PETROLEUM-PRODUCTION RESEARCH

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PRODUCTION research is a broad field in which so many valuable principles have been established that no attempt will be made in this place to cover the subject or to enumerate the outstanding contributions. An article of the present kind may more properly mention items that are likely to be of general interest, and at the same time indicate the scope of the field. In addition, the attempt should be made to point out the many existing opportunities for further improvement through research.

FLOW OF OIL, WATER, AND GAS THROUGH SAND

Much of the progress that has been made may be ascribed to the application of a few of the principles governing the simultaneous flow of oil, water, and gas through porous media. At present, few operators would allow the pressure to be exhausted unnecessarily from an oil formation, because they realize that the total production would suffer. Nearly everyone is now aware that maximum production ordinarily is obtained by operating the entire reservoir so as to allow water to enter the sand as rapidly as oil is removed, thereby minimizing the evolution of gas from the oil. Evolution of gas occurs when the pressure drops below the bubble point, and the resulting gas bubbles may interfere seriously with the flow of oil through the tiny sand pores. Furthermore, the restrictions are even greater in the proper handling of condensate fields, in which a reduction in pressure may give rise to retrograde condensation, with possibly irremediable loss of valuable hydrocarbons.

It was necessary to obtain a mass of data, both in the laboratory and in the field, in order to begin to understand reservoir mechanics, and a great deal still remains to be done. In fact, acquiring a thorough knowledge of multi-phase flow through porous media is such a major undertaking that many hope it will soon be made a cooperative effort by the entire industry.

VOLUMETRIC AND PHASE BEHAVIOR OF HYDROCARBONS

Research Project 37 of the American Petroleum Institute, which has been carried forward at the California Institute of Technology, may be cited as an outstanding example of the progress that can be made by properly directed cooperative effort. Professors Lacey and Sage and co-workers, in the investigations of "The Fundamentals of Hydrocarbon Behavior", have gathered an enormous number of excellent volumetric and phase data. Their work has become a manual for the pressure-volume-temperature relations of hydrocarbons, and has guided the design of equipment for such studies. In addition, their research in retrograde condensation has led to a better understanding of condensate fields and has aided in the design of equipment for processing the fluids from those fields.

EFFECT OF DRILLING FLUIDS ON SUBSEQUENT PRODUCTION

A particularly attractive part of production research is the study of the effect of drilling fluids on production. The possibilities in this direction are readily apparent, for a drilling fluid of some kind is present in the hole from the time the well is spudded until it is completed, and doubtless some of it remains long afterward. During most of the drilling operations, the pressure of the mud exceeds that of the fluids in the formation, and hence part of the mud may be forced into an oil sand. After the well has been completed, some of the mud remains plastered on the face of the well bore and some is left in the hole.

As a consequence, drilling fluids have ample opportunity to influence oil-well productivity. The part that enters the sand may reduce the permeability of the critical region near the well bore, and the part that remains in the well may restrict flow through it. Thus, either of these factors may seriously decrease the productivity of the well.

In the progress toward a solution of this important problem, many obstacles were encountered. For example, the sustained flow of liquids through porous media gave rise to plugging by bacteria and by traces of impurities that ordinarily cause little concern. Successful methods have been devised for treating liquids to remove impurities and to prevent bacterial growth. Again, natural sandstone cores are much less inert to water than might be supposed. This fact led to the discovery [1*] of the hydrational effects of clay-like materials contained in oil sands on the West Coast. It also required additional experiments conducted with more inert porous media, such as sintered Pyrex-glass filters.

It is probably apparent that the problem required separation of the variables. The portion of the mud remaining in the well bore presents a somewhat different problem from the portion penetrating the formation. The latter, in turn, may be separated into plugging by solids and by liquids. Finally, the liquids may give rise to globule resistance, to hydrational effects, or to precipitation of solids. By study of these variables separately, much gratifying progress has already been made.

ESTIMATION OF INTERSTITIAL WATER

Another interesting line of research has lain in developing a laboratory method of estimating the water content of oil formations. There is an acute need for this information as an aid in estimating oil reserves, since it is now widely accepted that oil sands are generally wet with what is termed interstitial water, the oil being held in the remaining pore space.

By the time a core taken in a conventional manner has reached the surface, it has been exposed to flushing by the drilling fluid and to depletion by the decrease in pressume from that of the formation to that of atmospheric. Accordingly, the residual con-

*References are given at the end of the article.

tents of oil, water, and gas give little hint as to the interstitial contents of the sand prior to coring.

A knowledge of the interstitial-water content, along with the porosity, would permit estimations of oil reserves in most virgin formations, as the pressure is usually at or above the bubble point and little free gas is present. Considerable expense is involved in the special technique and equipment required to measure the extent of infiltration or to prohibit it, and to prevent pressure depletion of the core while being brought to the surface. As a consequence, a great deal of work has been done [2-3-4] to develop a laboratory method that may be applied to the estimation of interstitial water through the use of cleaned core samples.

In brief, the technique involves making capillary contact between a water-saturated core and a water-saturated porcelain plate with an air-entrance pressure in excess of the highest pressure to be applied during the run. A predetermined pressure of air may be applied to all surfaces of the sample except the part making contact with the porcelain plate. Thus, water may be forced out of the core and through the plate by a constant pressure of air which may permeate all parts of the core without entering the plate. Water is forced out of the sample through the application of increasing pressures, until the pressure is observed to have little further effect.

An analogous method has been developed which involves removing the water by centrifugal force instead of by gas pressure. In either case, the water which is relatively difficult to remove from the core sample is considered as an approximation to the water content of the portion of an oil formation above the zone of transition from underlying water to oil. Both methods are based upon experiments performed earlier by soil technologists.

CORE ANALYSIS

Those interested in increasing oil-well productivity may spend considerable time in improving the methods used in analyzing samples cored from subsurface formations.

The most immediate use of core-analysis data lies in distinguishing oil sands from water sands. Especially when coupled with measurements of permeability, this knowledge aids greatly in the proper development of the drilling and completion program. By comparison of production data with those obtained from core analyses, the core oil-water ratio has been found [5] to be a fairly good empirical criterion for differentiating oil and water sands.

Various methods of determining oil-water ratios have been devised, all involving either distillation or extraction of the contents of the core. The information ordinarily is extended to include the proportion of the pore space occupied by oil or water, which involves the measurement of porosity.

The porosity, or percentage of the bulk volume which is void, may be obtained in a number of ways, and probably most of them have been tried at one time or another by the industry. The main problem involved is pertinent to core analysis as a whole, that of developing a method which is very rapid and yields results with deviations of 1 or 2 per cent. This is due to the need for fairly accurate results on a large number of cores rather than very accurate results on a few.

The determination of permeabiliy is probably more interesting from a fundamental standpoint than any other measurement common to core analysis. Of course, the property that is desired is the permeability of an oil formation to the reservoir fluids. Doubtless, water and oil are both present, and gas as well when the pressure drops below the bubble point. As indicated earlier, multi-phase flow is not thoroughly understood and the measurements are very time-consuming. Consequently, routine determinations of permeability generally have been restricted to the use of air with cleaned and dried core samples.

A recent investigation[1] has indicated the advisability of measuring single-phase permeability after the core solids have had the opportunity to hydrate in the presence of natural or artificial formation water. Oil sands on the West Coast contain varying amounts of hydratable material, and, when cleaned cores are resaturated with formation water, the permeability is often drastically reduced below the single-phase permeability measured with air. The effect of hydration may be emphasized by noting that the development of a satisfactory method of determining permeability to water required preventing disintegration of the core sample during measurement. This was finally accomplished by protecting each end of the sample with a firm pack of realtively permeable sand washed free of hydratable material. Apparently, the protecting sand usually prevents the movement of the outer layers of core solids, so that disintegration does not get a chance to begin.

Aside from the interest that has been aroused recently concerning the importance of determining permeabilities with formation waters, the measurement of permeability in the absence of hydrational effects has occasioned numerous fundamental discussions.

FUNDAMENTAL DISCUSSIONS OF PERMEABILITY

It has been known [6] for many years that slip at the wall affects the rate of flow of gases through capillary tubes; i.e., the gas molecules close to the walls of the tube have velocity components along the direction of flow. As a consequence, the quantity of gas flowing through a capillary is greater than would be predicted from Poiseuille's law for viscous flow, by the amount of superimposed plug-like flow. The correction for slip has been shown to be inversely proportional to the radius of the tube and directly proportional to the mean free path of the molecules. Hence, the correction increases with decreasing radii and with decreasing mean pressure.

Klinkenberg[7] was the first to call attention to the fact that the correction for slip was appreciable in the flow of gases through many oil-formation samples at the near-atmospheric pressures used for laboratory measurements. His data showed that determinations with the less permeable oil-producing formations often yield permeabilities 25 per cent or more above the values obtained by extrapolation to infinite mean pressure. In further agreement with theory, the values obtained with increasing mean pressures were found to approach sufficiently closely those measured with liquids free from electro-endosmotic effects.

The pores in oil formations have bulges, constrictions, and crevices, and their shapes are far from that of a cylindrical capillary. Nevertheless, it may be of interest that a capillary with a uniform radius of 0.0001 cm would have a correction for the slip of air at atmospheric pressure of about 25 per cent. Furthermore, other methods of estimating the effective pore diameter of such samples yield similar results, with values ranging up to 0.001 cm for the more permeable oil sands.

The principles involved in measuring permeability, as presented[7] to the industry in 1941, did not rest unchallenged for long. In 1943, Grunberg and Nissan[8] adduced evidence that the permeability to a gas depends not only upon the mean pressure, but also upon the pressure drop through the porous material. In fact, dimensional analysis and experimental data indicated that permeability is a function of each of these variables divided by the product of the gas density times the square of the linear velocity, as well as a function of the Reynolds number even in the viscous region. A similar study of permeability to liquids caused the authors to arrive at the conclusion that "the effective cross-section under viscous flow was different for different liquids, due to differences in surface energy and consequently differences in thickness of adsorbed layers". Experimental data supported the results of dimensional analysis which signified that the permeability is a function of "the ratio of resistance due to kinematic viscosity to that due to surface-energy effects".

Activities during the war have delayed experiments designed to test the accuracy of these deductions. A good deal hinges upon the results, especially in the proper operation of gas or condensate fields. The large differences between maximum and minimum values of permeability to a gas, which Grunberg and Nissan found to depend upon the Reynolds number in the viscous region, apparently apply to conditions prevailing in many reservoirs. There seems less likelihood of immediate application of the knowledge to improving methods of producing oil, since permeability to a liquid appears less subject to change.

WATER AND OIL

The relation of water to the production of oil has been of interest since the inception of the petroleum industry. At the turn of the century, oil producers in Pennsylvania and New York noticed substantial increases in oil production when water leaked through corroded casings of old wells into producing formations. As early as 1880, Carll[9] had recognized that when oil is produced, something has to reoccupy the vacated space, and that water might be the best flushing agent. Nevertheless, systematic water flooding was not legalized until 1919 in New York and 1921 in Pennsylvania. The delay undoubtedly was due to the fact that the haphazard use of water can do as much toward diminishing the production of oil as systematic flooding can do toward increasing it. Accordingly, the many examples of resulting damage caused the practice to be viewed with skepticism until much had been learned concerning the relations between oil, water, gas, and reservoir solids.

The gradual accumulation of knowledge related to the volumetric and phase behavior of hydrocarbons and to multi-phase flow through porous media slowly shed light upon the problem. In addition, information was needed concerning the wetting characteristics of reservoir solids.

Research Project 27, sponsored by the American Petroleum Institute, got under way during 1939 with Professor Bartell of the University of Michigan directing the study of the "Function of Water in the Production of Oil from Reservoirs".

The investigations have brought to light a large number of surface-energy relations between silica or limestone and various pure hydrocarbon constituents of petroleum. Laboratory methods developed in the project have been used throughout the industry with success.

The possibility that the solids in some reservoirs may be wet with water while the solids in others are wet with oil, or that wetting characteristics may be reversed in the same reservoir, has occasioned much discussion. A complete understanding of the situation will require wetting tests with reservoir solids and fluids at pertinent temperatures and pressures. This is a difficult undertaking, but doubtless the results would help in raising the percentage of oil recovered.

OTHER PRODUCTION RESEARCH

Space permits only the enumeration of a few other fields of production research. These include developing the following: liners which allow entrance of oil without sand, cementing materials and placement techniques effective in drilling and completion operations, and usable drilling fluids causing little or no damage to subsequent producton. In addition, there is the ever present need for improving the methods of research.

Recently, there has been organized on the West Coast the Study Group on Laboratory Methods of Production Research. The group has just become affiliated with the American Institute of Mining and Metallurgical Engineers as a subcommittee which is expected to develop a wide representation throughout the industry. The interchange of ideas through discussions, correspondence and reports should aid greatly in solving many perplexing problems.

Much has already been accomplished through research in this field, both by competitive and cooperative efforts. Only two research projects of the American Petroleum Institute have been included in the present discussion, but many others have contributed to the general knowledge. Furthermore, it would be difficult to overestimate the progress that has been made through the continual interchange of ideas which has taken place in the various committees and publications sponsored by the Institute. Likewise, the American Institute of Mining and Metallurgical Engineers has stimulated a large share of the research activity, through discussions and publications. Despite past progress, much still remains to be done, but there can be little doubt of the end result, provided a wise balance between competition and cooperation continues to prevail throughout the industry.

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