A Course in

FUNDAMENTALS OF PETROLEUM PRODUCTION

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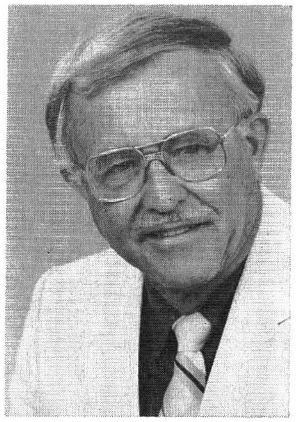

Francis A. L. Dullien has been a Professor of Chemical Engineering at the University of Waterloo since 1966. He received his Dipl. Eng. from the Budapest Technical University (1950), his M.A.Sc. and his Ph.D. from the University of British Columbia (1958 and 1960). He has been a Visiting Professor at Purdue University, at Karlsruhe University and at the Ecole National Polytechnique de Toulouse. He has published over 100 papers in the fields of flow through porous media, pore structure research, quantitative stereology, liquid and gaseous diffusion, mixing, air pollution control and spectroscopy, and is author of the research monograph "Porous Media-Fluid Transport and Pore Structure" Academic Press (1979). He has developed courses in flow through porous media, fundamentals of petroleum production, air pollution control, surface chemistry, statistical thermodynamics, transport phenomena, thermodynamics, fluid mechanics and engineering math.

OVER THE PAST DECADE an increasing number of graduates of the Chemical Engineering Department and also of some other engineering departments of the University of Waterloo have been hired by various petroleum companies, operating mostly in Alberta. The Faculty of Engineering at the University of Waterloo operates one hundred percent on the cooperative scheme. The students alternate between academic and work terms. An increasing proportion of our students have been hired in their work terms by the oil companies. This situation created a demand for a senior year elective course in the fundamentals of petroleum production which is also suited to the needs of first year graduate students specializing in some branch of flow through porous media research. There is no petroleum engineering department at the University of Waterloo, but there has been continuous basic research on certain aspects of this discipline for the past sixteen years, under the author's supervision. It was thus logical for the author to propose a course on Fundamentals of Petroleum Production, which was accepted by the Faculty of Engineering in 1978. Since then the course has been taught every year in the winter term.

The purpose of this course is to introduce the average chemical engineer, who has only a minimum of familiarity with the concepts of capillarity and flow through porous media, and none at all with reservoir engineering concepts, to petroleum production engineering. All this has to be accomplished in thirteen weeks (three contact hours per week), because with the coop system the lecture part of a term is only about three months long. Under these constraints the course on Fundamentals of Petroleum Production is limited in scope and, at the same time, conceptually difficult for the students.

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TECHNICAL CONTENT

The technical content of the course is best appreciated by perusing the course outline shown in Table 1. The rationale for this approach to the course is presented in the following paragraph.

The author does not think that a completely black box-type presentation of the material is in the best interest of either the student or the industry where the student may work. The black box approach pays no attention to the microscopic mechanisms, the interplay of the various forces on a microscopic scale and the microscopical geometric parameters of the environment in which the physical phenomena take place. It is true that a typical reservoir engineer is concerned with the control and prediction of macroscopic parameters but it is equally true that the observed macroscopic behavior is, to a large extent, the result of events that occur in small pores and which are determined by microscopic parameters. Staying mum on the microscopic aspects of petroleum reservoirs (an attitude which is quite common in some texts on reservoir engineering) is tantamount to pretending to be completely ignorant of some facts which are very important in determining the outcome of oil recovery operations, particularly when secondary and tertiary recovery are considered. Such an attitude is likely to mislead the student by keeping him ignorant about things that matter a great deal. The purpose of university education cannot be the maintenance of ignorance. This is the reason for starting this course with an introduction to capillary theory.

In the discussion of basic laws of capillarity, attention is drawn continually to the fact that petroleum reservoirs consist of a multitude of tiny interconnected capillaries. A petroleum reservoir is a permeable porous medium, not at all like the water reservoirs most people tend to think of immediately when they hear the word "reservoir." The major portion of this chapter deals with the capillary pressure curves: primary drainage, imbibition and secondary drainage capillary pressure curves, their methods of measurement in the lab and in the field, capillary hysteresis and the roles played both by the pore structure and the contact angle in bringing about the hysteresis. One of the difficult tasks to be accomplished in this portion of the course is to give the students a "feel" for the physical phenomena, "drainage" and "imbibition." It has been found indispensible to do a classroom demonstration of these phenomena. Transparent capillary micro-models are very useful for this purpose, as is an experiment consisting of placing a sandstone core plug, saturated with oil, in a beaker of water. The spontaneous imbibition of water into the plug is demonstrated by the appearance of oil drops on the plug's surface which have been displaced by the water.

The formation (resistivity) factor is then introduced and the fundamental difference between Darcy flow and electrical conduction in porous media is pointed out.

The second chapter introduces the student to the fundamentals of flow of a single fluid through a permeable porous medium. The discussion is centered on Darcy's law and the various types of pressure heads and fluid potentials which are

TABLE 1
Course Outline

1. CAPILLARITY
   - Laplace's equation of capillarity
   - Young's equation—The contact angle
   - Capillary pressure—Effects of the pore structure and the contact angle
   - Determination of the capillary pressure curve—Saturation
   - Capillary rise—Effects of the pore structure and the contact angle
   - Kelvin's equation
   - Capillary hysteresis—Effects of pore structure
2. FLOW OF A SINGLE FLUID THROUGH POROUS MEDIA
   - Porosity
   - Specific surface
   - Permeability—Darcy's law
   - Formation factor
   - Macroscopic heterogeneity of pore structure
   - Anisotropy
3. SOME APPLICATIONS OF DARCY'S LAW
   - Fluid potential
   - Linear flow vs. radial flow
   - Well stimulation
4. BASIC CONCEPTS IN RESERVOIR ENGINEERING
   - Calculation of hydrocarbon volumes
   - Fluid pressure regimes
   - Oil recovery—Recovery factor
   - Volumetric gas reservoir engineering
   - Gas material balance—Recovery factor
5. PVT ANALYSIS FOR OIL
   - Definition of the basic PVT parameters
   - Use of the PVT parameters
6. GENERAL MATERIAL BALANCE EQUATION FOR A HYDROCARBON RESERVOIR
   - Derivation of the general equation
   - Solution gas drive
   - Gascap drive
   - Natural water drive
   - Compaction drive
7. DISPLACEMENT OF OIL BY AN IMMISCIBLE FLUID
   - Generalization of Darcy's law for multiphase flow
   - Effective and relative permeabilities
   - The Buckley-Leverett theory of oil displacement
   - Mobility control
   - Tertiary flooding

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used in conjunction with this basic law of reservoir engineering and groundwater hydrology. Thus, careful distinction is drawn between the physical meaning of the hydrostatic pressure, P and the "datum pressure" or "psi-potential" $\psi \equiv P + \rho g z$, where z is distance measured vertically upward from an arbitrary datum, ρ is the fluid density and g is the gravitational acceleration constant. Generally, it is the gradient of the datum pressure, $\nabla\psi$, that must be used in Darcy's law. The heads $P/\rho g$ and $\psi/\rho g = P/\rho g + z$ represent distances in the vertical direction and are much more readily visualized than the corresponding pressures, P and ψ. $\psi/\rho g$, the so-called "piezometric head," is then the sum of the pressure head, $P/\rho g$ and the elevation head z. The fluid potential Φ is also introduced here.

The permeability, k, the porosity, ϕ, and the specific surface, s, are the most commonly used macroscopic pore structure parameters. By definition, their value does not depend on the fluids used in the measurement, but it is completely determined by the pore structure of the sample. The important role played by pore structure in determining reservoir behavior is stressed again when discussing the above mentioned parameters. The Kozeny-Carman equation is "derived", not because it is believed to be generally valid, but mainly to illustrate the kind of efforts that have been made to understand the relationship between flow and pore structure.

Simple integrated forms of Darcy's law are presented, and the special cases of gas flow, slip flow (Klinkenberg equation) and non-Darcy flow (Forchheimer equation) are discussed.

There follows a brief outline of some field applications of Darcy's law.

The formation (resistivity) factor is then introduced and the fundamental difference between Darcy flow and electrical conduction in porous media is pointed out. This is manifested by the fact that the electrical conductivity of small pores is the same as that of big pores whereas the fluid conductivity of a pore in creeping flow varies as A, the normal cross-section of the pore. Hence a fine-pored medium has a much lower permeability than a coarse-pored of comparable porosity, while the difference between the formation factors of the two materials may be relatively little.

It is pointed out that reservoirs are heterogeneous, i.e. they are characterized by a distribution of permeabilities, and anisotropic, i.e. the permeabilities at a given point are different, depending on the direction of flow.

At this point in the course the students already have a certain idea of the behavior and the pore structure of a reservoir. They are unlikely to confuse it with a water reservoir. Here the course switches to the subject which is conventionally at the beginning of reservoir engineering texts; the explanation of the basic concepts of reservoir engineering, such as hydrocarbon volumes, fluid pressure regimes, gas recovery factor, gas expansion factor, solution gas-oil ratio, oil formation volume factor, gas formation volume factor, producing gas-oil ratio, etc.

TABLE 2
Recommended Reference Books

F. A. L. Dullien, Porous Media-Fluid Transport and Pore Structure, **Academic Press, 1979.**

L. P. Dake, Fundamentals of Reservoir Engineering, **Elsevier, 1978.**

J. W. Amyx, D. M. Bass and R. L. Whiting, Petroleum Reservoir Engineering—Physical Properties, **McGraw-Hill, 1960.**

A. E. Scheidegger, The Physics of Flow Through Porous Media, **Univ. of Toronto Press, 1974.**

R. E. Collins, Flow of Fluids Through Porous Materials, **van Nostrand-Reinhold, 1961.**

Next, the general macroscopic material balance for a hydrocarbon reservoir is derived, discussed and applied to elucidate the various possible natural modes of petroleum production, the different so-called "drives."

At the end of the course the fundamentals of immiscible displacement are outlined. In this chapter some of the basic concepts, introduced in the early chapters, play an important role and are thus vindicated from an applications point of view which, of course, is the only point conceded by the average student taking this course.

There are usually four home assignments in this course, one on each of the following chapters: 1, 2-3, 4-6, and 7, and three tests, one on each of the following chapters: 1-3, 4-6, and 7. Final examination has been dispensed with. □