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# THE ORIGINS OF FLUID MECHANICS

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Ludwig Prandtl's 1904 paper *Ueber Flüssigkeitsbewegung bei sehr kleiner Reibung* is generally considered to have marked the beginning of fluid mechanics. By chance it appeared at the time that human flight was attracting considerable attention. Unfortunately, although empirical hydraulics and theoretical hydrodynamics had long been in existence, they were of little evident use to aeronautics, the one being too limited in scope and the other too impractical. Prandtl's boundary-layer theory, on the contrary, gradually found use in the analysis of airfoils, propellers, and the behavior of immersed bodies in general. However, convenient as it is to consider the dated establishment of a new science, the fact remains that (as is true of all knowledge) no principle is formulated independently of prior developments, and these in turn are based on still earlier experience. The true origins of fluid mechanics lie in the hydraulics and hydrodynamics of the previous century, and their beginnings can in turn be traced to the earlier growth of civilization itself, as outlined in the following pages.

Since hydrostatics is the very basis of fluid behavior, one must go back at least as far as the time of Archimedes (250 BC) and his discovery of the principle of buoyancy. Even a century earlier, however, the encyclopedist Aristotle was proclaiming (among other things) the so-called "medium theory" of motion, based on the concept that "Nature abhors a vacuum", fluid hence rushing in behind a moving body and thus propelling it. Far from contributing positively to our understanding of fluid flow, Aristotle is sometimes said to have held science back well over a millenium. Indeed, Thomas Aquinas and the Scholastics even had Aristotle's teachings adopted essentially intact by the Church as late as the 13th century. Traces of the medium theory are still to be found in Leonardo da Vinci's notebooks of the 16th century, though this is well counterbalanced by his first expression of the continuity principle. Nevertheless, Leonardo had little influence on such hydraulics as then existed, for he developed no appreciable school around him, and his notebooks were lost for several centuries after his death.

Galileo Galilei, at the beginning of the 17th century, added experimentation to Leonardo's practice of observation, and in addition he developed a following. Benedetto Casteli, one of his associates, rediscovered the principle of continuity, and another, Evangelista Torricelli, applied his mentor's law of gravitational acceleration to predicting the trajectory of a water jet. Torricelli also experimented with the liquid barometer, which was then stimulating the further study of hydrostatics. At about this time the Dutch engineer Simon Stevin formulated the hydrostatic paradox of boundary pressure, and not long afterward the French philosopher Blaise Pascal explained the action of the hydraulic press; Pascal likewise experimented with the baromheter and demonstrated the relation between topographic elevation and atmospheric pressure.

Aristotle's influence is seen indirectly in the Church's forcing of Galileo to disavow his claim that the sun was the center of the solar system. This in turn led the French savant René Descartes, around the middle of the 17th century, to attempt to reconcile the teachings of the Church and Science. He held not only that a fixed amount of motion had been established at the Creation, but that the planets were carried in their courses by tremendous heavenly vortices. Isaac Newton was then led, toward the end of the century, to conduct experimental investigations of four kinds of fluid resistance (tenacity, want of lubricity, elasticity, and density), to the end of proving that space contained no matter whatever, else the planets would be slowed down. Newton's analysis of planetary motion firmly established the principle of momentum —not to mention the use of his theory of fluxions, which we now call the calculus. A German contemporary of Newton's, Gottfried Wilhelm von Leibniz, also invented the calculus, and —to parallel Newton's momentum principle— the principle of energy. Though the two principles should have given comparable results, Leibniz had left the fraction 1/2 out of his term for kinetic energy, which contributed to a long-lasting disagreement between the two schools of thought.

Early users of Leibniz' teachings were members of the Swiss family

Bernoulli, in particular the mathematician Johann, who left his mark on the nomenclature of the calculus, and his son Daniel, whom he had taught mathematics. While with the Russian Academy of Sciences at St. Petersburg, Daniel wrote the book *Hydrodynamica*, which adapted Leibniz' two-term (kinetic and potential) energy principle to the description of fluid motion. A jealous man, his father then belatedly wrote the book *Hydraulica*, which he predated by ten years. However, for a lack a pressure term, neither really developed what came to be known as the Bernoulli Theorem. This was actually first derived in the middle of the 18th century by Leonhard Euler, who had also been trained by Johann and worked with Daniel at St. Petersburg; Euler truly understood the role of the pressure gradient and correctly integrated his equations of acceleration for steady flow in which both velocity and gravitational potentials existed.

Though a fair share of Euler's many papers dealt with hydraulics, he should be recognized as the founder of what is now called classical hydrodynamics. Several of his contemporaries also contributed markedly to the new science: d'Alembert, Lagrange, and Laplace in particular. In the same period, contributions to the secondary aspects of hydraulics also took place: Henri Pitot's invention of a "machine" for measuring velocity; Benjamin Franklin's towing-tank tests; John Smeaton's modeling of hydraulic machinery; Antoine Chézy's method of predicting channel resistance by similarity principles; and Pierre Louis Geor Du Buat's experiments on conduit and immersedbody resistance.

The first half of the 19th century saw the formulation of the Navier-Stokes equations for the acceleration of a vicous fluid, and of the Hagen-Poiseuille relationship for laminar flow through tubes. In this regard it must be noted that neither Hagen nor Poiseuille really understood laminar flow (nor did Stokes at first), and that it was Hagen rather than Reynolds who first demonstrated the difference between laminar and turbulent conditions.

Aside from Bernoulli, the two names used most frequently in describing fluid motion are William Froude and Osborne Reynolds, the former a naval architect and the latter an engineering professor, both Englishmen active in the second half of the century. It is interesting to remark that, just as Reynolds receives credit for certain of Hagen's discoveries, Froude is credited with contributions of a Alsatian naval instructor by the name of Ferdinand Reech. However, although the so-called Froude criterion for gravitational similarity was actually Reech's. Froude was not only among the earliest to observe the development of the boundary layer along the surfaces that he towed, but he was also the first to interpret experimental results obtained under conditions of both wave and surface resistance. Reynolds rather than Hagen first formulated the dimensionless number for the dividing line between turbulent and laminar flow, and showed how to rewrite the Navier-Stokes equations for both types of fluid motion; moreover, he was the first to apply the principle of gravitational similarity to tests on open-channel models —even for unsteady flow!

Contemporary with Froude and Reynolds were a series of mathematicians who contributed greatly to classical hydrodynamics. The Germans Helmholtz and Kirchoff covered a wide territory, with the analysis of vorticity predominat. The British Lords Kelvin and Rayleigh not only continued work begun by Helmholtz but originated analyses of wave motion, stability, and related phenomena. Their contributions and those of many colleagues were ably summarized in Horace Lamb's *Treatise on the Mathematical Theory of Fluid Motion*, which went through many later editions under the title *Hydrodynamics*. The Frechman Boussinesq, though strictly speaking a hydraulician, warrants mention at this point for his scientific writing on open-channel flow. The contributions of the Russian Joukowsky also deserve mention; though his understanding of water hammer is of hydraulic rather than hydrodynamic interest, his analysis —and that of the German Kutta— of the side thrust produced by circulation leads appropriately to the following discussion of fluid mechanics.

Late in the century Felix Klein, professor of mathematics at the University of Göttingen, made a trip to the United States, visiting among others one or more of the relatively new land-grant colleges. These are said to have impressed him so favorably with the practicality of their shops and laboratories that he resolved to add at least one engineering professor to his staff —a practice previously unheard— of in a German university. An invitation was in fact extended to Ludwig Prandl, then professor of mechanical engineering at the Hannover Technische Hochshule. Prandtl accepted and moved to Göttingen in 1904, the very year that his boundary-layer paper was published. The paper received little immediate attention, but Prandtl established a small research laboratory for solid and fluid mechanics, which gradually attracted such students as Theodor von Kármán, Heinrich Blasius, Walter Schiller, and Jakob Ackeret.

Prandtl and his students began the publication of a growing series of papers on mechanics, tending more and more toward fluids. Blasius, in particular, formulated the velocity distribution for the laminar boundary layer, and he later showed tha the Weisbach resistance coefficient for pipe flow must be a function of the Reynolds number. Von Kármán analyzed the vortex formation in the wake of a cylinder, and eventually played a major role in laying the groundwork for the analysis of fluid turbulence. This was actually to become a three-way competition between von Kármán (then at Aachen), his former professor Prandtl, and Geoffrey Taylor of Cambridge, with experimental data obtained at Göttingen by Johann Nikuradse in the late Twenties and early Thirties.

A veritable stream of books also began to appear, not only from Prandtl's school. The first of these was Franz Prášil's *Technische Strömungslehre* (1913), followed the next, year by Ludwig von Mises' *Elemente der technischen Hydromechanik.* Oskar Tietjen's two-volume compilation of Prandtl's lectures, *Hydro-und Aerodynamik*, appeared in 1929, and in 1931 the first edition of Prandtl's own *Abriss der Strömungslehre* also came from the press. The four volumes of the monumental *Handbuch der Experimentalphysik* devoted to fluid mechanics under Schiller's editorship were released from 1930 to 1932, and Paul Neményi's *Wasserbaulische Strömungslehre* followed in 1933. Among the authors, only Neményi and Franz Eisner, who wrote a section of the *Handbuch*, had any claim to a hydraulics background. The American W.F. Durand, it is interesting to note, was once a hydraulician, but during his long and active life he was also a naval architect, and then an aeronautical engineer when he edited the English-language *Aerodynamic Theory* published in Germany in 1934.

As a matter of fact, it will be recalled that Prandtl was originally a mechanical engineer, and most of his staff and other colleagues who contributed to the establishment of fluid mechanics as a viable science were either mechanical or aeronautical engineers. The question that concerns us at this point is how —aside from the contributions of Neményi and Eisner— did fluid mechanics come to play such and important role in hydraulics? The answer is to be found in the activities of a series of Americans —in part native-borne and in part naturalized citizenz.

Among the many accomplishments of the Yankee hydraulic engineer John R. Freeman, at least two have direct bearing on the situation under discussion: he arranged in the late Twenties that not only Prandtl but also Theodor Rehbock, Dieter Thoma, and Wilhelm Spannhake lectured in the United States; and he gave $ 25,000 each to the American Society of Mechanical Engineers, the American Society of Civil Engineers, and the Boston Society of Civil Engineers to establish three Freeman Traveling Scholarships. The first Freeman Scholars arrived in Europe in 1927, and these were followed by some 25 in the next 15 years. Most of them were civil engineers, and they visited primarily hydraulic engineering laboratories. At least a few, however, were mechanicals, and a fair number —including civils— spent time with Thoma at Munich, Prandtl at Göttingen, and von Kármán at Aachen.

Noteworthy among the early Scholars were Lorenz Straub, a civil engineer, Morrough O'Brien, a civil turned mechanical, and Robert Knapp, a mechanical with strong civil leanings. Straub was to establish the St. Anthony Falls laboratory at the University of Minnesota; O'Brien greatly strengthened the original American laboratory at the University of California; and Knapp developed not one but four laboratories at the California Institute of Technology. Though not a Freeman Scholar, the Armenian immigrant Garbis Keulegan became the mainstay of the National Hydraulic Laboratory at the Bureau of Standards, established in 1930 at Freeman's instigation; on retirement Keulegan became a consultant to the Waterways Experiment Station of the Corps of Engineers, at which a series of Freeman Scholars served as director.

At about the time that the first Freeman Scholars returned home, three European authorities migrated to the United States, there to have a great influence on the direction of American thought. The first was Boris Bakhmeteff, formerly a professor of hydraulic engineering at St. Petersburg and ambassador to the United States under Kerensky. Stranded in Washington by the Russian Revolution, Bakhmeteff eventually became a part-time professor at Columbia University in New York, where he published an English-language version of his Russian doctoral dissertation on open-channel hydraulics. This was followed in 1932-33 by the first American text of fluid mechanics —a two-volume *Compendium*. The next migrant was Theodor von Kármán who in 1930 became director of the Guggenheim Institute of Aeronautics at Caltech, where Knapp was already a member of the mechanical-engineering staff. The third was Wilhelm Spannhake of the Karlsruhe Technische Hochschule, who not only gave a series of lectures on the eastern seaboard but remained several years on the *MIT* staff.

Bakhmeteff's *Compendium* was followed in 1937 by Dodge and Thompson's *Fluid Mechanics* and immediately thereafter by O'Brien and Hickox's book under the same title, the former being a partially blended combination of hydraulics and aerodynamics and the latter a revised version of what had been a course in traditional hydraulics. My own experience of several years each under Rehbock at Karlsruhe, Spannhake at *MIT*, Bakhmeteff at Columbia, and von Kármán at Caltech bore fruit in the 1938 Engineering Societies Monograph *Fluid Mechanics for Hydraulic Engineers*. With hydraulics thus initially correlated with the broader fluid mechanics in various parts of the country, the stimulus of World War II saw a rapid development of defense-related research, particularly in two leading hydraulics laboratories: those at Caltech and Iowa. There intensive work was done on ship drag, torpedo design, water entry, cavitation, jets and plumes, fire streams, atmospheric turbulence, smoke and gas diffusion, fog dispersal, and related projects, many of which would previously have seemed out of place in the hydraulics laboratory.

While the two institutions just named were probably the ringleaders, others soon also became active in applying fluid-mechanics principles. Both Minnesota and California greatly strengthened their staffs directly after the War. Arthur Ippen, originally from Aachen, moved from Caltech to Lehigh and then to MIT, there to establish what was to become a world-renowned hydrodynamics laboratory. In Europe similar developments took place. The laboratories at Toulouse and Grenoble, France, displayed a strong fluid-mechanics flavor, as did those at Manchester, Cambridge, and London, England. Other countries in other parts of the world followed suit. The Soviet Union in particular showed marked activity in this respect, its international reputation unfortunately suffering from lack of ready communication.