THE SIGNIFICANCE OF FLUID MECHANICS TO THE HYDRAULIC ENGINEER

by

Boris A. Bakhmeteff

Columbia University

New York, N. Y.

WHAT IS FLUID MECHANICS?

The answer to the question "What is Fluid Mechanics?" should be sought in the unparalleled advance of Technology during the last decades, when mechanical civilization advanced by leaps and bounds with all the emphasis on *size* and *speed*. The gigantic structures and power machinery of our days require that the functioning of the natural forces be understood with an exactitude unknown in the past. Indeed, the effect of factors previously neglected has to be recognized. The tempo is too fast for the step-by-step advances of the oldtime practitioner to follow. The engineer is required to appraise things ahead by proper theoretical analysis, by suitable model investigations, or preferably by both. Life has met these demands by substituting elasticity for the old-time strength of materials, by inducing the mechanical engineer to operate with advanced notions of vibrations, of dynamic balancing, etc. Over three hundred years ago, referring to the aims to be achieved by man through science, Bacon of Verulam spoke of "Sovereignty over nature, which can be founded on knowledge alone." This sovereignty was said to be "lost" by the learning of Bacon's days, which bore the markings of medieval scholasticism, with nothing left but "vain notions and blind experiments." How fresh and appropriate do these words sound today! In his time Bacon was witnessing the final passing of the dark ages and heralding the coming of Galileo and Newton. In our days, the old-time craft of the skilled technician is making room for "Engineering Science." Fluid Mechanics signifies that life has knocked at the door of the hydraulic profession and with inexorable authority demands that the "vain notions and blind experiments" cease, and that the problems connected with the motion of water be dealt with on the same level of professional aptitude which has established itself in other branches.

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NEW METHODS AND APPROACHES OF ENGINEERING SCIENCE

Are modern scientific methods preeminently mathematical? Undoubtedly, a higher mathematical level is indispensable. Indeed, a source of weakness of the average engineer has been an inadequate mathematical training, inherited mostly from the secondary school. A mere glance at the present-day periodicals shows the mathematical level exacted nowadays from the structural engineer. The hydraulician so far has not been really taken to task, but the trend of life is unmistakable.

And yet mathematics is only a tool. A powerful and most effective means to an end, but still only a means. The *end* in engineering science, as in all scientific pursuit, is an all-around plenitude and quality of knowledge; an approach which disdains "vain notions" and seeks to comprehend and estimate in the most thorough and discriminating manner the ways in which natural forces act. In this endeavor engineering science resorts to each and every means which human ingenuity has been able to conceive, and rejects no tools, no matter how new or "difficult."

A basic principle is the universality of science. In the past, one has discriminated between pure and applied sciences. Different branches of engineering were being forced into petty compartments. It is time to do away with such barriers. Indeed, a startling unity is being manifested between apparently unrelated domains. Meteorology, Oceanography, Geophysics—all are now investigating the same basic physical factors, which dominate the realm of fluid mechanics. Then so many hydraulics cases are identical in essence with problems satisfactorily dealt with in other branches, the accumulated treasure of which may therefore be used to advantage by the hydraulician.

For example, water hammer, being a matter of propagation and reflection of waves in elastic media, is directly analogous to sound phenomena and can be greatly benefited by the science of acoustics. In the instance of surge tanks, installed between a conduit leading from a reservoir and the service penstocks, the securing of stable regimen and the eliminating of dangerous self-induced pendulations reverts to the general criteria of stability in vibrating systems. Obviously no amount of practical "flair" would help the proper dimensioning, which is best served by resorting to the laws of

advanced dynamics. Again, turbulence research, to which the Iowa
Institute has contributed so directly, has been elevated during the
last decade to a quantitative level by introducing notions developed
in statistical mathematics. In the same domain, the "spreading"
of suspended material in natural streams, once more a favorite
Iowa problem, is essentially a case of turbulent diffusion. And in
mathematical physics, the laws of diffusion are best studied in their
relation to the conduction of heat. So the "analytical heat theory,"
initiated by the immortal Fourier, becomes a source of direct
inspiration to the hydraulic engineer of our days. . . . . . .

Von Kármán appropriately alluded once to the "golden age" of
mathematics. This term could equally apply to the early stages of
engineering science, a century or so ago, when pure and applied
disciplines marched forward in unity. The present era of engineer-
ing science seems to bear the happy markings of a similarly promis-
ing epoch.

THE SUBJECT MATTER OF FLUID MECHANICS

The first and natural step in modernizing hydraulic curricula
and texts was to borrow concepts and methods developed in aero-
nautics and to intertwine them with the traditional hydraulic
subject matter. In its time, a decade or so ago, this was a decided
step forward. At present it falls short of requirement. Indeed,
the problems faced by the hydraulic engineer are different in
character and detail. Actually they are more complex. While the
aeronautical men deal mostly with potential motion around com-
paratively simple forms, the hydraulician in his structures faces
the most varied and complicated outlines. Furthermore, flow in
hydraulic practice is largely in the turbulent state, and hydraulic
turbulence is not the simple isotropic brand, but one exhibiting
all the unwieldiness arising from roughness and separation. There
are, furthermore, the unfathomable interreactions between flowing
water and bed load, and, last but not least, cavitation. One may
easily surmise that, before adequately meeting hydraulic exigencies,
the tools serving in aeronautics will have to be substantially
extended and sharpened.

In fact, speaking broadly, hydraulics as a whole urgently requires
a complete overhauling, from the very bottom to the top. The
"vain notions and blind experiments," so characteristic of the not-

distant past, must make room for comprehensive dynamic analysis and for systematic observations aimed at a clear and detailed grasp of the ways in which water actually behaves in the course of its motion. Indeed, the baffling and infinitely complex physical aspects of such motion are the first feature to be recognized in the research to come. One may say that the prime task is a "physical phenomenology of flow."

To illustrate the new emphasis, take the example of orifice flow. In the past it was mainly "coefficients." Today one keeps in mind the design of apertures and outlets in dams, etc., thinking specifically of the bell-shaped entrances through which water is accelerated to the often colossal velocities with which it spouts from the outlets. The smallest error may lead to cavitation, destructive pitting, vibrations, etc. The case, of course, is germain to shaping a spillway crest so as to conform with the natural outline of an aerated nappe. And is it not characteristic that spillway literature still uses Bazin's data of over sixty years ago, and that for orifices there are still no adequate published data covering in detail the physics of the case?

In relation to the physical phenomenology of flow, the mind naturally turns to the splendid work of the laboratories maintained by the different engineering services of the Government. Indeed, model testing has become a necessary concomitant of hydraulic design. Unquestionably the laboratories have gathered a mass of infinitely valuable experimental material. Their direct and immediate object, nevertheless, is to serve the specific needs arising from practical construction. Accordingly, their work is naturally directed towards the "particular." There still remains the final, culminating step — that of synthetically interpreting the observed material, with the purpose of discerning and formulating general laws — the design which Aristotle so aptly described as the aim of all natural sciences: namely, the "discovery of the universal in the particular." No better and more inspiring definition of the essence of engineering science could be imagined. Indeed, in this light Fluid Mechanics may properly be said to look towards a "natural philosophy" [1] of fluid motion, where knowledge of the

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[1] Isaac Newton used the Aristotelian term in naming his *opus magnum*. All the "particulars" of the motion of the celestial bodies follow from a few "universal" dynamic principles.

"universal" would permit each particular concrete case to be handled with the highest competence, economy, and effectiveness in practical result.

With these observations in mind, it is proper now to pass in brief review the more significant concrete topics of Fluid Mechanics.

THE MATHEMATICAL THEORY OF AN IDEAL FLUID

The direct usefulness of the science of hydrodynamics in the aeronautical field is universally accepted. With regard to hydraulic practice, the important feature is that flow through apertures, over spillways, and, generally speaking, all accelerated motion through structures, differs but very slightly from the *potential pattern* which would obtain were the fluid ideal or frictionless. The principal dynamic property of potential motion is that the energy present in the flow is the same at each and every point and equal to the initial head. Since water, on the other hand, is a
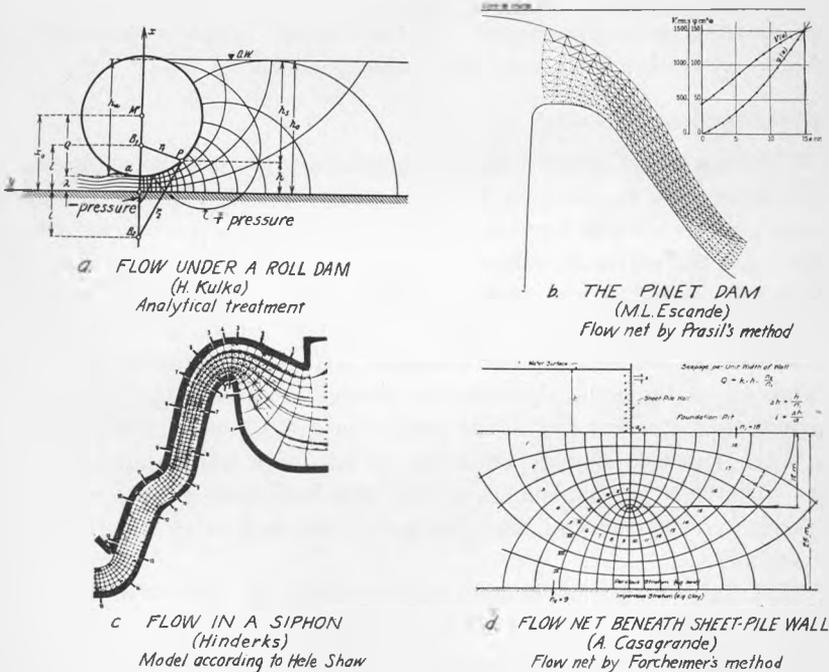

a. FLOW UNDER A ROLL DAM
(H. Kulka)
Analytical treatment

b. THE PINET DAM
(M.L. Escande)
Flow net by Prasil's method

c FLOW IN A SIPHON
(Hinderks)
Model according to Hele Shaw

d. FLOW NET BENEATH SHEET-PILE WALL
(A. Casagrande)
Flow net by Forcheimer's method

FIG 1.—EXAMPLES OF THE USE OF THE FLOW NET.

fluid of small viscosity, the energy losses suffered over the comparatively short length of a structure are relatively small. Hence, in practice only slight differences in energy will actually obtain, and the nearly ideal motion in structures will closely approximate the inviscid theoretical patterns. Many of the treasures accumulated by hydrodynamics, therefore, can be most advantageously put to the service of the engineer. By far the most useful tool in this connection is the so-called flow net. Some of the practical uses of the latter are illustrated in Fig. 1. The legend indicates also the different procedures by means of which flow nets may be obtained. Probably the most expedient is the method of analogy—that is, direct observation of the flow lines and the equipotential lines in electrical or viscous (Hele Shaw) models. Generally speaking, both the notions and the procedures, in so far as the application of the ideal motion theory is concerned, are quite clear and well defined, and the tools lie ready for the use of the engineer. It would seem, indeed, that flow-net geometry and analogy methods are of such basic importance that they should properly constitute obligatory equipment of any hydraulic specialist.

RESISTANCES AND LOSSES

This vast realm offers a far less satisfactory picture. The subject, of course, goes to the very heart of practical engineering. In the past, tireless efforts were spent in determining empirical expressions for the different resistance terms. Very little, however, was done in disclosing the internal mechanism by which losses are effected. At present the subject has gained prime practical importance, in connection, for example, with such problems as the handling of the colossal amount of energy released from overflow structures. The key lies in the proper control of turbulence, which in turn substantially depends on an adequate understanding of the turbulence mechanism. A similar situation prevails with regard to bed load, suspension, insufflation of air, and other mystifying phenomena.

Hydraulic resistance is one topic in which the understanding of the "universal" is preeminently important. It is also in this realm that the prevailing customary notions are especially inadequate. In so many respects, indeed, it is imperative for the present-day hydraulician basically to reorient his views and to build wholly

anew the notions and conceptions with which he is to operate in the resistance field.

HYDRAULIC FRICTION AND THE BOUNDARY LAYER

To illustrate what such reorientation may imply, consider the familiar case of frictional resistance. The latter is habitually associated with the uniform, established patterns as in long pipes or channels. So strongly embedded are these concepts that one perchance extends them to all friction cases, such, for example, as determining the Manning coefficient for water flowing down the face of a dam, or for appraising friction in a short outlet.

The scarcely realized fact is that established flow is rather an exception — particularly so in structures, where the total path is short and where flow is mostly accelerated. The actual pattern, in these instances, will be distinctly of the *transition* type, with friction wholly concentrated in the *boundary layer,* and with the major part of the core practically in the potential state. An example, referring to a broad crested weir, is given in Fig. 2a. Similar phenomena have been observed on spillway models. Obviously, the practice of resorting in such cases to Manning coefficients or to any other established flow parameters has no physical foundation. If friction in transition structures has to be appraised numerically, this must be done in terms of boundary-layer motion, which only means that many familiar usages have to be studied anew.

A "universal" function of the boundary layer is its role in shaping the flow. Take, for example, the question of whether motion in a pipe will be laminar or turbulent. One customarily resorts to a "bulk" Reynolds Number $R = ud/v$, with a well defined lower limit ($R = 2000$ to 2100), below which flow will always be laminar, no matter how disturbed the oncoming flow. The physical significance of this lower limit is clarified in Fig. 2b, the ultimate state of motion being conditioned wholly by the boundary zone. In its inception the layer starts naturally in laminar form. While the size of the expanding boundary layer remains below a certain limit, implied in the critical value of $R_\delta = (u\delta/v)_{cr}$, motion in the layer will continue as stable and laminar, irrespective of all the "pounding" which the boundary flow may receive from the disturbances prevailing in the central reaches. Accordingly, if the size of the conduit is sufficiently small ($d < 2\delta_{cr}$), the gradually expanding

layer will "elbow out" the disturbances, and in filling the cross sections will impose a lasting laminar imprint on the subsequent uniform motion. The opposite case is featured by Fig. 2c. Here the oncoming flow is free from disturbances, and there are no apparent disturbances to interfere with stable laminar motion in the boundary layer. Observations show, however, that, as the transverse dimensions of the latter increase, the originally recti-linear and stable laminar filaments commence to pendulate, the fluctuations increasing in frequency and amplitude with R_δ. The oscillations are explained by the inherent unstability of the highly strained viscous sheets. Any small, incidental deformation will
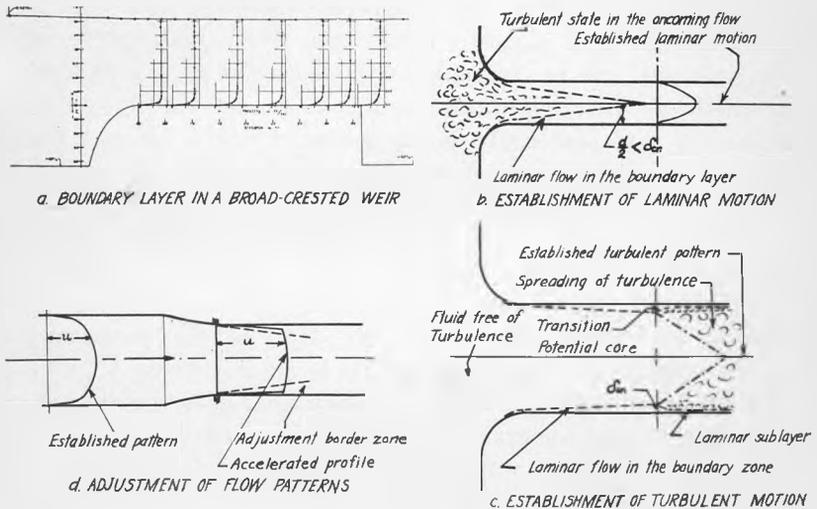

a. BOUNDARY LAYER IN A BROAD-CRESTED WEIR

b. ESTABLISHMENT OF LAMINAR MOTION

d. ADJUSTMENT OF FLOW PATTERNS

c. ESTABLISHMENT OF TURBULENT MOTION

FIG. 2.—EFFECT OF BOUNDARY LAYER IN SHAPING FLOW.

tend to grow, prompted by factors engendered by the initial deviation.[1] A stage is finally reached at which all vestiges of stability are lost and the heretofore slow laminar pendulations break up into high-frequency turbulent oscillations. Thus, the transition from laminar to turbulent flow is a boundary-layer phenomenon. The bulk Reynolds number only indicates that the boundary layer reaches its critical transverse size δ_{cr} before fill-ing the cross section. Turbulence, once engendered in the bound-

[1] Dynamically it is a case of so-called self-induced vibrations.

ary zone, rapidly spreads over the cross section, finally imposing the turbulent imprint on the pattern of motion as a whole.

A final instance of the shaping action is given in Fig. 2d. Here the function is to adjust flow forms. Over the conical transition piece flow is rapidly accelerated, resulting in a nearly uniform pattern. At once boundary friction action arises in the layer, gradually bringing the velocity profile to its new established shape.

DISCONTINUITY SURFACES

The full significance of the boundary layer as a source of shaping action is best apprehended in connection with the hydrodynamic notion of discontinuity surfaces. An example of the latter is the efflux of an ideal jet into a frictionless fluid which is at rest (Fig. 3a.). Across the surface the velocity is discontinuous, as over an infinitely thin layer it changes by the finite amount u_0, that is, $(du/dy = u_0/0 = \infty)$. The case typifies a generic group of free discontinuity sheets, or free stream lines. In Fig. 3c an ideal fluid is taken to move with a finite velocity next to a solid surface. The discontinuity is between the flow (at the rate u_0) and the zero velocity of the boundary.

The concept of discontinuity surfaces is of the deepest significance to the engineer, and constitutes one of the most "universal" features of the resistance mechanism in general. What, in fact, is their physical counterpart in the actual motion of viscous fluids? In the case of Fig. 3c it is obviously the *boundary layer* (Fig. 3d). As to Fig. 3a, the physical counterpart is separation (Fig. 3b).

The practical significance of these parallels is their relation to the basic function which underlies the mechanism of all hydraulic losses — namely, the *engendering of vorticity*. The ultimate source of all resistance is viscosity. The latter, exemplified by the familiar μ coefficient, is a physical property germain to all fluids. The fact that fluid matter is always viscous does not mean, nevertheless, that viscous action will be revealed under all circumstances. As a matter of fact, viscous stress $(\tau = \mu \, du/dy)$ will arise only in the presence of a proper transverse velocity gradient, when the kinematic structure implies rotation or vorticity.

The ideal concept has led to a beautiful theory of vortex motion, the striking feature of which is the "immortality" of a vortex
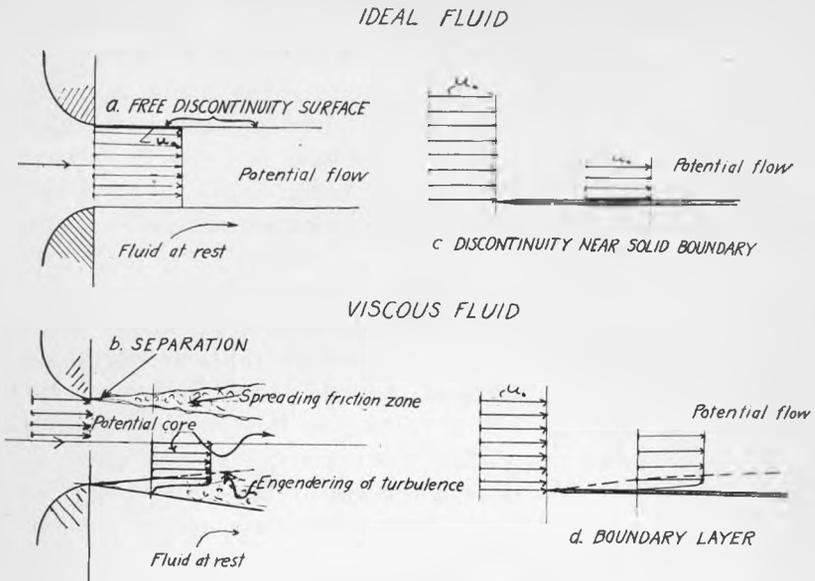
FIG. 3.—DISCONTINUITY SURFACES.

unit. Once engendered in ideal media, vortex motion cannot perish but will continue forever, maintaining its strength and bodily constitution. In equal fashion, moreover, in an ideal fluid subject to the action of conservative forces such as gravity, vorticity, generally speaking, cannot arise. In other words, once ideal motion starts as irrotational it will continue as such indefinitely, as there are no ordinary means by which vortices can be generated. The significance of discontinuity surfaces lies in the fact that they constitute a natural source of vorticity. Indeed, the ideal discontinuity surface (Fig. 3a) is customarily referred to as a vortex sheet, the vorticity in the sheet being theoretically infinite. One may visualize indeed the block of moving fluid as gliding relatively to the other over a train of minuscule rollers.

Where and how will vorticity and the concomitant viscous stress arise in an imperfect fluid body? No such stress can arise, for example, inside the rectilinear uniform velocity core in the initial sections of Fig. 3b, for in the absence of a transverse velocity gradient viscosity will not "assert" itself. This case exemplifies a rather general property. In actual motions dealt with by the

hydraulic engineer, friction action usually does not arise inside the fluid body, but starts in the boundary zones, either of the "free" kind (Fig. 3b) connected with separation, or (Fig. 3d) of the boundary-layer type. In either case, the prime source is connected with the initial discontinuity. Starting as a sheet of infinite vorticity, the friction effect gradually spreads transversally, "eating" into the heretofore unaffected fluid. This spreading is referred to as diffusion of vorticity, and obviously means diffusion of frictional action. When the transverse latitude is small, the phenomenon will continue on the initial *molecular scale,* exhibiting characteristics associated with laminar motion. Otherwise, the engendering of vorticity will assume *molar* proportions, manifested by turbulence. The whole phenomenon of turbulence is explained physically by the presence in the flow of a host of eddies which swarm in apparently irregular fashion and superimpose their fluctuating kinematics on the steady local pattern. These eddies are engendered in the boundary zones. Turbulence resistance arises from the fact that mechanical energy is continuously withdrawn from the store carried by the main flow, and is invested in the turbulent eddies, such investment implying the process of conversion of energy from translation to rotational form. In real fluids the physical counterpart of the theoretical "immortality" of vortices is the fact that energy once converted into vortical form is non-reversible. Once invested into eddies, in other words, the energy cannot be restored to the flow, and its only fate is finally to be dissipated into molecular heat, such ultimate loss taking place in the course of viscous attrition which accompanies the tumultuous and irregular mixing.

SEPARATION AND LOCAL RESISTANCE

As a special turbulence-engendering region, the free discontinuity sheets (Fig. 3b) occupy a position of their own, as they constitute by far the most intensive source of turbulent action. Such, indeed, is the intensity of the energy-conversion process, that the formation of eddies, as lumps of concentrated vorticity, can be visualized directly. Incidentally, the observed facts stand in good accord with the theoretical computations of the successive stages of deformation of the unstable discontinuity sheets.

The particular practical significance of free separation sheets

is that they furnish the source of all so-called local resistance. Bends, knees, valves, sudden expansions, etc., as well as rollers at the toe of dams and in hydraulic jumps, all exhibit pronounced separation effects, in which vorticity is engendered on an exceptionally intensified scale. The sudden drop of head, familiar to the engineer in connection with such resistances, manifests the fact that unusually high amounts of flow energy have been locally invested in turbulent eddies. The Iowa Institute (Kalinske) made a valuable start in the study of energy exchange in divergent conduits. In general, however, knowledge of the dynamics of local phenomena is in an infant stage. There have been many endeavors in the past to organize empirical data into unified charts. Even in the simplest instances, such as elbows in pipes, the complexity of the phenomenology has defied the attempts. The key to the situation would seem to lie first in the study of the "universal" features, namely the general behavior of water in separation sheets. A problem of particular importance in this connection is the turbulent exchange as it occurs between the live flow and adjacent rollers.

ESTABLISHED FRICTION PATTERNS

The engendering of turbulence in this case (long pipes and channels) is usually not on as intensive a scale as in the free separation
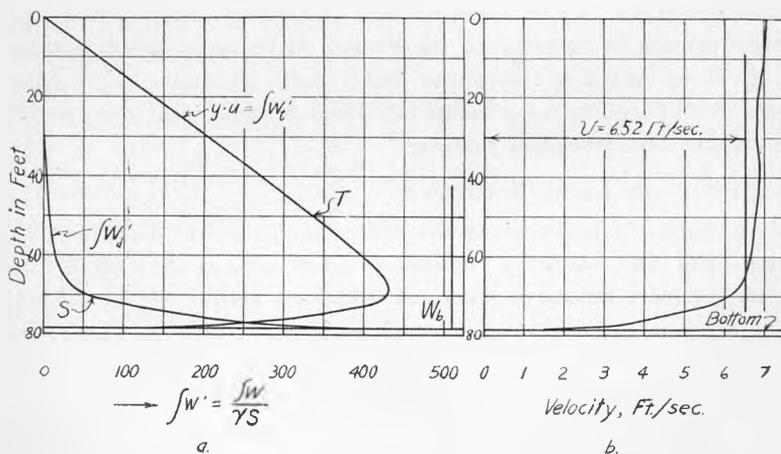

FIG. 4.—ENERGY EXCHANGE AND VELOCITY VARIATIONS AT A MISSISSIPPI
RIVER GAGING STATION.

sheets. Perhaps that is at least one reason why the process so far has escaped direct observation. Indirectly, however, all available evidence points essentially towards an analogous mechanism — namely, the rolling up of the unstable boundary vortex sheets into chains of turbulent eddies. These eddies, endowed with energy borrowed from the flow, are generated in close proximity to the wall. The ultimate dissipation of the energy occurs in a subsequent phase, during the swarming of the cast-off eddies through the main body of the flow. Concentrated eddy engendering near the wall obviously requires that the energy withdrawn from the flow should be transmitted towards the locus of intensified conversion near the solid boundary. These features have been elucidated lately by Bakhmeteff and Allan, Fig. 4a picturing the energy exchange at a gaging station on the lower Mississippi River, the velocity profile for which is shown in Fig. 4b.[1]

The cumulative curves 0T and 0S in Fig. 4a indicate respectively the rates at which energy is transmitted and spent on resistance in the respective fluid blocks at the depth y from the surface. The quantities are to be compared with the total loss $W_b = \gamma q S$ in the vertical. The 0S outline, typical for turbulent flow in general, is specifically meant to illustrate the eventual interrelation between the energy exchange and the work done by a river, as regards bed load, etc. While energy is withdrawn principally at the upper regions in accord with the outline of $u = f(y)$ in Fig. 4b, the expending is concentrated largely near the bottom. Actually over 90 percent of the total W_b is consumed in the lower 10 percent of the vertical, while 50 percent is lost in the last foot of the 78-foot-deep river. The total power spent by the watercourse on resistances at the particular stage amounts to near 30,000 horse-power per mile. Assuming that the conditions of Fig. 4 obtain more or less for the reach as a whole, it follows that within the space of a foot from the bottom over 15,000 horse-power of mechanical energy are converted into rotary eddying form. One may easily conceive the resulting mechanical effect on the solid bed, by imagining the power invested in the eddies to be replaced by an equal output of dredging pumps or other rotary machinery.

In the past, studies of bed-load movement have principally sought

[1] The author owes the underlying data to the courtesy of the Mississippi River Commission, Vicksburg, Mississippi.

to establish bulk empirical relations. Perhaps the more expedient way of reaching a dependable goal would be to start once more from the ''universal'', aiming first at a comprehensive account of the dynamic interactions which unfold between the bed of solids and the turbulent fluid. Of course, any real advance in this domain would depend on the progress in the general field of turbulence. And with turbulence the trouble again is paucity of factual information, once more the question of ''physical phenomenology.'' Unfortunately, the techniques so far disclosed (Fage, Kalinske, etc.) are too tedious to be extensively used. So the hydraulic profession is anxiously looking for a device which would be at least as convenient in water as the hot-wire anemometer has shown itself to be in air.

Perhaps these brief allusions will help to elucidate what was meant by stating that hydraulics has to be rebuilt from top to bottom on a new scientific foundation. This undertaking, which in subject matter has to be closely guided by actual practical needs, in method and spirit must aim at nothing less than establishing a ''natural philosophy'' of flowing water. It is no mean task. It calls for infinite patience and discriminating judgment in collecting and interpreting experimental evidence. It requires new techniques and in many branches advances in theoretical means, outreaching substantially the tools available at present. On the whole, nevertheless, it is one of the most fascinating and promising goals, which, moreover, as matters stand, will have to be accomplished mostly by hydraulicians of this hemisphere. Nowhere else, indeed, is engineering hydraulics applied on a scale comparable to that in the New World. The laboratory facilities of this continent, furthermore, are unsurpassed. To start the work on an adequate scale will require special dispensation on the part of Government agencies and seats of learning. Action is certain to follow once the profession at large realizes the imperative necessity of the effort.