Prediction of Pressure Gradients for Multiphase Flow in Tubing

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ABSTRACT

An 8,000-ft experimental field well was utilized to conduct flowing pressure gradient tests under conditions of continuous, multiphase flow through 2 3/8-in. OD tubing. The well was equipped with 10 gas-lift valves and 10 Maihak electronic pressure recorders, as well as instruments to accurately measure the surface pressure, temperature, volume of injected gas and fluid production.

These tests were conducted for flow rates ranging from 75 to 936 B/D at various gas-liquid ratios from 105 to 9,433 scf/bbl. An expanding-orifice gas-lift valve allowed each flow rate to be produced with a range of controlled gas-liquid ratios. From these data an accurate pressure traverse has been constructed for various flow rates and for various gas-liquid ratios.

A comparison of these tests to Poettmann and Carpenter's correlation indicates that deviations occur for certain ranges of flow rates and gas-liquid ratios. Numerous curves are presented illustrating the comparison of this correlation with the field data. Poettmann and Carpenter's correlation deviates some for low flow rates and, in particular, for gas-liquid ratios in excess of 3,000 scf/bbl. These deviations are believed to be mainly due to the friction-factor correlation. However, Poettmann and Carpenter's correlation gives excellent agreement in those ranges of higher density. This was as expected and predicted by Poettmann. He pointed out that their method was not intended to be extended to those ranges of low densities whereby an extreme reversal in curvature occurs.[1]

As a result of these experimental tests, correlations using Poettmann and Carpenter's method were established between the friction factors and mass flow rates which are applicable for all gas-liquid ratios and flow rates. Definite changing flow patterns do not allow any one correlation to be accurate for all ranges of flow.

INTRODUCTION

The ability to analytically predict the pressure at any point in a flow string is essential in determining optimum production string dimensions and in the design of gas-lift installations. This information is also invaluable in predicting bottom-hole pressures in flowing wells.

Although this problem is not new to industry, it has by no means been solved completely for all types of flow conditions. Versluys,[2] Uren, *et al*,[3] Gosline,[4] May,[5] and Moore, *et al*,[6,7] were all early investigators of multiphase flow through vertical conduits. However, all of these investigations and proposed methods were very limited as to their range of application. Likewise, many are extremely complicated and therefore not very useful in the field.

Only in the last decade have any significant methods been proposed which are generally applicable. The most widely accepted procedure in industry at the present time is a semi-empirical method developed from an energy balance, proposed by Poettmann and Carpenter[8] in 1952. Their correlation is based on actual pressure measurements from field wells. Accurate predictions from this correlation are limited to high flow rates and low gas-liquid ratios.

Although this method will be discussed in detail later, it should be pointed out that two important parameters, namely the gas-liquid ratio and the viscosity, were omitted in their correlation. The viscosity was justifiably omitted since their data was in the highly turbulent flow region for both phases, and most wells fall in this category. The gas-liquid ratio was incorporated to some extent in the gas-density term. In 1954, Gilbert[9] presented numerous pressure gradient curves obtained from field data for various flow rates and gas-liquid ratios for the determination of optimum flow strings. However, no method is presented for predicting pressure gradients except by comparison to these curves. Baxendell, *et al*,[10] proposed a method based on Poettmann and Carpenter's procedure

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[1]References given at end of paper.

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for high-rate flowing wells. Similarly, Tek[11] presented a procedure for calculating pressure gradients in two-phase flow by employing a two-phase Reynolds number and friction-factor function in Poettmann's correlation.

Undoubtedly, the most significant correlation since Poettmann and Carpenter's is the one proposed by Ros.[12] This is a general, but complicated, procedure which is based on a pressure balance between any two points in the flow string. The relationships between all variables were investigated by dimensional analysis from which irrelevant groups were eliminated. The resulting relationship consists of a dimensionless pressure gradient expressed in terms of a friction term and a liquid hold-up term (depending on slip only) for various flow patterns. However, this correlation is only for two-phase flow but may be linearly interpolated on the basis of percentage water-cut in the case of oil, water and gas systems (considerable error may be introduced by this interpolation). Using our data, Ros reported agreement was excellent in all ranges of flow rates and gas-liquid ratios (+0.60 bias using his improved method). It should be emphasized that this method is extremely tedious and complicated for ordinary field use unless a large computer is available.

This paper represents the continuous-flow portion of an experimental gas-lift project covering both continuous and intermittent flow. The project was conducted by The U. of Texas and was jointly sponsored by the Marathon Oil Co. (formerly the Ohio Oil Co.), Sun Oil Co. and Otis Engineering Corp. A paper on intermittent flow was reported by Brown and Jessen.[13] This was also given in more detail in a technical report to Marathon Oil, Sun Oil and Otis Engineering,[14] as well as in a dissertation by Brown.[15]

The purpose of these tests was to establish pressure traverses in 2 3/8-in. OD tubing for varying liquid flow rates as produced with varying gas-liquid ratios. The range of liquid flow rates was between 75 and 936 B/D. Each liquid flow rate was produced with a gas-liquid ratio that varied from 105 to 9,433 scf/bbl, depending upon the total liquid volume.

It was further intended to establish the reliability of known methods for calculating pressure traverses. Poettmann[8] had mentioned the possible limitations of his method in the range of high gas-liquid ratios and very low densities. Also, it has been anticipated that at high gas-liquid ratios a reversal in curvature occurred in the pressure traverse. This investigation afforded an opportunity to establish the exact gas-liquid ratio at which reversal occurred.

Because the well was making 95 per cent water, the effect of viscosity could not be ascertained. However, it has been pointed out by other authors[8,16] that viscous shear is negligible. In addition, because water is more difficult to lift than oil, the water-gradient curves can be used with confidence for the purpose of artificial-lift design.

Another objective was to obtain sufficient pressure-traverse data to allow accurate prediction of the pressure traverse in 2-in. tubing for any liquid flow rate, and for any gas-liquid ratio in the range of these tests.

EXPERIMENTAL TESTING EQUIPMENT AND PROCEDURE

The details of the experimental set-up and testing procedure has been previously outlined in a paper by Brown and Jessen.[13, 14] The test well was capable of making 1,000 B/D of total liquid (95 per cent salt water). The physical properties of the oil, water and gas are shown in Table 1.

The production rate was controlled by a bottom-hole choke located at 6,077 ft. Once a particular flow rate had been set by a predetermined bottom-hole choke size, this particular liquid flow rate was maintained over a range of gas volume rates. This technique made possible the production of each barrel of liquid at different gas-liquid ratios. These gas-liquid ratios changed from 9,433 scf/bbl for the lowest liquid rates, to as low as 250 scf/bbl for the highest liquid rates. The upper range of gas-liquid ratios was limited only by the maximum rate at which gas could be supplied. Fortunately, a peak gas supply of over 1.4 MMscf/D was available.

In order to be able to lift each liquid rate with varying volumes of gas, a flexible-sleeve gas-lift valve was used. It operates essentially as an expanding-orifice regulator (Fig. 1). The resilient element acts as an expanding orifice, and will open to pass the desired gas. This, in turn, allows one predetermined liquid rate to be produced with varying gas volumes. For example, the resilient element could pass both the maximum rate of 1.4 MMscf/D and the minimum rate of 34 Mscf/D. A valve of this type was necessary for these tests because a fixed-orifice valve would not allow this flexibility.

Fig. 2 shows all of the down-hole equipment. As can be seen, some 10 flexible-sleeve gas-lift valves were installed along with 10 Maihak electronic pressure transmitters. These pressure transmitters have been described previously in detail;[17] therefore, only a brief discussion will be presented. These instruments measure the frequency of a stressed wire which is correlated with pressure.

TABLE 1 — PHYSICAL PROPERTIES OF OIL, WATER AND GAS

API Gravity at 60 F	34.0°
Formation Volume Factor at 3,375 psig	1.313
Gas in Solution at 3,375 psig	620 scf/bbl
Oil Viscosity at 3,375 psig	0.46 cp
Salt Water-Chlorides	60,000 ppm
Estimated Specific Gravity	1.065
Specific Gravity of Injected Gas at Standard Conditions	0.57
Specific Gravity of Solution Gas at Standard Conditions	0.65
Bottom-Hole Pressure, March 14, 1961	3,375 psig
Original Reservoir Pressure	3,575 psig
Original Reservoir Temperature	193 F
Saturation Pressure	3,575 psig
Tubing Size	2 3/8-in. OD Plastic-coated

Each transmitter was connected by one conductor to the surface with the tubing acting as ground to complete the circuit. By individually switching from one transmitter to the other, a recording of the pressure at each transmitter location could be obtained. Calibration both before and after each test indicated a maximum error of 0.62 per cent for any one instrument. Most of the continuous-flow tests were conducted with gas being injected at a valve located at 2,774 ft. The valves above and below were closed to prevent the installation from moving from one valve to the other as the rate of gas injection was changed.

As can be seen from the surface installation (Fig. 3), an input-gas regulator was used to maintain a constant downstream pressure and a uniform rate of gas injection. The liquid and gas production was measured to the nearest 1/4 gal by a Rollo Test Separator. Production was also measured at another calibrated test separator and liquid test meter before entering the tanks.

The pressure was recorded at all points above the point of injection. Gas was injected through Valve No. 9 or 10 at 2,774 ft or 2,182 ft, respectively (Fig. 2). Therefore, pressure recordings were made using Maihak Pressure Transmitters 7, 8, 9 and 10 located at 477, 969, 1,685 and 2,493 ft, respectively, and at the surface. From these recordings (all above the point of gas injection), the pressure traverse down the hole was obtained for a controlled gas-liquid ratio.

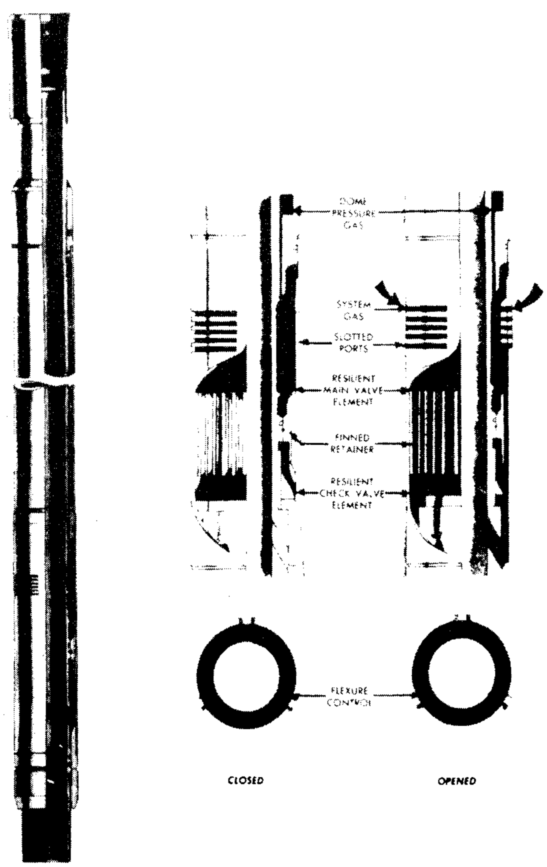

FIG. 1 — FLEXIBLE SLEEVE VALVE.

METHODS OF PREDICTING PRESSURE GRADIENTS

Many methods have been developed for predicting pressure gradients in vertical, multiphase flow. However, this discussion is limited to Poettmann and Carpenter's method[8] because it seems to be the most reliable and is the generally accepted method. Also, a correlation which is based on Poettmann and Carpenter's work has been developed. It is shown that their method can be extended to include other ranges of flow.

POETTMANN AND CARPENTER'S METHOD

This semi-empirical correlation of Poettmann and Carpenter is based on field data from 49 wells (34 flowing wells and 15 gas-lift wells) covering only a limited range of flow rates and gas-liquid ratios. The gas-oil ratios or gas-liquid ratios were constant for each flow rate. Most of the tests on the gas-lift wells were in the range of total liquid flow rates between 300 and 800 B/D and gas-liquid ratios between 100 and 800 scf/bbl.

An energy balance between any two points in the flowing string in which the flowing fluid was treated as a single homogeneous phase was developed as the basis for their correlation. The irreversible energy losses were incorporated in a Fanning-type friction-factor term. A correlation was developed by back-calculating the friction term from field data and plotting it against the numerator of the Reynolds number. Viscosity effects were not included in this correlation due to the high degree of turbulence of both phases. Viscous shear is negligible if both

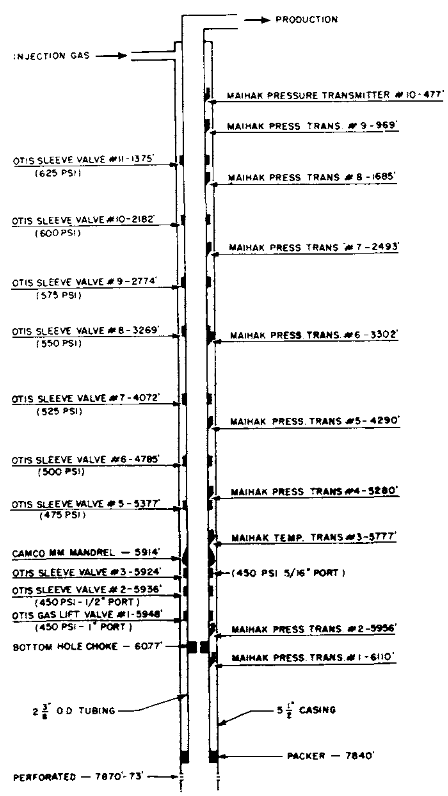

FIG. 2 — DOWN-HOLE EQUIPMENT.

phases are in a high degree of turbulence. However, for highly viscous fluids, a calculation of the Reynolds number may show one fluid to be in the viscous flow region. It is known that, if either fluid is in the viscous flow region, then viscosity cannot be neglected. Poettmann has pointed out that their correlation is not valid for those regions of flow where either fluid is in the viscous flow region.[1] Also, the slippage of the gas by the liquid was not separated from wall friction in their correlation.

However, this irreversible energy loss is inherently incorporated in their friction-factor correlation because it was obtained empirically from field data in which slippage undoubtedly occurred.

In programming Poettmann and Carpenter's method for the 1604 Control Data Corp. computer, it was necessary to make several assumptions and approximations. Equations were written for the solution gas and formation volume factor as a function of pressure. Two simplifying assumptions were also necessary. The flowing temperature gradient was assumed to be linear and the average flowing temperature was used. In several tests, the flowing surface temperature was obtained from the correlation between flowing surface temperature flow rate and gas-liquid ratio. (Fig. 4) *Also, the compressibility factor of the gas was assumed equal to one. This should not be neglected for high pressures and gases with numerous impurities.* In these tests, a dry gas (specific gravity = 0.57) and pressures less than 600 psig were encountered. Two comparisons were made using the program procedure and the original method, with no assumptions. The maximum deviation between the two procedures was ± 0.80 per cent.

PROPOSED CORRELATION

When Poettmann and Carpenter's correlation was applied to the field data, deviations were noted in several ranges of flow rates and gas-liquid ratios (Figs. 24 through 32). Because of these deviations, an empirical correlation based on their method was developed to fit the field data for the particular

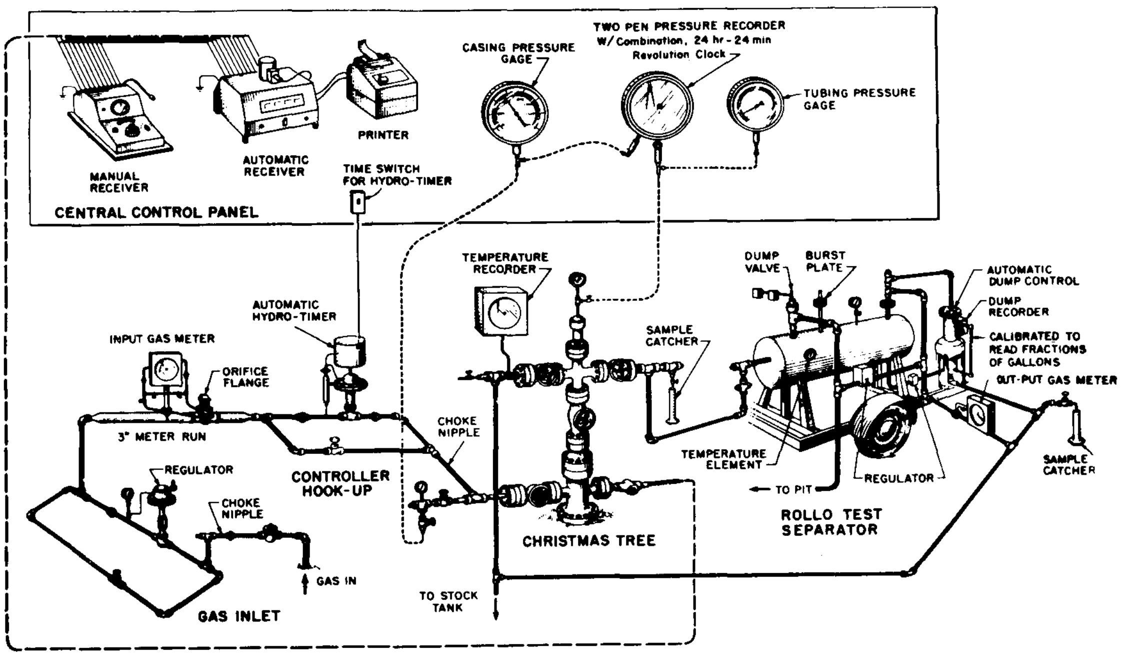

FIG. 3 — SURFACE TESTING EQUIPMENT.

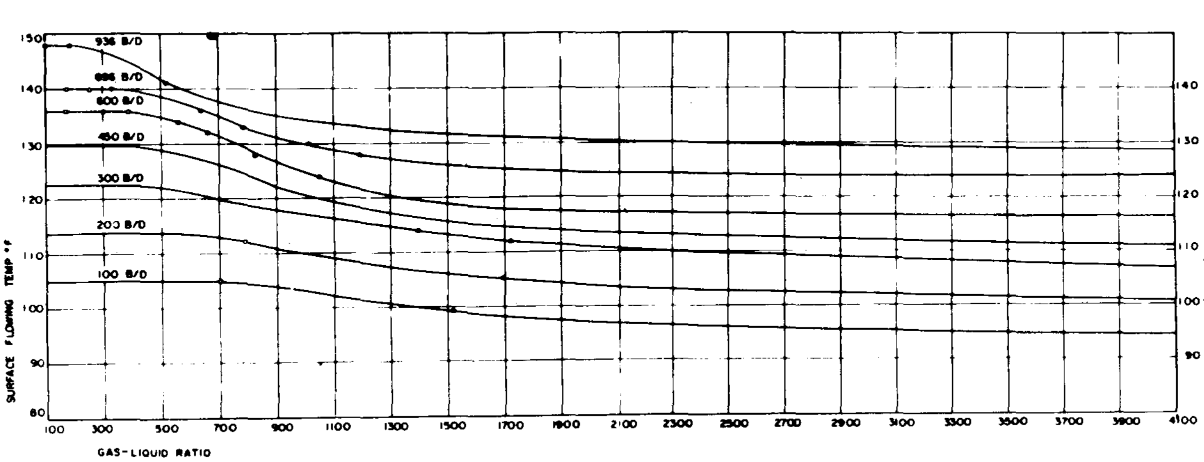

FIG. 4 — CORRELATION FOR SURFACE FLOWING TEMPERATURE.

ranges of flow rates and gas-liquid ratios involved.

Viscous shear was also found to be negligible in these tests due to the high degree of turbulence of both phases. However, the original Poettmann and Carpenter correlation was extended to cover the lower density ranges (in particular less than 10 lb/cu ft for 2-in. tubing), which Poettmann stated was outside the range of their original data.[1] This lower density range was further correlated by using the producing gas-liquid ratio as an additional parameter.

The irreversible-energy-loss term was evaluated by back-calculation using field data to determine the pressure gradient from the following equation.

$$f = 7.413 \times 10^{10} \, (\rho)(d)^5 \times 144[(dp/dH) - \rho]/q^2 \times M^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

where f = Fanning-type friction factor,

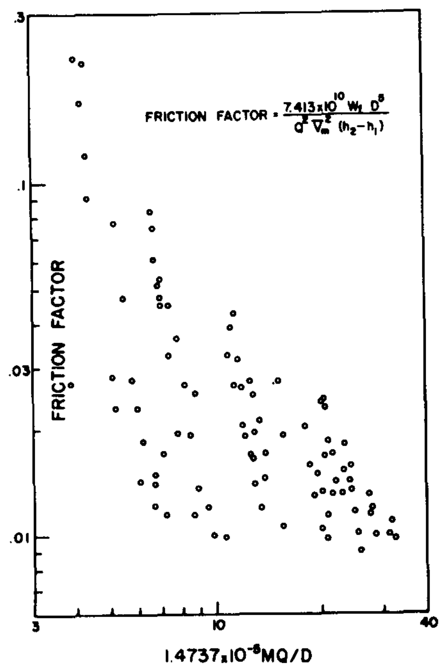

FIG. 5 — BACK-CALCULATED FRICTION FACTOR.

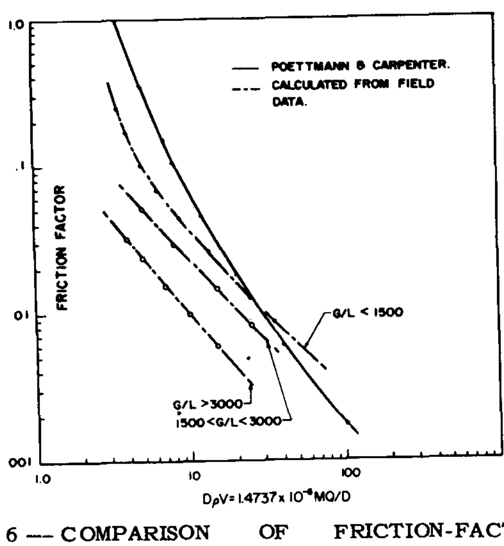

FIG. 6 — COMPARISON OF FRICTION-FACTOR CORRELATION.

ρ = flowing density, lb/cu ft,

$\frac{dp}{dH}$ = pressure gradient, psi/ft,

q = oil flow rate, B/D,

d = diameter of pipe, ft.

The Fanning-type friction factor was plotted against the numerator of the Reynolds number (Fig. 5). The scattering of points in this correlation suggests that an important parameter (or parameters) was neglected. By employing the gas-liquid ratio as an additional parameter, a correlation was developed between the Fanning friction factor and the numerator of the Reynolds number for three ranges of gas-liquid ratios (Figs. 7, 8 and 9). In comparing this correlation to that of Poettmann and Carpenter (Fig. 6), only a small deviation is found for gas-liquid ratios below 1.5 Mscf/bbl and qM/d's between 15 and 50. This is to be expected because Poettmann's correlation was based on data in these ranges. Also, it should be noted that, as the gas-liquid ratio increases, the wall friction decreases (Fig. 6). Although the friction factor is decreasing, the pressure gradient increases at high gas-liquid ratios due to a decrease in the flowing density as shown in the following equation.

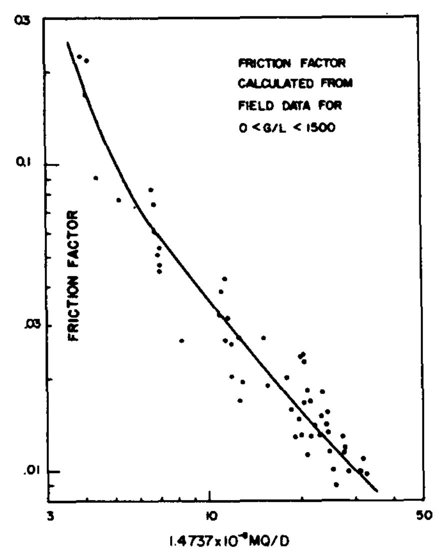

FIG. 7 — FRICTION-FACTOR CORRELATION.

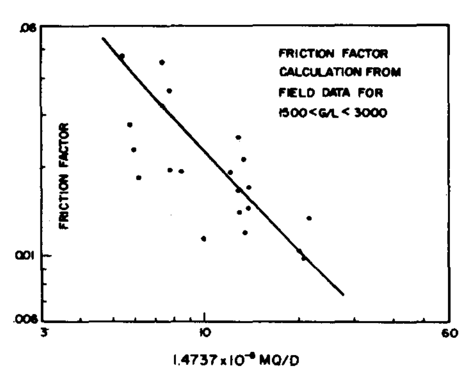

FIG. 8 — FRICTION-FACTOR CORRELATION.

$$\frac{dp}{dH} = \frac{1}{144}\left[\rho + f\left(\frac{q^2 M^2}{7.413 \times 10^{10}\,\rho\, d^5}\right)\right] \quad . \; . \quad (2)$$

Therefore, as the gas-liquid ratio increases and the liquid rate decreases, pressure gradients calculated from Eq. 2 are influenced more and more by the second term of Eq. 2.

Correlations were developed for the producing gas-liquid ratio (Figs. 6 through 9). Correlations have been previously developed for in situ gas-liquid ratios. However, it was found that excellent agreement was obtained by using the producing gas-liquid ratio as a parameter.

DISCUSSION OF RESULTS

In discussing the results of this investigation, the reliability and range of application of both correlations, viscosity, the effect of gas-liquid ratio, heading phenomena and reverse curvature will be discussed.

POETTMANN AND CARPENTER'S CORRELATION

Pressure traverses predicted by this method were in close agreement to field data for flow rates of 936 to 420 B/D in the range of gas-liquid ratios possible to obtain (Figs. 13 through 22). For flow rates greater than 600 B/D in all ranges of gas-liquid ratios, the average deviations were less than ± 5.0 per cent. For flow rates of 552 and 504 B/D and gas-liquid ratios of 1.7 and 1.9 Mscf/bbl, the average per cent deviations were – 10.3 and – 11.7, respectively. Except for these two flow rates, all deviations were less than ± 10 per cent in all ranges of gas-liquid ratios for flow rates greater than 414 B/D. In general, for flow rates less than 414 B/D, considerable deviation was found, regardless of the gas-liquid ratio. In particular, for flow rates less than 312 B/D, average deviations were greater than – 20 per cent. For gas-liquid ratios greater than 1 Mscf/bbl and for flow rates less than 192 B/D, the average deviations were greater than – 80 per cent (Figs. 27, 28, 31 and 32).

These results are to be expected from Poettmann and Carpenter's correlation since, as mentioned previously, all irreversible energy losses are incorporated in a friction-factor term, for the range of their data, and fail to hold for the low density ranges. This correlation shows that the original Poettmann and Carpenter correlation can be used to give greater accuracy in the low density ranges by using the gas-liquid ratio as a parameter (Fig. 6).

PROPOSED CORRELATION

Predicted pressure traverses were in excellent agreement for all flow rates and gas-liquid ratios for liquid flow rates greater than 330 B/D (Figs. 13 through 23). The maximum error was ± 5.8 per cent. For flow rates between 192 and 330 B/D, the maximum average deviation was – 22.2 per cent; however, in all but four tests, the deviation was less than ± 10.8 per cent. In general, for flow rates below 192 B/D, agreement was good for all ranges of gas-liquid ratios (Figs. 26 through 32). The average deviation exceeded ± 10 per cent in only five tests in which the maximum deviation was – 26.7 per cent. In this range of flow rates and gas-liquid

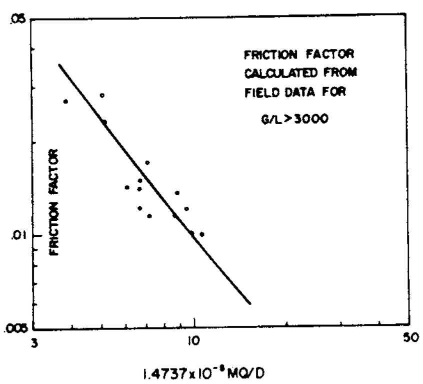

FIG. 9 — FRICTION-FACTOR CORRELATION.

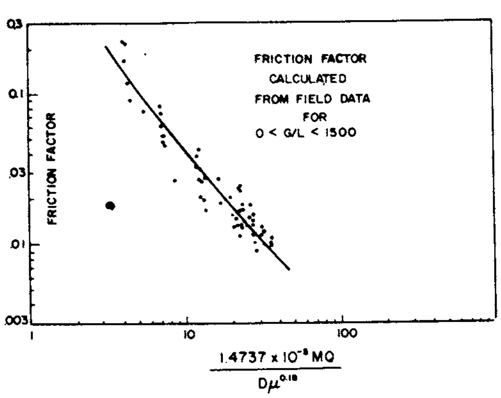

FIG. 10 — FRICTION-FACTOR CORRELATION INCLUDING THE LIQUID VISCOSITY.

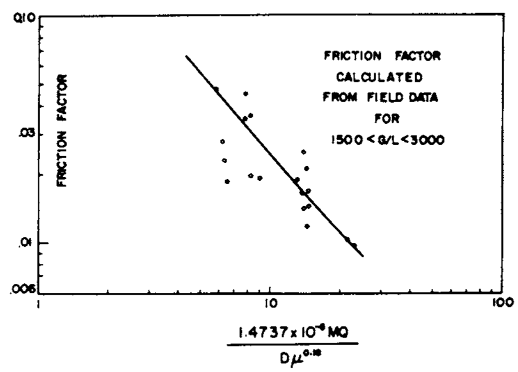

FIG. 11 — FRICTION-FACTOR CORRELATION INCLUDING THE LIQUID VISCOSITY.

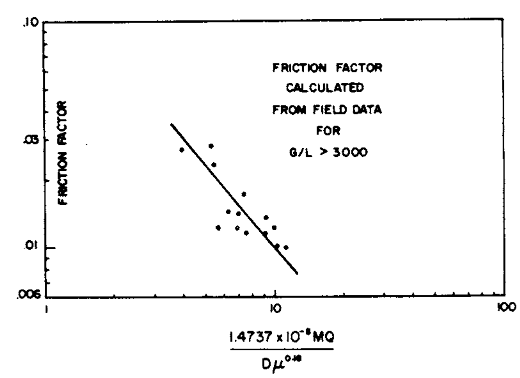

FIG. 12 — FRICTION-FACTOR CORRELATION INCLUDING THE LIQUID VISCOSITY.

ratios, Poettmann's correlation resulted in deviations greater than – 100 per cent for most tests (Figs. 31 and 32). Again, it should be emphasized that Poettmann and Carpenter did not expect their correlation to hold for all these ranges.

VISCOSITY

The effect of viscosity on the friction-factor correlation was investigated. It was determined in these tests that the viscosity of the liquid mixture was negligible (Figs. 10, 11 and 12).

Poettmann and Carpenter[8] found that viscous shear was negligible. This is true if both phases are in highly turbulent flow, as was the case for their correlation. However, Ros[12] indicated that the viscosity has a significant effect on pressure-traverse predictions for fluids with viscosities greater than 6 cstk. This undoubtedly places the liquid in a viscous or partial-viscous flow region.

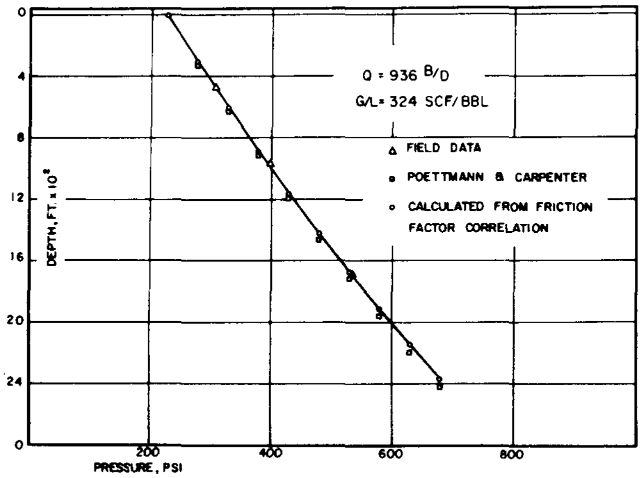

FIG. 13 — COMPARISON OF PRESSURE TRAVERSES.

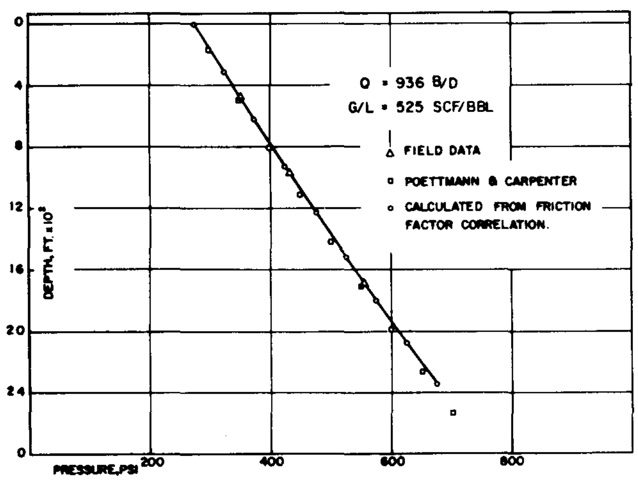

FIG. 14 — COMPARISON OF PRESSURE TRAVERSES.

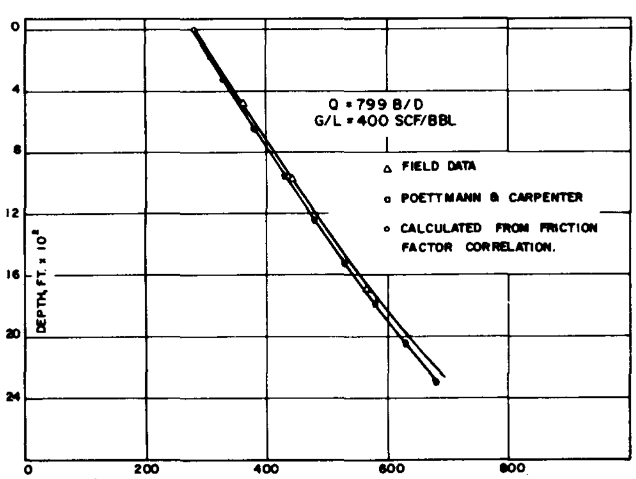

FIG. 15 — COMPARISON OF PRESSURE TRAVERSES.

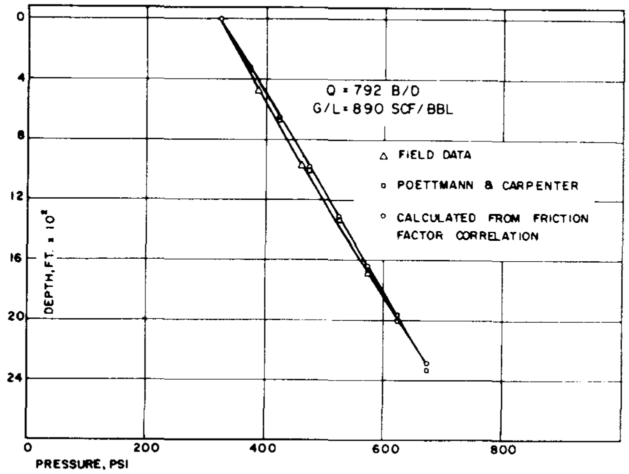

FIG. 16 — COMPARISON OF PRESSURE TRAVERSES.

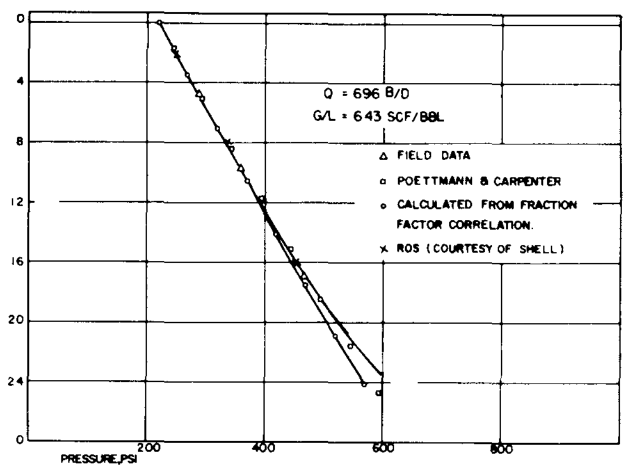

FIG. 17 — COMPARISON OF PRESSURE TRAVERSES.

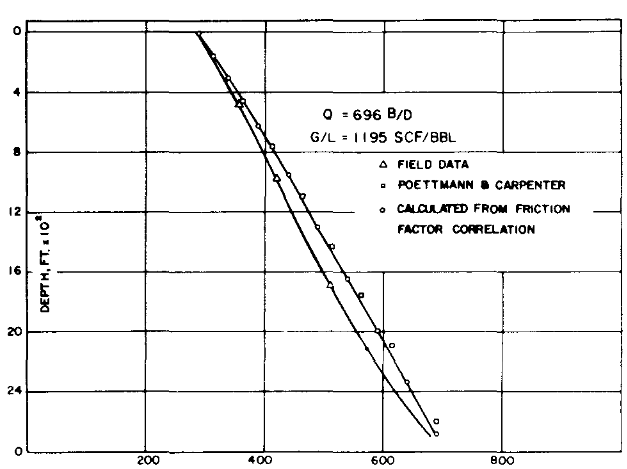

FIG. 18 — COMPARISON OF PRESSURE TRAVERSES.

However, it was impossible to establish the effect of viscosity on the pressure traverse because the well was producing 95 per cent salt water.

GAS-LIQUID RATIO

The results indicate that the gas-liquid ratio is a very important parameter. In particular, it must be considered for flow rates less than 300 B/D, regardless of the gas-liquid ratio.

For any mass flow rate, the friction term decreases as the gas-liquid ratio increases. Due to this fact, separate friction-factor correlations were developed for three ranges of gas-liquid ratios — 0 to 1.5 Mscf/bbl, 1.5 to 3.0 Mscf/bbl, and greater than 3.0 Mscf/bbl. Using the gas-liquid ratio as an additional parameter, accurate pressure traverses were predicted for all flow rates and gas-liquid ratios.

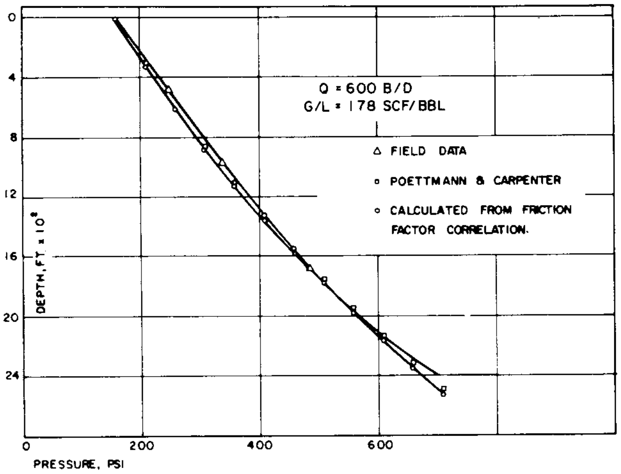

FIG. 19 — COMPARISON OF PRESSURE TRAVERSES.

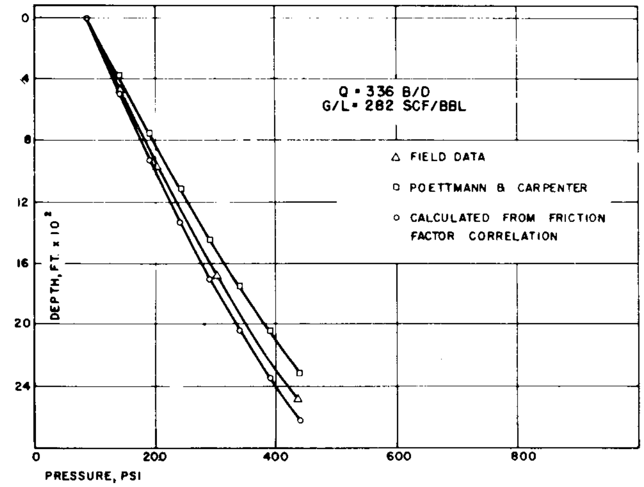

FIG. 22 — COMPARISON OF PRESSURE TRAVERSES.

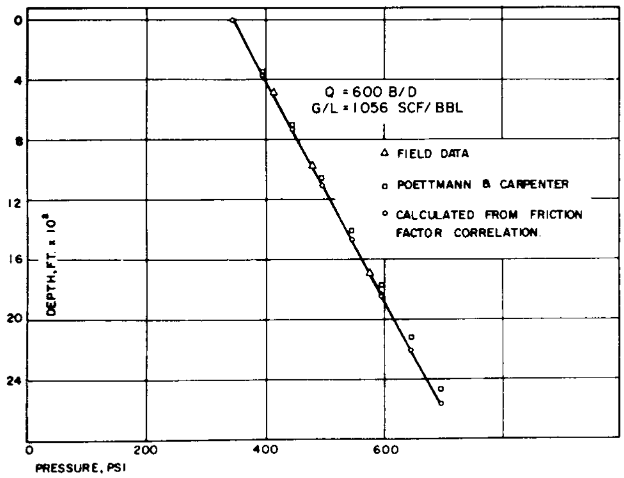

FIG. 20 — COMPARISON OF PRESSURE TRAVERSES.

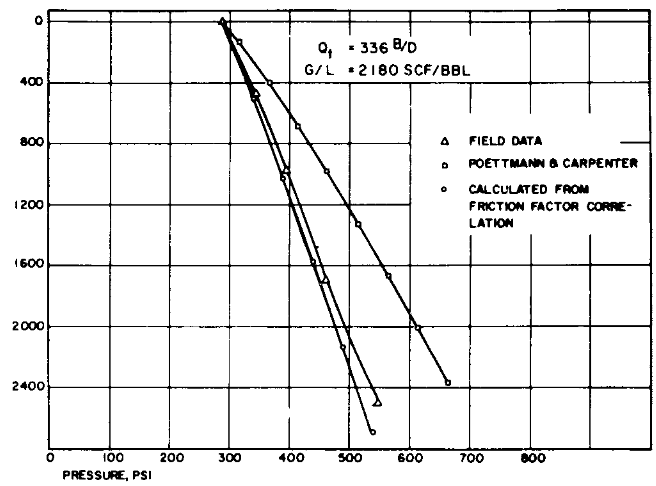

FIG. 23 — COMPARISON OF PRESSURE TRAVERSES.

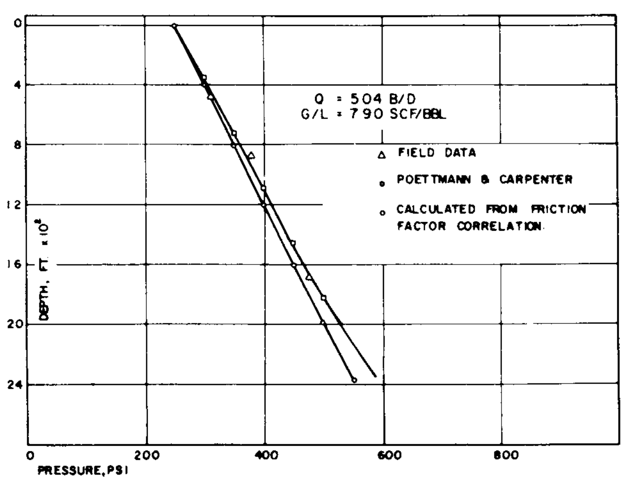

FIG. 21 — COMPARISON OF PRESSURE TRAVERSES.

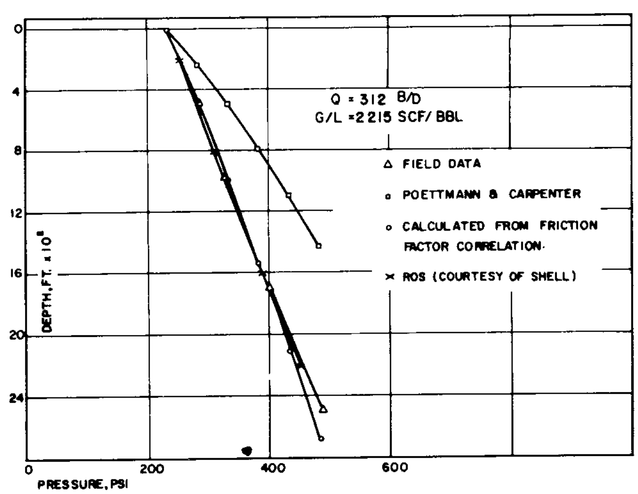

FIG. 24 — COMPARISON OF PRESSURE TRAVERSES.

HEADING

Severe heading occurred in several tests (Figs. 26, 27 and 32). In these figures, all pressures recorded at 477, 969, 1,685 and 2,493 ft were plotted and indicate the pressure variations; i.e., the pressure did not stabilize as in the other tests. The dash lines indicate the maximum and minimum pressure traverses recorded. These pressure variations cannot be attributed to end-effects because the fluid level was well above the bottom-hole choke and critical flow existed through the gas-lift valve. Great care was taken also to minimize surface restrictions which might affect the flow. The casing pressure remained constant during each test, but the tubing pressure fluctuated (Fig. 33). No correlation could be found between heading, flow rate and gas-liquid

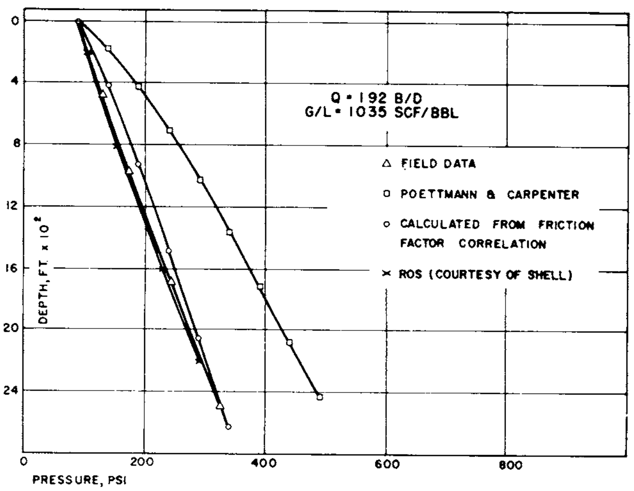

FIG. 25 — COMPARISON OF PRESSURE TRAVERSES.

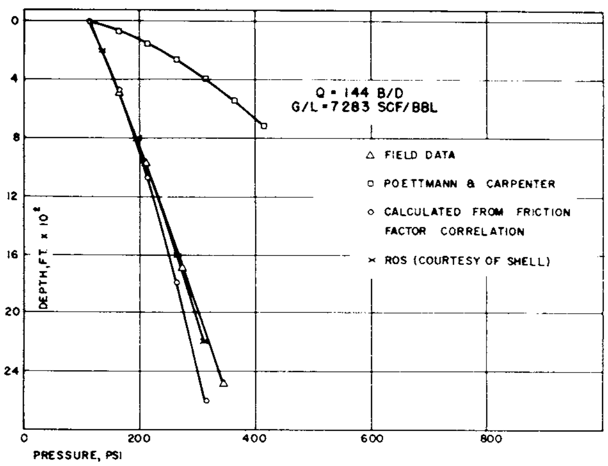

FIG. 28 — COMPARISON OF PRESSURE TRAVERSES.

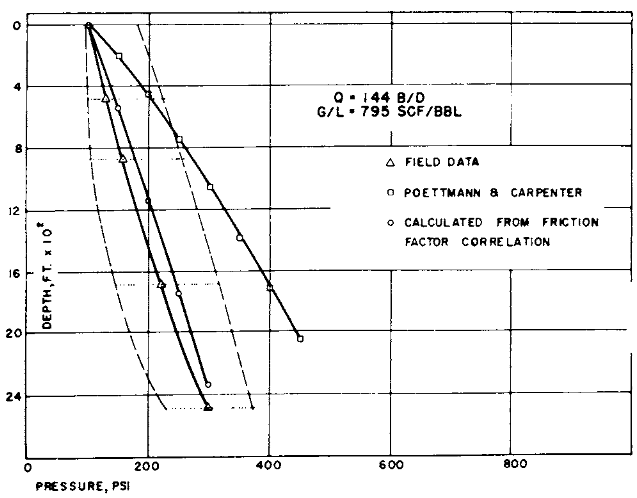

FIG. 26 — COMPARISON OF PRESSURE TRAVERSES.

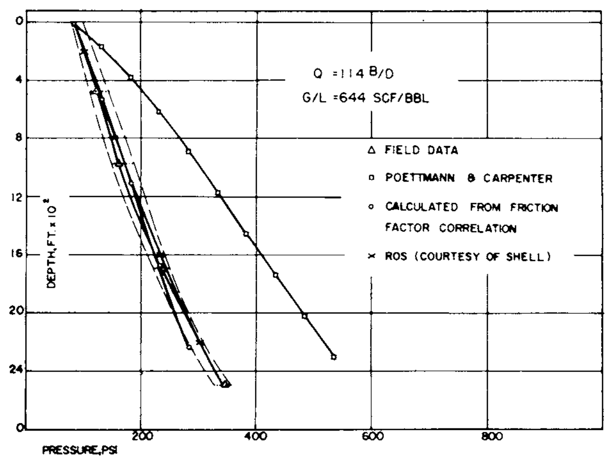

FIG. 29 — COMPARISON OF PRESSURE TRAVERSES.

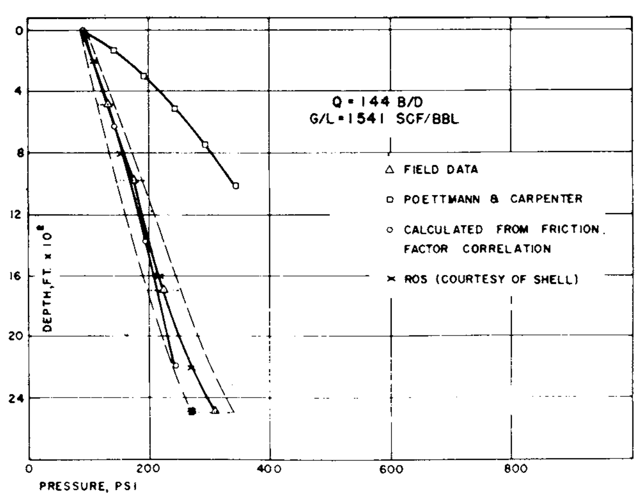

FIG. 27 — COMPARISON OF PRESSURE TRAVERSES.

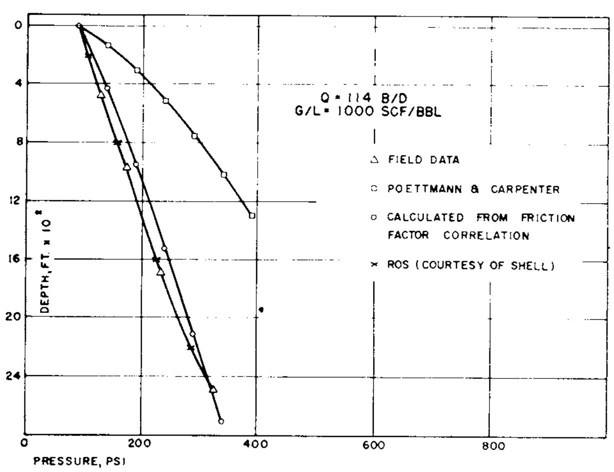

FIG. 30 — COMPARISON OF PRESSURE TRAVERSES.

ratio. However, heading always occurred at flow rates below 192 B/D.

This heading phenomenon would make the design of a gas-lift installation somewhat more difficult. A safe design would be to use the maximum pressure traverse occurring, whereas the use of the average traverse might result in a stymied condition in attempting to reach the operating gas-lift valve.

REVERSE CURVATURE

At very high gas-liquid ratios, a reversal in curvature in the pressure traverse (9) was expected. However, the reversal in curvature appears to be not only a function of the gas-liquid ratio, but also of the flow rate and pressure. In general, as the flow rate decreases and the gas-liquid ratio increases, a reversal in curvature occurs at a particular gas-liquid ratio for flow rates less than 400 B/D (Figs. 23, 28 and 32). In particular, for flow rates of 336, 312 to 192, 144 and 114 B/D, a reversal in curvature occurred for gas-liquid ratios greater than 2.0, 3.0, 4.0 and 4.5 Mscf/bbl, respectively. Both correlations predict a reversal in curvature for flow rates below 400 B/D, regardless of the gas-liquid ratio. A reversal in curvature is expected to occur at the very low pressures and low density ranges.

CONCLUSIONS AND RECOMMENDATIONS

Poettmann and Carpenter's method of correlation is shown to be applicable to predict pressure gradients outside the range of their original data. This has been done by including the gas-liquid ratio as an additional parameter. Their original correlation has been shown to give excellent agreement in the medium-to-high density range. Deviations begin to occur at the point in their correlation where low densities occur. This was the point where a reversal in curvature was shown to occur and the point at which Poettmann indicated that their correlation may not hold.[1]

CONCLUSIONS

1. Poettmann and Carpenter's correlation shows excellent agreement for high flow rates, but results in large deviations for low flow rates and low density ranges.

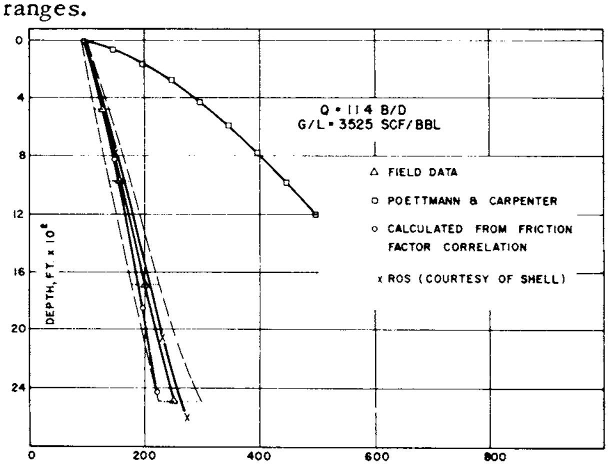

FIG. 31 — COMPARISON OF PRESSURE TRAVERSES.

2. In general, the proposed correlation is valid for all flow rates and gas-liquid ratios in the range of these tests with an accuracy of ± 10 per cent.

3. The gas-liquid ratio is definitely a significant parameter in the friction-factor correlation.

4. Severe heading was noted in several ranges of gas-liquid ratios for flow rates less than 192 B/D; however, it was impossible to determine any correlation between heading, flow rate and gas-liquid ratio.

5. A reversal in curvature occurs in pressure traverses for flow rates in the low pressure region and low density regions.

6. It is believed that these data will allow additional correlations to be checked.

RECOMMENDATIONS

This work should be extended to cover the following factors.

1. These tests should be extended to cover other tubing sizes because it might be erroneous to attempt to correlate these results to any other size of pipe.

2. A complete set of pressure traverses should be established for small tubing sizes.

3. The effect of viscosity should be established for all tubing sizes.

4. A complete set of working curves should be prepared to eliminate tedious calculations. (Fig. 34)

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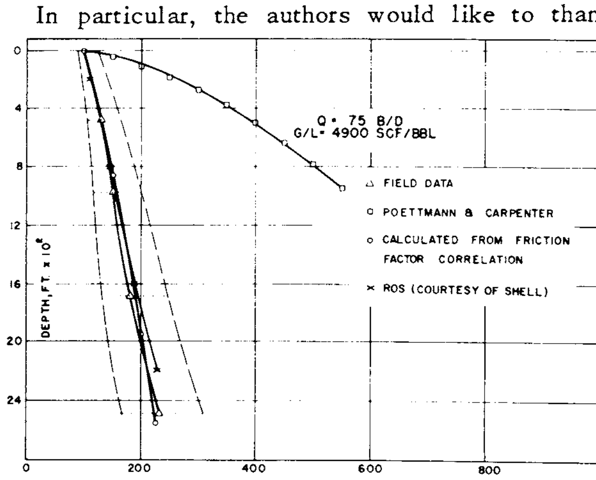

FIG. 32 — COMPARISON OF PRESSURE TRAVERSES.

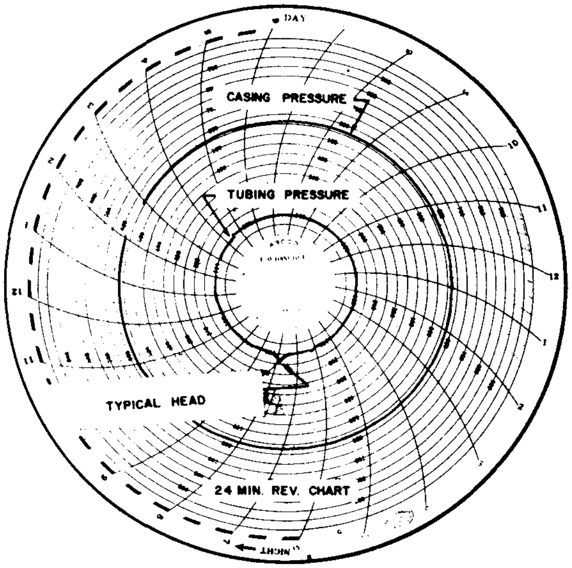

FIG. 33 — EXAMPLE OF HEADING.

Fred Poettmann of Marathon for his original interest in the project and for his many comments and suggestions in preparing this paper.

It was from his original suggestion — that his correlation may not be valid in the very low density ranges — that this project was instigated.

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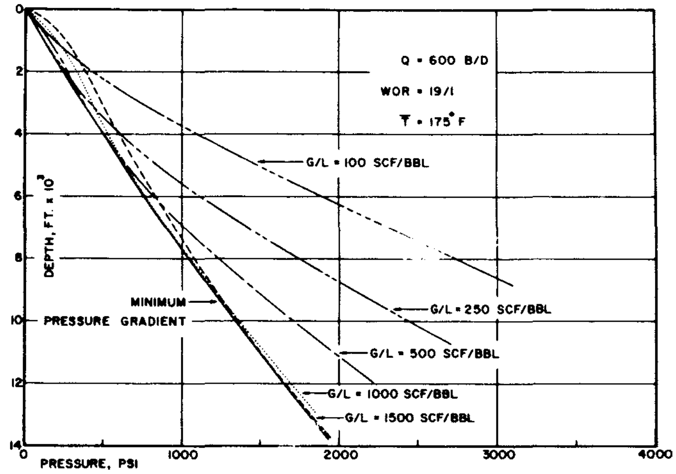

FIG. 34 — WORKING CURVES.

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