fluid entrance to the fracture still existing as the fluid flowed through the test section of the fracture.

For relative surface roughnesses (z/W_f) above 0.10, once turbulence is established, the friction factors f are relatively insensitive to higher rates of flow. At z/W_f values below 0.10 investigated in this study, f values in the turbulent range increase slightly above the values established at the beginning of turbulence. It appears that at Reynolds numbers above 20,000, the curves describing the friction factors effective for the various relative roughnesses studied would be parallel.

Friction factors for flow in rough-surface fractures are compared with those of Nikuradse (*15*) for circular conduits in Figure 6. At sufficiently large Reynolds numbers where f is dependent only on z/W_f, an empirical relation obtained from the flow data on fractures is

$$f = 0.055(z/W_f)^{0.472} \qquad (12)$$

In comparison of f values obtained with Equations (5), (7), and (12) the agreement is within 15%; however, none of these equations are valid when f is dependent on both the Reynolds number and the relative surface roughness. This condition is usually obtained with small relative surface roughness at low Reynolds numbers in the turbulent region of flow. An extrapolation of the curves for the various z/W_f values of the fractures to the lower range of Reynolds numbers is not attempted. However, from Schiller's (*17*) work, which reported that large increases in the friction factor for high relative roughnesses are produced immediately after complete turbulence is developed, it would be expected that the extrapolations would probably join the smooth-surface, friction-factor curve at a Reynolds number of about 3,500.

In Figure 7 a comparison of the friction factors calculated from experimental flow data on packed fractures is made with those predicted by Equation (11). The correlation parameters used in the calculations are essentially the same as those first proposed by Blake (*2*), namely, the friction factor

$$f = \frac{\Delta P g_c D_p \epsilon^3}{l_f \rho U^2 (1-\epsilon)} \qquad (13)$$

and the modified Reynolds number

$$Re = \frac{D_p U \rho}{\mu_{(1-\epsilon)}} \qquad (14)$$

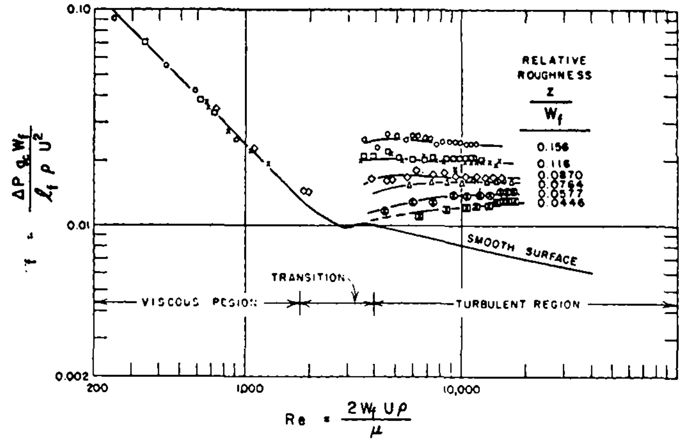

Fig. 5. Friction-factor–Reynolds-number relation for flow in rough-surface fractures.

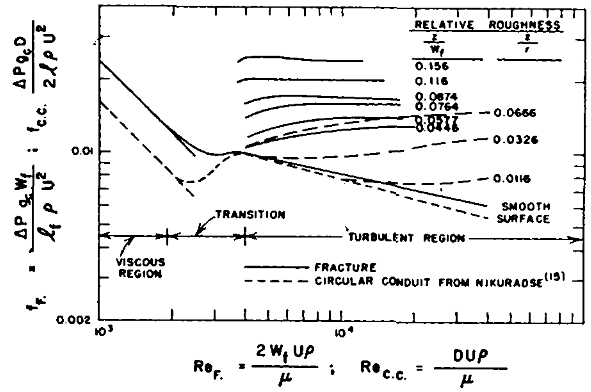

Fig. 6. Friction-factor–Reynolds-number relation for flow in fractures and circular conduits.

The values of the friction factor f calculated from flow data are higher than those calculated with Equation (11) in the Reynolds number range of 5 to 100, but the agreement is good at Reynolds numbers below or above this range. The higher values of the friction factor could be due to the flow discontinuity at the entrance to the sand pack. For Reynolds numbers less than 10 the kinetic energy effects can be neglected, which results in Equation (10) reducing to Equation (8). Also, for Reynolds numbers greater than 1,000 the viscous energy effects can be neglected and Equation (10) becomes the same as Equation (9). In the Reynolds number range of 10 to 1,000, both the viscous and kinetic energy effects must be considered, in which case only Equation (10) is adequate.

The sand-pack porosities used in the friction-factor calculations were those obtained from the correlation shown in Figure 8. The porosity ϵ_f exhibited by the sand in the fracture was as much as 1.4 times greater than the bulk porosity ϵ. The dependence of porosity on the ratio D_p/W_f is somewhat similar to that described by Furnas (*9*) for the wall effect in packed columns; however, in most cases the ratio D_p/W_f is greater in fractures that that reported by Furnas on columns. The largest size sand fraction used in this study was 20-35 mesh and the smallest was 120-200 mesh (U. S. sieve series). The bulk-sand porosity values ϵ ranged from 35 to 41 vol. %; the sand porosity in fractures ranged from 38 to 52 vol. % in fracture widths of 0.64 to 1.47 mm. In cases where D_p/W_f is less than about 0.1, ϵ_f and ϵ are the same. For D_p/W_f ratios above 0.1 it is necessary to know the value of ϵ_f. Provided that the true value for ϵ_f is used, the Ergun (*8*) equation appears adequate for flow calculations involving sand packs in fractures.

Figure 7 also allows comparison to be made of friction factor values calculated from flow data using a radial flow system of sand packs between glass plates with those values predicted by Equation (11). The data are limited, owing to the low differential pressures necessary with the apparatus. For the case of radial flow, l_f becomes the difference between the radius of the glass plates and the radius of the inlet. Also, the bulk velocity is based on the log mean flow area of the empty fracture, in which case

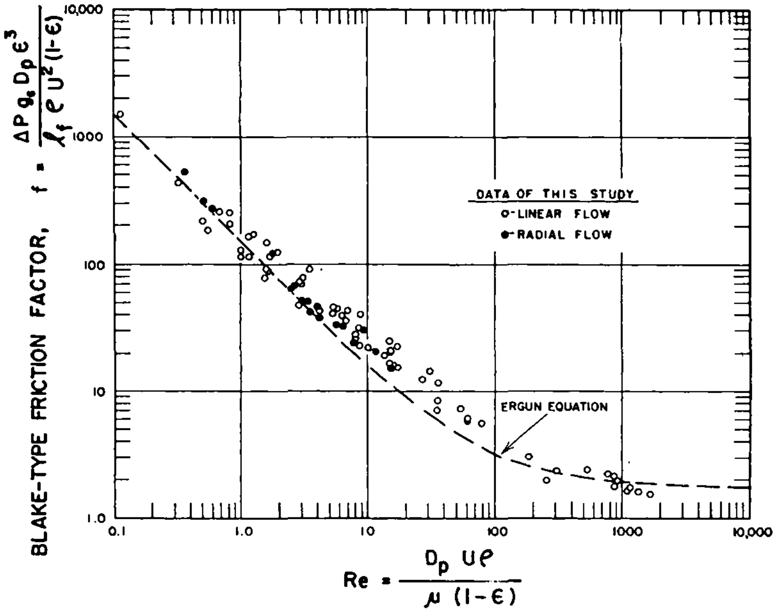

Fig. 7. Blake-type friction-factor–Reynolds-number relation for flow in fractures.

$$U = \frac{Q}{A_m} = \frac{Q}{W_f\left(\frac{2\pi[R - R_w]}{\ln \frac{R}{R_w}}\right)} \tag{15}$$

With these modifications the correlation parameters used are the same as Equations (13) and (14). As in the case of linear flow, the agreement between the friction factor calculated from flow data and predicted with Equation (11) is good; however, above *Re* of 5 the friction factor calculated from flow data is somewhat larger in the range of *Re* studied.

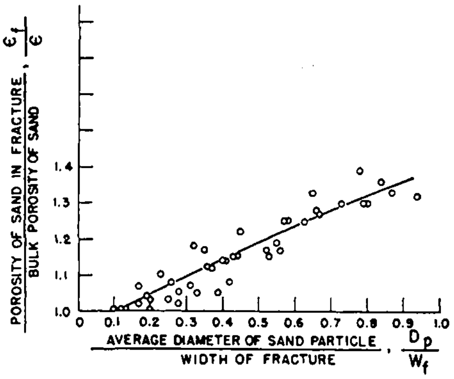

Fig. 8. Porosity–particle-diameter–fracture-width relation.

APPLICATIONS

One of the primary uses for the information presented in this investigation is in the engineering analysis of flow problems in fractured reservoirs. It is realized that values for some of the variables which are relatively easy to measure in the laboratory cannot be determined for an oil reservoir by the present methods of analysis; however, with the use of information presented here, useful approximations can be made for various reservoir problems involving fractures.

The "propping" of induced and widened fractures with sand has received considerable attention in recent years (*5*). The propping agent would rarely form a pack throughout the entire fracture; however, as a limiting case the flow calculations made on a sand pack in a fracture could serve as a model to describe the nature of flow that might be expected under certain reservoir conditions.

It is considered likely that the normal production rates from oil wells rarely create turbulent flow in planar fractures; however, during hydraulic well-treatment processes, and under some of the more unusual production conditions, it is probable that turbulent flow exists in the fractures in the vicinity of the well bore. As shown in Figure 5, surface roughness plays an important part in the flow calculations. A laboratory flow experiment employing both viscous and turbulent flow conditions with a formation core sample containing a fracture of known or measurable width could produce data useful in estimating surface-roughness characteristics of reservoir fractures.

SUMMARY AND CONCLUSIONS

The results reported in the literature cited in this paper together with the new data obtained from the study reported here show that fluid flow in fractures can be treated similarly to fluid flow in circular conduits and that satisfactory friction-factor correlations permitting engineering flow calculations for fractured systems result. The principal conclusions that may be drawn are

1. Viscous flow in planar fractures is limited to Reynolds numbers of less than 1,800. The surface roughness has no appreciable effect upon the resistance to flow when the flow is of a viscous nature.
2. Flow in planar fractures departs from viscous flow at a Reynolds number of about 1,800, but the flow does not become completely turbulent until a Reynolds number of about 4,000 is exceeded.
3. In the region of turbulent flow the effect of surface roughness becomes prominent. The extent to which the friction factor is controlled by the surface roughness is dependent on the relative surface roughness and the Reynolds number.
4. The flow in packed fractures can be treated similarly to flow in a packed column. The porosity exhibited by the sand pack in the fracture is dependent on the ratio of the particle diameter to fracture width. By use of an appropriate porosity value, flow calculations can be made adequately with the Ergun (*8*) equation.

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NOTATION

A_m = log mean cross-sectional flow area
b = depth of fracture
C_1, C_2 = constants
D = diameter of circular conduit
D_p = average diameter of particles, if the particles are assumed to be spheres
f = friction factor, as defined by the appropriate equation for the existing conditions
g_c = mass-force conversion factor
l = length of circular conduit
l_f = length of fracture
ΔP = pressure differential (force units)
Q = volumetric flow rate
r = radius of circular conduit
R_w = radius of source of fluid
R = radius of sump for fluid
Re = Reynolds number, as defined by the appropriate equation for the existing conditions
U = bulk average velocity, based on empty conduit
W_f = width of fracture
z = height of surface roughness
z/r, z/W_f = relative surface roughness
ϵ = bulk porosity exhibited by a bed or sand pack as determined in a porosimeter
ϵ_f = porosity exhibited by sand pack in a fracture
μ = absolute viscosity of fluid
ρ = density of fluid

LITERATURE CITED

1. Bazin, H., *Mémoires à l'Académie des Sciences de l'Institute de France*, **32**, No. 6 (1902).
2. Blake, F. E., *Trans. Am. Inst. Chem. Engrs.*, **14**, 415 (1922).
3. Burke, S. P., and W. B. Plummer, *Ind. Eng. Chem.*, **20**, 1196 (1928).
4. Carman, P. C., *Trans. Inst. Chem. Engrs.*, **15**, 150 (1937).
5. Clark, J. B., *Trans. Am. Inst. Mining Met. Engrs.*, **186**, 1 (1949).
6. Darcy, H., *Mémoires à l'Académie des Sciences de l'Institute imperial de France*, **15**, 141 (1858).
7. Davies, S. J., and C. M. White, *Proc. Roy. Soc. (London)*, **119A**, 92 (1928).
8. Ergun, S. K., *Chem. Eng. Progr.*, **48**, 89 (1952).
9. Furnas, C. C., *U.S. Bur. Mines Bull.* 307 (1929).
10. Hopf, L., *Z. Angew. Math. u. Mech.*, **3**, 329 (1923).
11. Huitt, J. L., *Bull. Am. Assoc. Petroleum Geol.*, **38**, 159 (1954).
12. Kozeny, J., *Sitzber. Akad. Wiss. Wien, Mathnaturw. Kl.*, **136**, 271 (1927).
13. Lamb, Horace, "Hydrodynamics," 6 ed., Dover Publications, New York (1945).
14. Mises, R. V., "Elemente der Technischen Hydrodynamik," S. G. Teuber, Leipzig (1914).
15. Nikuradse, J., *Forsch. Gebiete Ingenieurw. Forschungsheft*, (Sept.–Oct., (1932); reprinted in *Petroleum Engr.*, **11**, No. 6, 164; No. 8, 75; No. 9, 124; No. 11, 38; No. 12, 83 (1940).
16. Page, F., Jr., W. H. Corcoran, W. G. Schlinger, and B. H. Sage, *Ind. Eng. Chem.*, **44**, 419 (1952).
17. Schiller, L., *Z. Angew. Math. u. Mech.*, **3**, 2 (1923).
18. Stanton, T. E., *Proc. Roy. Soc. (London)*, **85A**, 366 (1911).

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Plate Efficiency with Chemical Reaction—Absorption of Carbon Dioxide in Monoethanolamine Solutions

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The effect of chemical reaction on plate efficiency has been given little attention in the determination of bubble-plate efficiencies, although it is of importance in many operations. A typical example is the absorption of carbon dioxide in monoethanolamine solutions.

The over-all Murphree gas-phase plate efficiency can be shown to be a function of $K_g(A/V)$ where A/V is the interfacial surface area formed per tray per unit volume of gas. In order to evaluate variations in tray efficiency due to factors influencing K_g, data available in the literature for the absorption of carbon dioxide in monoethanolamine were considered. These showed that the liquid film was controlling and that for a packed column at constant liquid rate the absorption coefficient could be satisfactorily expressed by an equation that resembles somewhat equations which have been developed for the effect of rapid second-order reactions on k_L. However, the observed effect of carbon dioxide partial pressure in the gas is not so great as the theoretical equations would predict.

By use of the equation mentioned above to predict K_g, satisfactory correlation of observed plate efficiencies is obtained for a commercial column over a considerable range of conditions. It appears that the correlation can be extended to other pressures, flow rates, and column designs by an evaluation of the effect of these variables on A/V and K_g.

The estimation of plate efficiencies has only recently been approached from a theoretical basis, and for the general cases of distillation and physical absorption some success has been noted. The effect on plate efficiency of chemical reaction in the liquid phase has apparently been given little attention, although a large number of industrial absorption operations depend upon processes of this type.

Methods of estimating plate efficiency based upon an attempted visualization of the actual bubbling action at a single point have been discussed by Geddes (*6*), West et al. (*20*), Chu (*2*, *3*), and others. The problem of predicting the effect of chemical reaction upon absorption has been treated by Sherwood and Pigford (*14*); by Van Krevelen and Hoftijzer (*17*); and recently by Perry and Pigford (*12*), who used a digital computer to solve the diffusion equations for the case of second-order reactions. The ultimate answer to the calculation of plate efficiency in the presence of chemical reaction would be to determine the effect of the reaction on the liquid-film coefficient by means of a fundamental treatment and, subsequently, to relate both liquid and gas film coefficients to the plate efficiency through an accurate analysis of phenomena occurring in the bubble zone. Unfortunately,