The dedication was followed by a symposium, sponsored by the Warner and Swasey Company, on "Galactic and Extragalactic Structure," the program of which was given in SCIENCE for March 3, 1939. The majority of the symposium papers will be published in the *Astrophysical Journal.*

BIOPHYSICS AND HYDRAULIC ENGINEERING

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How many hydraulic engineers have had their attention attracted to the circulatory system of man and animals? Perhaps it is the most ingenious hydraulic engineering feat in nature. Few investigators have taken a broad glance at the circulatory system from an engineer's point of view.

The purpose of the present paper is to describe some fundamental problems which confront the biophysicist who is interested in the circulatory system. These problems require a thorough understanding of applied fluid mechanics. The hydraulic engineer is better prepared than the average biophysicist to attack such problems.

In the blood vascular system we have a circulatory system in which the average pressure is maintained at a relatively constant value unless an emergency alters it, whereupon a mechanism is called into action which promptly restores or attempts to restore normal conditions. When certain defects develop, the normal pressure becomes inadequate for performing the necessary functions. Under these conditions the system operates at a higher pressure, thus introducing its compensatory mechanisms. The various mechanisms whereby the circulatory system accomplishes its functions of (1) supplying nutritive materials to different parts of the body, (2) eliminating the waste products of catabolism, (3) regulating the pressure, (4) regulating the temperature and (5) distributing hormones and various chemicals to their proper depots, would fascinate any hydraulic engineer.

The particular problems which confront us at the moment and which I wish to describe have to do with pressure and with flow and will be treated separately.

PRESSURE

Methods of measurement. The ideal method for measuring blood pressure is still lacking. True enough, the measurement of the pressure is an everyday affair. The universally used method is an indirect one where pressure is applied in order to cause a complete collapse of the blood vessel. If arterial pressure is being observed, both systolic and diastolic pressures are recorded. These pressures are those which occur simultaneously with certain arbitrary sounds heard over the given artery by means of a stethoscope on releasing the collapsed vessel. I shall not take time to describe the details of the apparatus and the technique used in this (auscultatory) method. The standard method which is used experimentally consists in cannulation of a given blood vessel and proper communication with a suitable manometer.

The ideal method would be one which permits continuous recording of blood pressure—an automatic method, so to speak. The indirect method obviously does not permit continuous observation. The direct method makes constant recording impossible because there is no anticoagulant which keeps blood from clotting for an indefinite period. In addition, the isolation and cannulation required also limit the time of recording.

One might imagine a possible relation between the pressure on the wall of a partially closed blood vessel and the true pressure of the contained blood. If such a relation could be found to be consistent, the pressure on the wall of the vessel might be recorded by using the principle of piezoelectricity. Such a method as this would permit continuous observation of blood pressure.

To put the problem in question form: how would you measure the pressure of a coagulable fluid circulating in a closed elastic system without either direct communication with the fluid or completely collapsing the elastic "pipe"?

Differential pressure. Owing to the action of the pump in this circulatory system the pressure varies throughout the cycle of the pump (cardiac cycle). When the pump is contracting, the pressure in the system is maximal and is named systolic pressure. When the pump has finished its contraction and is temporarily in a state of rest, the pressure in the system is minimal and is called diastolic pressure. One may also observe the average pressure throughout the cardiac cycle. As in other hydraulic systems there is a gradual decrease in the average pressure throughout the system from the output to the input sides of the pump. The term pressure-gradient characterizes this well-known variation. However, if one considers the systolic pressure only, an interesting phenomenon presents itself—the systolic pressure in the leg artery (femoral artery) is about 30 to 50 mm of mercury higher than that in the neck artery (common carotid artery) in spite of the fact that the leg artery is much further away from the pump than the neck artery. This difference in systolic pressure exists even when the body is lying in a horizontal plane. This observation is a well-known fact among those measuring blood pressures. However, no one knows why. Many explanations have been offered, all of which reduce to three basic principles:

(1) A transformation of kinetic energy into pressure energy—a Pitot tube effect. The change of momentum of the moving fluid acting in addition to the lateral pressure causes an increased pressure. Pitot tubes are so constructed as to make use of this effect in measuring velocity of fluids.

(2) A water hammer effect. The more or less abrupt change in velocity that the blood in the femoral artery undergoes gives rise to pressure waves similar to those observed in water pipes. The velocity in the common carotid artery does not change so abruptly.

(3) An effect due entirely to the elastic property of the "pipes" which brings about a higher systolic peak in the femoral than in the carotid artery.

Text-books on applied fluid mechanics indicate that one could distinguish between a Pitot tube effect and a water hammer effect. If the Pitot tube effect exists then the difference in pressure indicated by the Pitot tubes is proportional (approximately) to the square of the velocity of flow. If the effect is due to a water hammer, then the relationship between change in pressure and change in velocity will be linear.

The solution of the problem calls for accurate methods of measuring pressures and velocities of blood. The biophysicist and physiologist can measure pressures very accurately. However, there is not, at present, a method of measuring blood velocity which would be entirely satisfactory for solving this problem.

The physiologists have known about this interesting phenomenon of differential systolic pressures for almost fifty years. A completely satisfactory explanation of the phenomenon has never been attained.

FLOW

Methods of measurement. A direct method of measuring anything is always preferred from the point of view of accuracy. However, in the measurement of blood flow an indirect method is preferred if one wishes to maintain normal physiologic conditions in studying the characteristics of flow. The peripheral circulatory system is so close to the condition of turbulence that any interference with it may produce turbulence, especially on the arterial side. A continuous indirect method is the ideal method since it preserves normal physiologic conditions, providing the indirect method does not require operative procedures which alter the normal conditions. When one considers the physiologic variation, he realizes that to develop an absolutely accurate method of measuring blood flow would be a waste of time even if it were possible. One learns in his study of physics, as well as of other sciences interested in measurement, that the accuracy of the method should conform to the conditions of the problem. It is as ridiculous to have too accurate a method as it is to have too inaccurate a method in certain studies. One's common sense must be used in all cases.

In order to use certain indirect methods properly, a knowledge of the character of flow is absolutely essential. The method may be very reliable as long as the flow is laminar or streamline but may be 100 or 200 per cent. inaccurate when the flow becomes turbulent.

To describe the various methods of measuring blood flow developed since the time of Volkmann would require the space of a fair-sized book. It is sufficient to say that most methods consist in the application of well-known physical principles such as the Venturi meter, rate of cooling, change of electric resistance with change of temperature, electromagnetic induction, the hydrometric pendulum and other devices.

Character of flow. The method of measuring flow which I have used for several years is dependent on the type of flow. I am much interested in the question. Is the blood flowing in a given vessel streamline or turbulent?

This paper is written primarily with the hope that the hydraulic engineer will be able to offer suggestions for answering the question or better yet that he will want to take an active part in the study of this interesting problem.

So far as I know, two methods are available for answering this question, a theoretical method and a practical one.

Theoretical. "As has long been known from the classical researches of Osborne Reynolds and others, the steady isothermal flow of a fluid through a long straight pipe may occur by one of several mechanisms. When the dimensionless Reynolds number $\frac{DV\rho}{\mu}$ is sufficiently small, the individual particles of fluid flow in straight lines parallel to the axis of the pipe, without appreciable radial component as shown. . . . This type of motion is variously described as streamline, straight-line, viscous and laminar. At sufficiently high values of Re, the motion is said to be turbulent, because of the presence of innumerable eddies or vortices present in the central portion of the pipe, as indicated. . . ."[1]

In the preceding quotation Re stands for Reynolds number, which is calculated from the formula $\frac{DV\rho}{\mu}$, where

[1] W. H. McAdams, "Heat Transmission," pp. 99–100. New York, McGraw-Hill Book Co., Inc., 1933.

D = diameter (inside) of pipe
V = average velocity
ρ = density
μ = viscosity

One can calculate the Reynolds number for blood from the above formula and determine whether the flow is in the streamline or turbulent range. According to such calculations for, say, the femoral artery of a dog, the flow is below the critical value for turbulence. However, I feel that it may, at times, become turbulent.

Practical. One may make an exact model of the hydraulic system in question and directly observe the nature of flow by introducing a contrasting color to the fluid at the desired location. This would be rather difficult to do for the problem in question. According to Franklin[2] and others nature offers conditions for the direct observation of the character of blood flow in certain veins. The blood flowing into the abdominal vena cava from the reproductive organs of certain animals is like arterial blood in color and serves as an excellent contrast to the venous blood already present in this vein. According to observations the arterial-like blood flowing into the vena cava at this site continues in its own channel without mixing with the blood already present. This indicates a streamline type of flow. The vein has a thin wall so that the contrasting color may be easily observed. The artery is not so transparent.

Artificial circulatory systems have been made and have proved useful in the perfusion of various organs with blood. I have observed that small constrictions in such systems give rise to turbulent flow. The degree of turbulence produced experimentally is dependent on the type of constriction. Blood vessels *in situ* may have such constrictions under certain conditions, for example, arteriosclerosis and coarctation.

It would be helpful to know exactly the nature of the flow of blood in any given blood vessel at any time. The character of the flow in the great vessels near the heart as well as that in the coronary vessels would be particularly interesting. Attempts have been made to study this problem in acute experiments where a general anesthetic, artificial respiration and anticoagulants are required. All these alter the normal conditions profoundly, so that one can not say the results of the study are maintained in the normal intact animal.

The hydraulic engineer usually works with fairly homogeneous fluids flowing in rigid pipes, so that a problem in which blood, a heterogeneous fluid, circulates in an elastic closed system might present new difficulties.

[2] K. J. Franklin, "Respiration and the Venous Return in Mammals." In "A Monograph on Veins," pp. 236–267. Springfield, Charles C Thomas, 1937.

OBITUARY

RECENT DEATHS AND MEMORIALS

DR. CHARLES HORACE MAYO, emeritus professor of surgery in the Medical School of the University of Minnesota and in the Graduate School of the Mayo Foundation; founder, with his brother, Dr. William James Mayo, of the Mayo Clinic at Rochester, Minn., died on May 26 in his seventy-fourth year.

DR. WITMER STONE, emeritus director of the Academy of Natural Sciences of Philadelphia and a member of its staff since 1891 as conservator of ornithology and curator of vertebrates, died on May 23 in his seventy-third year.

ARTHUR E. WELLS, professor of metallurgy at Harvard University from 1926 to 1931, director of the American Cyanamid Company of New York, died on May 24. He was fifty-five years old.

DR. J. EDMUND WOODMAN, professor emeritus of geology at New York University, died on May 19 at the age of sixty-five years.

WILLIAM H. KAVANAUGH, for twenty-three years professor of experimental engineering at the Towne Scientific School of the University of Pennsylvania, died on May 6 in his sixty-sixth year.

FRANK W. DURKEE, since 1907 head of the department of chemistry at Tufts College, died on May 21 at the age of seventy-seven years.

PROFESSOR WILLIAM L. HUNTER, head of the department of industrial arts at the Iowa State College, died on May 23. Mr. Hunter had been a member of the faculty of the Iowa State College since 1927, having previously taught at the State University of Iowa and at the Bradley Polytechnic Institute.

DR. MAURICE BRODIE, laboratory director of Providence Hospital at Detroit, Mich., for the last two years, died on May 9 at the age of thirty-six years.

SIR FRANK DYSON, from 1910 to 1933 Astronomer Royal of England, previously from 1905 to 1910 Astronomer Royal of Scotland, died while on a voyage from Australia to South Africa on May 25. He was seventy-one years old.

DR. YOJIRO WAKIYA, the Japanese ichthyologist, was killed by an electric car near Tokyo, on April 21, at the age of sixty-seven years. He was known particularly for his studies of the Carangidae, Salangidae and Salmonidae of the Japanese Empire, but also published investigations on many other groups of fishes and on oysters. For many years he was director of the fisheries institute at Fusan, Chosen, which he de-