Laboratory Instruction in the Mechanics of Fluids

by
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State University of Iowa
Studies in Engineering
Bulletin 41

http://ir.uiowa.edu/uisie/41
LABORATORY INSTRUCTION

IN THE

MECHANICS OF FLUIDS
Laboratory Instruction
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Iowa Institute of Hydraulic Research

Published by the University
Iowa City
1961
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*Frontispiece:* Laminar and turbulent jets of oil from a \( \frac{3}{4} \)-inch brass pipe at \( R = 3000 \). Capillary fin below laminar jet includes outermost portion of flow that was retarded in pipe by viscous shear. Turbulence was artificially stimulated by rod across bell inlet 15 feet upstream. Exposure, 1/20,000 second.
LABORATORY INSTRUCTION
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MECHANICS OF FLUIDS

INSTRUCTIONAL GOALS

Engineering curricula have long stressed the concept that mental and manual instruction are mutually complementary, that seeing and doing are as essential to learning as reading and hearing, and that without the opportunity of testing or applying textbook principles these will remain unassimilated by the student. Drafting rooms, shops, laboratories, and summer camps have thus played a prominent part in technological education, and the physical plants of the relevant institutions have grown accordingly. Such growth would seem to have no future limit were it not for a number of rather conflicting trends that have become apparent in recent years.

When engineering was young, there was relatively little professional variation either vertically or horizontally. However, the initial distinction between the civil and the military gradually spread to include such divisions as mining, mechanical, marine, electrical, and so on; and at the same time it became evident that engineers with a university education usually possessed more highly developed powers of reasoning than those who had learned solely by experience. Paradoxically, both of these trends have now almost reversed themselves, at least in many localities: rather than promote ever-increasing specialization, some colleges seek to give all engineering students practically the same education; and rather than appreciate the advisability of preparation at different levels according to ability, students all want a university degree. The net result is the rather peculiar situation of an effort being made to spread laterally (bifurcation) to produce a difference between the creators, the constructors, and the operators of engineering projects, when this represents in considerable measure a vertical differentiation.

In a sensibly organized society, technological education would be apportioned between technical universities, technical institutes, and trade schools, the first-named accommodating the smallest number and the last-named the largest. The universities would take only those of highest creative ability and would produce the planners. The technical institutes would emphasize the ability to detail and execute. The trade schools
would train the artisans. Instead of this, American engineering colleges are faced with the necessity of producing men in two if not all three categories, whether or not the degrees or college catalogs admit as much. In other words, despite the meeting of minimum accreditation requirements by most engineering colleges, a certain few of them have the reputation of producing top-level engineers and the many others that of supplying the masses that will do the routine design or construction jobs. The colleges accommodating undergraduates en masse can differentiate vertically only through graduate study. It falls to the few technical institutes and the least effective of the colleges (or of the college graduates) to provide the multitudes that are needed at the subprofessional level.

What bearing these generalities have upon the subject at hand is as follows. Hydraulics was long taught in American engineering colleges as a vocational rather than a scientific course. Experiments involved the use of gages, the calibration of flow meters, the measurement of head loss in a pipe, and performance tests on a pump or turbine. Most courses in hydraulics have today been replaced by courses in the mechanics of fluids, though sometimes with a change in name only, and usually with no change whatever in laboratory exercises. There is, to be sure, nothing about the use of instruments, the calibration of meters, and the performance of machinery that an engineer should not know. The error lies in disregarding the fact that he needs to know a great deal more. Whereas much of what is still taught in college laboratories is on the trade-school level — of prime importance a century ago, but definitely secondary today — the true university level is that on which the curriculum emphasizes grasp of scientific principle rather than practice in manipulating equipment.

Current trends away from such vocational courses as those in drafting, surveying, and shop would perforce include all laboratories as well were it not for several facts. First of all, laboratory equipment can be designed to illustrate far more than manipulation; indeed, all knowledge is the direct or indirect result of experience, and it is the controlled reproduction of such experience that the instructional laboratory should be designed to accomplish. The engineering sciences — particularly those requiring experimental verification and amplification of analytical deductions — are difficult to teach solely by written and spoken word, and hence the laboratory must play much the same part in teaching as it has in research. In teaching, to be sure, its role may be one or more of three: a studio for the preparation of motion pictures to be distributed among colleges with limited facilities; a site of intermittent demonstrations by the instructor to classes as a whole, even to the extent of providing quan-
titative data for subsequent interpretation; and an assemblage of well-planned facilities upon which the students themselves perform specified experiments.

With the explicit understanding that what is under consideration is instruction in the mechanics of fluids at the true university level, the provision and use of laboratory equipment designed for this specific purpose will be discussed herein. Such matters have been the basis of study at the Iowa Institute of Hydraulic Research for the past two decades. The instructional equipment has been in a continuous state of development, and several of the units have been reproduced in various parts of the country. Members of the Institute staff, moreover, have participated in the design of laboratories and equipment in four foreign countries. Whereas the Institute cannot well issue plans and specifications prepared under contract to the many others who request them, it has always welcomed inspection and duplication of its own facilities. The present bulletin is being prepared to afford further assistance to those who are interested in providing laboratory instruction on the same scientific level.

To offset the customary American belief that it is the equipment as such that counts, let it be emphasized at once that what is of primary importance is the use to which the equipment is put. For the goal that is sought herein, it matters little whether the facility is made of wood or of stainless steel, so long as the flow principle under consideration is properly demonstrated. It is true that the initially more expensive unit will probably be more durable and hence cost less in the long run. Otherwise, however, the matter of expense should not deter the college of very limited means, for small units are often as effective as large and much cheaper to build or buy. In fact the keynote paper in the founding of present-day fluid mechanics [1] was illustrated by photographs made in the simplest of demonstration equipment (see Fig. 1). The most striking experiment on conduit resistance that the writer has ever witnessed, moreover, was performed in the classroom by a physics professor using only compressed air, a coil of rubber tubing, two manometers, and a stagnation tube. In a word, the principal expenditure in the realization of a laboratory might best be that of time given to its planning.

Basic Facilities

Perhaps the most important requisite of an effective laboratory is uncluttered space. All too often a new establishment is planned like an engine room, in the belief that it is the complexity of machines, pipes, valves, and meters that establishes the proper atmosphere. Surely such items are not necessarily to be concealed from view, but they are just as
surely not the primary feature. Moreover, a clean, dry, well-painted room is preferable to the dark, dank, and dirty laboratory quarters so typical of past decades.

A good fluids laboratory should utilize at least water, air, and oil as experimental media. Air possesses the obvious advantage of being practically everywhere and hence causing no storage problem. Oil is somewhat the opposite; that is, unless properly stored, it eventually tends to be found everywhere—due to the fact that, unlike water, it does not evaporate at points of minor leakage. However, if proper attention is given to tightening joints and catching such drips as may still occur, the problem is not a major one, particularly since the use of oil

Fig. 1. Ludwig Prandtl and the Recirculating Channel Which He Built at Hannover Near the Beginning of the Century.
will probably be restricted to a few self-contained units. Water, of course, is usually stored in a reservoir just below the laboratory floor, though sometimes either more-remote or less-convenient storage may be necessary. The reservoir should hold a sufficient quantity of water to fill all equipment and still maintain the necessary depth of submergence of pump inlets. Provision of an adequate overflow and wasteway will insure against the grief that often results from careless overfilling. A bottom outlet to the sewer is desirable for cleaning purposes.

Constancy of the flow provided by the laboratory pumps and blowers can be effected by electrical control of the motor speeds, and it is generally desirable to have such controls (if only in the form of a synchronous motor) on closed-circuit units such as those containing oil are likely to be. For groups of units, on the contrary, it is usually cheaper to use some form of constant-head device employing skimming weirs. These operate on the principle of constantly wasting fluid in such a manner that a large change in the quantity wasted produces only a small change in the head at which the fluid is supplied to the experiment. This is illustrated for the case of water in Fig. 2. If the pump is assumed to yield a more-or-less-constant rate of flow into the tank, any change in the flow to one or another of the experiments will cause a change in head on the skimming weir that is inversely proportional to the two-thirds power of the length of weir crest. This change can evidently be

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**Fig. 2.** Constant-Head Tank for Water.

**Fig. 3.** Constant-Pressure Tank for Air.
held to any desired fraction of the overall head \( h \) on the equipment by proper skimming-weir design. Figure 3 illustrates a comparable constant-head device for small rates of air flow—provided, for example, by the pressure line from a centrally located compressor. As before, the supply is adjusted so that the air wastes continuously under the skimming weir and the desired pressure is controlled by the depth of water \( h \) in the standpipe.

Certain points are to be kept in mind in the design and installation of a constant-head tank for water (see item A in list of suggested vendors of equipment on page 56). Not only should the skimming weir \( W \) (Fig. 4) be long enough to maintain the desired limit of head variation, but the freeboard and return pipe \( R \) should be large enough to take the entire discharge of the pumps when all experiments are shut down. In general, a separate pipe \( E \) should run to each of the experiments to be operated simultaneously, because supply by a common line will permit the flow to one experiment to be affected by changes of another. Moreover, the outlets to each of the experiments should be judiciously placed with respect to one another and in particular with respect to the inlet \( P \) from the pump, so that minimum disturbance will result. Cross effects can also be minimized by making the tank large or by baffling the inlet (see slotted header \( H \)) and shielding the outlets. A rule-of-thumb for tank capacity is 100 cubic feet for each cubic foot.
per second of flow. One of the two large Institute tanks is 2000 cubic feet in volume, with 650 feet of skimming weir, for a discharge of 10 cubic feet per second; a smaller one is 400 cubic feet, with 90 feet of skimming weir, for a discharge of 11 cubic feet per second. The first was greatly overdesigned relative to the pumpage finally installed, whereas so many pumps were eventually connected to the second that it required considerable baffling to yield even barely passable results.

Prime movers (see B, page 56) differ greatly in size and specific speed from one laboratory to the next, depending as they do upon discharge and head requirements—and method of acquisition. Use of a centrifugal unit to produce a large rate of flow, or an axial-flow unit to obtain a high pressure (even when the units stem from gift or surplus sources), is almost as poor pedagogy as sacrificing principle to manipulation. Most units, of course, will have their particular purposes—general supply of fluid to a constant-level tank, fluid propulsion in a closed-circuit tunnel, and so on. On the other hand, laboratories which must prepare temporary demonstration or research assemblies from time to time would do well to keep at hand several portable pumps and blowers of different types and sizes.

In most instructional-laboratory installations the supply pressures are so low—at least in the larger conduit sizes—as to warrant the use of light-weight pipe, whether of the longitudinal- or spiral-weld type. This is particularly economical and easy to assemble or modify if used in conjunction with Victaulic-type couplings and fittings (C).

Any laboratory that provides facilities for quantitative experimentation rather than purely qualitative demonstration should have at its disposal some primary standards of flow measurement. For water these will probably involve weight determination by means of small tanks on scales or volume determination by means of large tanks of known geometric form. The latter can sometimes be improvised by bulkheading a portion of the reservoir proper to serve as a volumetric basin; if the walls are sensibly vertical, geometric measurement of a horizontal section can be used as a check on—or conceivably in lieu of—volumetric calibration. The capacity of such a tank or basin should be sufficient to accommodate the largest expected rate of flow in a time interval that can be measured with the desired degree of precision; similar considerations (i.e., the precision of depth measurement) should control the depth-area proportion. It is seldom satisfactory to make depth (or weight) and time measurements "on the fly." Instead, some method of flow diversion should be provided so that the observations can be made with sufficient care. Unless the movement of the diverter is relatively rapid and the registration of time automatic, an effort should be made to obtain sym-
metry of operation in the two directions (Fig. 5), the time then being noted as the axis of symmetry is passed in either direction and initial and terminal errors balancing out.

Volumetric measurement of air (or other gas) flow is usually feasible only for relatively small quantities. Two nesting tanks are fitted together, the inner one upside down (see Fig. 6), and the space between is filled with water. The flow to be determined is introduced into the inner tank and the latter is raised at a rate sufficient to maintain atmospheric pressure in the air collected. Simple geometric evaluation of the volume discharged at this pressure in a measured interval of time yields the rate of flow under standard conditions.

For greater rates of air flow, recourse must be taken to an indirect method of measurement that is also conveniently used for the calibration of velocity instruments for either air or water. A nozzle so shaped as to yield a uniform jet (see Fig. 7) with minimum boundary-layer development requires a single determination of either the pressure drop $p$ or the stagnation pressure $\rho v^2/2$ at a point within the irrotational core (where $\rho v^2/2 = p$) to yield the rate of efflux with close approximation—the nozzle diameter being used as the effective jet diameter and the core...
velocity as the average velocity for the effective section. Essentially the same order of accuracy will obtain for either free or submerged efflux (i.e., the surrounding fluid has little effect upon the jet at the efflux section), which makes the method readily applicable to the determination of rates of air flow. As a matter of fact, nearly as great accuracy can be obtained with a contracting jet, provided that the discharge or contraction coefficient is known. For free or submerged efflux of either air or water from a sharp-edged circular orifice in the wall of a large tank, it can be assumed for this purpose that $C_d = C_e = 0.61$ [2].

For reasons of convenience, every unit of experimental equipment should include some sort of flow meter, each of which should have been calibrated in place using one of the methods already discussed. Such devices include weirs of rectangular, trapezoidal, or triangular form, the latter being especially suitable for small rates of flow; Venturi meters; nozzles and orifices, whether within the conduit or at its outlet; and other standard devices. However, it should be noted that almost any change in boundary alignment is suitable for the purpose if calibration is possible. Elbows, inlets, and other section changes (Figs. 8 and 9) are frequently used in this manner, piezometers being placed at points of greatest differential pressure. In fact, it is often feasible to introduce a local change in the form of a cylinder or streamlined strut (Fig. 10) spanning
the flow section, to secure a maximum differential pressure between an
opening at the front and one at the side or at the pipe wall. The use
of a different method of flow measurement for each experiment is not
without instructive value; indeed, the more novel they are, the better.
Only three words of caution should be noted: indications of depth or
pressure should not be made in zones of fluctuation; the meter should
be so devised that its indication will not be affected by a change of
experimental conditions; and such free-surface controls as weirs are
preferably located upstream if the experiment involves the rapid estab-
ishment of one or more specified rates of flow.

Experimental Equipment

Towing Devices

Flow phenomena to be studied experimentally can be divided into
three categories: the motion of a body through a fluid, the motion of a
fluid through a conduit, and the motion of one fluid under, through, or
over another. Generally speaking, it is the relative displacement of
fluid and boundary that is of interest, so that it does not matter in prin-ci-
ple which actually moves. A ship passing through a canal, for example,
produces surface disturbances not unlike those around a stationary bridge
pier in a stream. Similarly, it is sometimes convenient to tow an open-
ended section of a duct (as in the preparation of Fig. 11) through

![Fig. 11. Pattern of Flow at a Two-Dimensional Constriction.](http://ir.uiowa.edu/uisie/41)

either stagnant water or air to isolate local effects for observation. In a
word, flumes, tunnels, and towing devices can often be used interchang-
abley to reproduce the same phenomenon of relative motion, and the
choice of equipment is sometimes dictated only by convenience or avail-
ability. Nevertheless, each type possesses one or more advantages (and disadvantages) over the others, and it is as important herein to indicate these as it is the similarities.

Towing devices on an extensive scale are probably the least useful to the instructional laboratory of the several types of equipment producing relative motion. The largest towing tanks are those constructed for testing model ships in naval-research institutions, and only in a school of naval architecture would a small-scale ship tank be a logical teaching unit. Towing tanks of appreciable size are also used for the calibration of current meters, and for this reason some of the engineering colleges have considered them essential equipment—albeit for the vocational type of course. Because of the space that such a facility occupies, only a very short one could be justified in an instructional laboratory of the sort herein discussed. Such a small tank with towing carriage is most desirable, however, because it provides the simplest means of demonstrating or photographing elementary patterns of two-dimensional flow. (Still simpler, but definitely subject to scale effects, is the very small projection apparatus (D) devised by Eck [3]).

A tank for this purpose need be only fifteen or twenty inches in width, half a foot in depth, and eight or ten feet long. A carriage on smoothly turning wheels should roll longitudinally without appreciable vibration, for it must carry the boundary form under study, as well as the lights and camera if still or motion pictures are to be taken. The two-dimensional boundary profile (whether simulating an immersed body or a conduit transition) is mounted on a false bottom suspended by side plates from the carriage (Fig. 12), and everything visible is painted a dull black except the top of the boundary which is painted aluminum. The tank is filled with water nearly to the top of the profile (objectionable capillary “creep” can be eliminated with a light coating of paraffine

Fig. 12. TOWING-TANK ARRANGEMENT FOR PHOTOGRAPHING FLOW PATTERN OF FIG. 11.

http://ir.uiowa.edu/uisie/41
or waterproof grease), the water surface is dusted with a coarse, oil-free aluminum powder or "flitter" from a large picnic salt shaker, and the carriage is moved along the rails at some uniform speed below that at which appreciable waves are produced. Propulsion by hand will suffice for most demonstration purposes. For photography or more refined observation, mechanization is preferable. The best transmission is an endless tape (not the more elastic stranded cable) of phosphor bronze or steel, one of the two end pulleys being driven by motor. To avoid the initial jerk of a constant-speed motor, a simple friction clutch or a more elaborate variable-speed drive (E) is recommended. The shielded photographic lights must be low enough to avoid direct reflection from the water surface, yet the reflectors must provide an even illumination over the field of view.

Before leaving the subject of towing devices, it should be noted that two other basically different versions also exist: the rotating arm, and the inclined wire or track. The revolution of test bodies at some distance from a vertical axis has long been used effectively, in air as well as water and at both small and large scales, and there are instances in which its present consideration might well be warranted; an alternative version is a rotating tank with stationary body under study. The inclined wire or track is usually restricted to the guided movement of bodies through air under gravitational motivation; an extreme condition, of course, is the free (though sometimes vertically guided) fall of bodies through either air or water—or even through liquids of higher viscosity. In the latter events both the initial acceleration and the ultimate steady state can be studied by careful observation of displacement against time, whether visually or photographically.

Air and Water Tunnels

Air and water tunnels perform the same function as the foregoing towing devices, but with the added convenience of a stationary point of observation and the added drawback of a fluid that is already in motion—and hence probably turbulent. The simplest air "tunnel" is the free jet from a ducted fan, and a primary item of the simple yet very imaginatively planned Eck [3] demonstration equipment (D) is just that—albeit the duct is properly shaped and contravanes beyond the fan yield a stream that is free from appreciable spiral flow. The simplest water tunnel, on the other hand, is a closed or open conduit connecting the discharge and suction sections of a pump. At once evident are the basic distinctions between the two fluids as research media. As a matter of fact, a water tunnel is preferable to an air tunnel only when the formation or initial presence of an air-water interface is involved (i.e., in the study
of cavitation phenomena or phenomena involving a continuous free surface), and then there is no choice.

Because of the desirability of pressure control in cavitation experiments, a water tunnel is usually a closed circuit. (This is not indispensa-

![Diagram of a water tunnel](https://ir.uiowa.edu/uisie/41)

**Fig. 13. Osborne Reynolds' Cavitation Experiment.**

ble, however, for cavitation can readily be produced by velocity control alone, even—see Fig. 13—in flow at very small scale from a city water line; then, however, the air content cannot be kept low enough for more than qualitative observations.) Tunnels for research are usually specially designed and fabricated (A, F). For small installations in which efficiency is not a factor, ordinary tanks, piping, and pump can be used (Fig. 14), only the test section being given special attention. The pump
is usually located a floor below the test section to avoid cavitation at the impeller (G). Pressure controls may consist simply of valved lines to open tanks twenty or thirty feet above and below the test section, but this has the disadvantage of admitting dissolved or suspended air to the system. A supplementary vacuum pump (B) and tank connected to a high point of the tunnel will permit the same deaerated water to be used continuously (a rise in temperature is then to be expected with time if a means of cooling is not provided). Unless the system is extremely airtight, the vacuum pump must be operated constantly and the pressure regulated by means of a needle-valve bleeder on the vacuum tank. The packing glands of the pump are usually the most difficult to make airtight, and it is often necessary to surround them with a simple water bath. The size of pump to be used depends upon the size of the test section; it should have a great enough capacity to produce considerable cavitation at a typical boundary section at moderately high pressure, so that the phenomenon can be produced by variation of either pressure or rate of flow.

Test sections are of either the open-throat or closed-throat type and arranged for either two-dimensional or three-dimensional (including axisymmetric) boundary forms. A two-dimensional section—the simplest for instructional purposes—is perforce of the closed type, one or two of the four walls preferably being transparent. Dimensions are of course arbitrary, though the length of section is usually greater than the height, and the cross section may flare slightly to counterbalance boundary-layer growth. The transparent walls can be of glass (preferably tempered, if there is danger of breakage during observation), or—when they must contain piezometer openings or screws to mount centrally located profiles—of thick sheet plastic (H). The use of plated brass or stainless steel should be considered for at least the remaining surfaces of the test section, because of the difficulty of maintaining a painted surface in zones of high-velocity flow. (In this connection a warning should be noted against placing various metals—particularly brass and aluminum—side by side under water, because of the electrolytic pitting that results.)

Air tunnels can take many forms, in part because of the small pressure loads that are involved and in part because the unit can draw from and discharge into the atmosphere without any other precaution than avoidance of disturbance to (or from) the immediate vicinity. If a tunnel is thus an open circuit, the test section must be of the closed-throat type (I) or of the open-throat type surrounded by a closed chamber (Fig. 15)—on the assumption, to be sure, that for all but the simplest units the fan should be downstream from the test section. But whereas an open-throat water tunnel must always have such a housing, the great ad-
vantage of an air tunnel is that use of a closed circuit will permit the test section to remain unhoused (Fig. 16). Bodies under study can be simply supported within the open jet, and observation and instrumentation are greatly simplified. It should be noted that the open length of section must not be much greater than its diameter; otherwise flow pulsations will develop, which shaping, venting, or baffling of the downstream section can only partially eliminate. Further note might be made that the lack of flow confinement in an open-throat section produces a smaller velocity and pressure change around a body than would occur in an infinite stream, whereas the constriction effect of a closed-throat section increases the velocity and pressure change; an effort is sometimes made to play the two against each other (and thus simulate a great expanse of section) by using a so-called slotted throat—i.e., longitudinal strips of test-section wall with equal spaces between them.

Air tunnels can be made very simply of plywood on light wood fram-
ing, for scoring of the plywood on the reverse side permits it to be curved at will. Vanes for the corners are available commercially (J) or may be constructed of sheet metal formed as shown in Fig. 17. The smaller the chord of the vanes, the smaller the scale of the residual turbulence in their wake. As in any tunnel or flume, the effect of upstream disturbances can be diminished in proportion to the reduction in area between plenum chamber and test section. A four-to-one ratio is about average. A great advantage of air flow is its relative freedom from detritus, which permits very fine screens to be placed at the end of the plenum chamber to reduce the intensity of small-scale turbulence [5]. Disturbances that cannot so simply be eliminated (for example, those resulting from too rapid a divergence) can usually be controlled by means of baffles of wood strips in lattice form, to correct for velocity variation across the section, or by egg-crate or mailing-tube honeycombs for flow containing large eddies or spirals. The fan itself (B) may introduce such nonuniformities if it is not well streamlined and provided with contravanes. The fan capacity, of course, depends upon the mean air speed desired at the test section; this in turn should be considerably greater than that producing the lowest local velocity that can be measured with acceptable precision.

Flumes

One of the primary contributions of hydraulics to the fluid-mechanics laboratory is the glass-walled flume, and it continues to be indispensable

Fig.17. Details of Deflecting Vanes [4]; Tangents May Be Omitted If Desired.
in the demonstration or study of almost any phenomenon involving a continuous free surface. Experimental flumes are long or short, shallow or deep, wide or narrow, of fixed or adjustable slope, depending upon the uses for which they are intended. They can be constructed of wood, plastic, glass, concrete, aluminum, brass, steel, or stainless steel, depending in part upon probable use and in part upon funds available. Wood is often quite satisfactory, provided that it is kept dry internally by the application (and penetration) of an oil, paraffine, or plastic sealer. Finishing with a waterproof enamel or varnish after fabrication, and careful draining immediately after each use, will lengthen its useful life. Plastic (H), though expensive and popular for its workability, is actually not much better than wood in the long run, for it warps and mars rather readily; its basic advantage is that it is easily drilled, shaped, and cemented—and only when these qualities are necessary should it be used in place of other substances. Concrete (or even masonry) has its place in localities where steel is relatively unavailable, and a good workman can produce very satisfactory and inexpensive results; such structures are, of course, necessarily fixed in place for their useful existence. Though once used only for infrequent observation windows, glass is found to occupy more and more space in present-day laboratory flumes; not only are the walls often wholly transparent, but the floors are sometimes glass as well, whether for purposes of observation, smoothness, or accuracy of alignment. As a matter of fact, adhesives are now at hand which permit the construction of flumes of moderate size entirely of glass. Normally, however, the frame and head tank are of steel, the more expensive facilities advisedly using either stainless steel or stainless-clad mild steel for wetted surfaces.

For the average instructional laboratory, two flumes of radically different types will surely suffice: one that is short, deep, and fixed; and one that is long, shallow, and tiltable. The former will accommodate underflow and overflow sections that produce considerable backwater, and the latter can be used for a series of things—including the small towing facility already discussed. Absolute size is not a critical matter, and most free-surface phenomena can be reproduced effectively in flow sections only 6 inches wide or deep. However, both viscous and capillary influences increase in relative importance as the scale is reduced, and these secondary effects eventually become primary ones. On the other hand, costs and difficulties of operation increase about as the cube of the scale. The Iowa Institute has for twenty years used a flume varying in depth from 3 to 2 feet (Fig. 18), with a glass-walled length of 12 feet and a width of only 1 foot; its extreme narrowness is the only drawback, for a few additional inches would permit it to accommodate the shoulders of a
workman much more comfortably. The Institute tilting flume (Fig. 19)
is 30 feet long, 2 feet wide, and 1 foot deep, with stainless-clad bottom.
The pivot is about 5 feet from one end and a motor-driven pair of jack
screws is located about that distance from the other, with a slope varia-
tion of about 3°. The motor drive is admittedly an unnecessary—though
greatly appreciated—luxury. Hand-cranked jacks, not to mention chain
hoists or other inexpensive mechanical arrangements, are surely just as
serviceable.
Flume head tanks are usually the problem children of the facility

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family, because of the frequent necessity of calming the high-velocity inflow from a pipe having a small fraction of the cross-sectional area and often entering either laterally or discharging freely from above. Considerable trouble is saved if the supply piping and valving are made symmetrical and enlarged for at least a short distance upstream, or if the outlet is in the form of a perforated or slotted tee (also symmetrical) completely spanning the bottom of the head tank (Fig. 20). As in the case of the air and water tunnels, the size of the tank in comparison with that of the flume is an important factor. Since the free surface is often continuous from head tank to flume, enlargement must be sidewise and downwards (though, paradoxically, high-head tanks are usually put under pressure so that their height is not excessive). Stilling that cannot be accomplished by tank size—for lack of space or funds—must be made up by baffling. Crushed-rock baffles, though obviously inefficient, have long been popular. It should be noted in this regard that any baffle will make a poor flow better—but a good flow worse—and that crushed-rock baffles are good only for poor flows. Lattice screens [6] are baffles that produce a relatively small correction, but they are very effective when used in tandem. They should have a ratio of open to total area of at least 50%; otherwise the jets will coalesce unevenly and thus increase rather than reduce local nonuniformities. Their spacing should be at least eight or ten times the mesh size. Screens should be of as small a mesh as the scale of the detritus in the water will permit (the larger the scale, the longer the resulting turbulent eddies will persist, and vice versa). Honey-
combs of egg-crated sheet metal or stacked thin-walled tubing are again suitable to remove swirls or large-scale eddies.

Not far behind the problem of stilling-tank design is that of glazing. Two matters are involved: the choice of panel thickness, and the method of sealing joints. So far as the first is concerned, criteria of stiffness and of strength will lead to quite different results, and only the latter will be considered here. Structural handbooks give for the various kinds of glass the following moduli of rupture: window, 500 psi; plate, 6500 psi; semi-tempered, 20,000 psi; and fully tempered, 30,000 psi (the process of tempering plate glass adds about 100% to the cost). However, these values are for loads of short duration, and they must be reduced by 30% for a duration of 10 minutes and by 40% for a duration of 1 hour. Moreover, glass tends to become weaker with age in an unpredictable fashion. Plate-glass panels used in the Iowa Institute (⅛ inch for a 1-foot depth, ½ inch for a 2-foot depth, ¾ inch for a 3-foot depth) are overdesigned according to the foregoing values, but cracking is frequently caused by other factors than water loading (for example, thermal stresses, and deflection due to settling). Because of the latter situation, the Institute has departed from its earlier practice of using a cement mortar to form a rigid external pressure surface for the panels. This practice was initially adopted to avoid the plastic flow of ordinary window putty under load. At the time of writing, modeling clay (K) is used entirely around the edge (see Fig. 21), except for the provisional live-rubber support, since it has the advantage of minimal deformation without becoming at once rock-hard like mortar. However, it has the disadvantage, not shared by window putty or aquarium cement, of not adhering to the glass surface if the latter is slightly retracted—say by thermal contraction. The product known as 3M Sealer (L) adheres very tightly but shrinks somewhat as
it dries. Perhaps the best solution now at hand would be a substance like modeling clay on the outside and one like window putty on the inside. It is to be noted that neither should be used next to a porous surface such as unpainted concrete or wood, for this will draw out the oil and cause the remaining material to crumble.

Almost every flume should be equipped with an instrument carriage moving longitudinally on a track that can be accurately leveled (or, in the case of a tilting flume, made parallel to the bottom). The rails can be of steel (or brass) bars or angles, but by far the best are those of stainless-steel centerless-ground shafting with studs and adjusting nuts as indicated in Fig. 21b. Whereas a towing carriage must be mounted on wheels, simple brass shoes (a pair fitted to the rail on one side and a single flat one on the other) are preferable for a carriage that carries instruments. If the flume is very wide, cross rails on the carriage will permit motion of the instruments in the lateral direction as well. It is simplest, of course, to support the side walls by means of cross ties spanning the channel; however, these interfere with the free movement of the instrument carriage and can readily be eliminated by designing the vertical members of the structure as cantilevers. For best visibility through the glass walls these members should be as narrow in the longitudinal direction as proper sealing of the glass joint will permit. In this regard it is to be noted that the bottom support of the glass (Fig. 21a) should be low enough to permit unobstructed visibility of the flume bed.

Hinged head- or tailgates in a flume can be sealed at the edges by live-rubber tubing or weather stripping. Even considerable leakage at the tailgate is usually of little consequence. However, appreciable leakage at the headgate is objectionable and can be prevented by closing the lower ends of the rubber-tubing seal, inserting a tire valve in the upper joint, and expanding the seal with a bicycle pump once the gate is in the desired position. Operation of a vertical gate is most satisfactory if it slides in grooves. These are conveniently arranged between successive glass panels either by machining a steel bar that is then welded in place, or by forming such a section with three thin bars, side by side, one of which is enough narrower to provide the required depth of groove; stainless steel is recommended in either case. If the flume is short, the provision of such grooves at each panel joint is desirable, and they will be found useful for the insertion of weirs as well as gates. For complete visibility, of course, structures to be studied must be mounted at the center of a panel, and provisional methods of sealing or supporting must then be employed. In any event, bottom openings should be provided at each point that an overflow structure is likely to be introduced, so that piezometer leads do not have to be carried upward through the flow;
plugs or plates that are flush with the bed can readily be installed when the openings are not in use. Bed piezometers can be drilled either directly in the flume bottom or—to avoid corrosion of the edges—in stainless-steel plugs inserted (press fit rather than threaded) at the proper points.

**Pipe Systems**

Experimental units illustrating one aspect or another of closed-conduit flow (whether liquid or gaseous) can usually be constructed to a great extent of commercial pipe and fittings. These vary so extensively, however, that mention might well be made of available materials. They include aluminum, brass, copper, steel, stainless steel, cast iron, galvanized iron, wrought iron, flexible and rigid plastics (M), glass, asbestos cement (transite), concrete, terra cotta, and vitrified tile. Fittings are available for each, though in a variety that depends upon the material and its frequency of usage. The more common materials are also to be had in various weights depending upon the expected pressure and length of service. For low-head installations (those normally encountered in an instructional laboratory) in which ease of installation and modification is important, the use of light-weight longitudinal- or spiral-weld galvanized pipe with Victaulic-type couplings and other fittings is highly recommended for sizes above 2 or 3 inches (C). Standard-weight galvanized pipe with threaded fittings is just as practicable in the smaller sizes, but seamless brass is preferable for the more precise installations.

Comments previously made about head tanks, stilling devices, and flow measurement are quite as applicable to pipe systems as to tunnels and flumes. Nonuniformities peculiar to pipes are due usually to disturbances introduced by valves and elbows. Such effects of control valves can be avoided in most circumstances by placing them downstream from the region under investigation. Adverse effects of elbows can be greatly reduced by replacing the standard fitting with one that is vaned—not available commercially but easily fabricated in all but the smallest sizes. The pipe is simply cut on a 45° angle, rewelded to form a 90° miter elbow, and then slotted by torch to permit the insertion of a series of vanes cut from a pipe of the proper size (see Fig. 22); these are fixed in place and the elbow is simultaneously sealed by external welding. In zones of special importance such fittings as cast reducers can be replaced advantageously by machined transitions, and any residual effects can usually be eliminated by the introduction of a fine honeycomb (a selected section of a scrapped automobile radiator is quite effective).

Perhaps the most critical factor about a laboratory pipe installation is the condition of the piezometer openings. These must be precisely at right angles to the plane of tangency to the flow surface (whether in an
elbow or in the pipe itself), free from burrs, and small compared to at least the radius of curvature of the surface. While it was once thought that the error varied with the absolute diameter, and then with the ratio of diameter to laminar-film thickness, it now appears [7] that the error relative to the boundary shear is a function of the geometry and a Reynolds number consisting of the diameter, the shear velocity, and the viscosity. It was also thought that the relative error was a minimum when the depth of hole was at least twice the diameter, but the error now seems to decrease with relative depth. However, misalignment, imperfection of the edge, and asymmetry of the two ends of the hole are probably the major factors contributing to erroneous indications. A hole inclined upstream will cause a positive error, and vice versa. A burr will increase or decrease the reading, depending upon whether it is on the downstream or upstream side. And a hole that is sharp-edged at one end and rounded or beveled at the other will yield a biased indication if there are frequent pulsations, owing to a smaller resistance to flow in one direction. Burrs can be obviated by drilling against the surface of a tight-fitting metallic plug, the tapered halves of which (Fig. 23)

Fig. 23. Details of Piezometer Construction.

can be wedged together at the desired position. The tempered-steel tool shown to greater scale at the right of the figure can be used to clean (and very slightly round) any dubious edges.

Instruments

Scales and tapes for the measurement of length are readily available in a variety of forms, and mention need only be made of the fact that the
brand known as Wyteface (N) is particularly convenient for mounting on laboratory equipment. A type of linear measurement peculiar to the fluids laboratory is the indication of surface level in an open channel. This is accomplished most generally by means of a pointed shaft or hook mounted on a graduated rod which can be moved vertically relative to a zero line or vernier; contact with the surface is best observed in the reflection of a window or light. The most convenient type of drive for the rod is a rack and pinion. Such gages are commercially available (O) in ready-to-use form, or else the graduated rods can be purchased and mounted as desired. In zones of hydrostatic pressure distribution the depth can be determined by connecting a conveniently located piezometer to a manometer column or to a stilling well with point gage. Several electrical methods are available, such as the variable resistance of the liquid between two parallel wires passing through the surface, or the variable capacitance of the air space between two plates, one at the bottom of the flume and the other a short distance above the free surface; these require calibration before and after every run, but they permit the recording of rapid surface fluctuations.

For the measurement of time, the familiar stop watch with 0.1- or 0.2-second divisions will usually suffice. In some laboratories the indication of time intervals to 0.1 second with a synchronous motor and counter that can be electrically engaged and disengaged is standard practice, but this is usually an unnecessary refinement. Electronic devices such as the Strobotac (P) can be used for the measurement of frequencies or rotational speeds.

Velocity, the magnitude of which is a simple combination of length and time scales, is sometimes determined directly as such. For example, by timing a float over a known distance the average rate of displacement can be computed. More significantly, exposure of a camera for a short time interval will permit the measurement of streaks made on the film by surface floats or particles carried in suspension to indicate the local displacement in the given interval. If the illumination is interrupted intermittently by the segments of a rotating slotted disk, the film will contain a series of dashes along the path of each float or particle, from which the entire velocity field can be ascertained; use of the light from a Strobolume (P), activated by a Strobotac, will accomplish the same purpose.

There are also various indirect means of velocity indication depending upon one or another of its effects. A small propeller can be calibrated in terms of revolutions per unit displacement or, more specifically, rotational speed against linear speed. The displacement of a disk mounted on a spring or a pendulum forms the basis of a closely related device.
By far the most common is one or another type of instrument employing the Bernoulli relationship: the Pitot tube, Pitot cylinder, Venturi tube, and so on [8]. Related devices have already been mentioned for the indication of the flow rate, and the so-called velocity indicators differ only to the extent of tending to show the motion at a section of a small stream tube rather than of the gross one. The Prandtl Pitot tube (Fig. 24) is designed to yield a coefficient of essentially unity; that is, the side openings are located at the section at which the decrease in pressure around the longitudinal member is just counterbalanced by the increase ahead of the supporting shaft. Moreover, the size of the tip opening is that at which the effect of angularity on the tip and side openings is the same for angles of yaw as great as 15°; this means, however, that the tube indicates the vector magnitude rather than the longitudinal component. A Pitot cylinder for two-dimensional flow is one placed at right angles to the plane of motion and containing two (or three) piezometer openings usually 30° apart (see Fig. 25). The direction of flow is found by turning the tube till there is a zero differential reading between the two holes and then turning forward or back 15° so that one hole lies at the point of stagnation, whereupon the velocity reading is made; though the 30° opening is close to the point of neutral pressure, the tube must be calibrated for satisfactory use. Another type of direction-velocity in-

Fig. 24. PRANDTL PITOT TUBE.

Fig. 25. PITOT CYLINDER.

Fig. 26. DIRECTIONAL PITOT.
indicator is made by drilling three (or five) longitudinal holes in a short cylindrical rod, rounding one end, and setting connecting tubes into the other, as shown in Fig. 26. This is usually so mounted that rotation about the axis (or about two axes for the five-tube instrument) does not appreciably displace the point; the operation of such an instrument is somewhat like that of a three-hole Pitot cylinder and it likewise must be calibrated. Mention should also be made of the single blunt-ended hypodermic needle very frequently used as a stagnation tube; it yields the total head regardless of angularities even beyond 15°, and independent determination of the pressure distribution (say by wall piezometers, if the flow is two-dimensional) permits the velocity distribution to be evaluated by the usual calculation.

Mass measurement must proceed by virtue of one or another property of matter—mass attraction, gravitational attraction, or inertial resistance to acceleration—only the second of which is commonly used. Since a beam balance permits the comparison of the gravitational attraction exerted on the body under consideration with that on a standard body at the same location, it is actually a direct indicator of relative mass. A spring balance, on the other hand, is a direct indicator of force and only an indirect one (through the fundamental relation $M = W/g$) of mass. Weight density and mass density depend for their determination upon the measurement of volume as well as of mass or weight. The volume of a solid body of arbitrary shape can be measured by weighing it suspended in air and in water, the difference being the weight of an equal volume of water of known density; a pycnometric flask $(Q)$ contains a specified quantity of water, and its use obviates the need for suspension. Specific gravity—a misnomer, since it refers to the mass density of the substance relative to that of a reference fluid (water or air) under standard conditions—is evidently determinable from these values as a numerical ratio.

In addition to the measurement of force (or torque) by the deformation of a calibrated spring, the beam type of balance mentioned above is also applicable. Simple dynamometers for the determination of drag (and lift) can be made of either type, the force being applied at a known radial distance from a single knife-edge pivot or a parallelogram suspension being used, as indicated in Fig. 27. (In place of a knife edge, it might be noted, a brass sleeve on a taut piece of piano wire lubricated with graphite is often satisfactory.) The supporting members in such a system are either shielded or placed outside the fluid stream, or else their tare drag is separately determined. Commercially available strain gages $(R)$ can also be mounted on flexible supports that deform under the force action so that their change in electrical resistance will serve upon calibration as a meas-
ure of the applied load; for example, fixed-ended sections of clock spring, with strain gages at points of maximum bending, could be substituted for the vertical members of the parallelogram of Fig. 27. Alternatively, very sensitive transformer-type displacement indicators (S) can be mounted on elastic members such as diaphragms or bellows subject to force action. Sometimes, finally, the total force acting upon a surface is determined by integration of the measured distribution of force intensity.

Just as a total force can be evaluated by the summation of elementary values, a local force intensity is determinable as a first approximation by measuring the force acting on a small boundary element of known area. This is rather difficult mechanically, since it requires very precise mounting and balancing of the movable element. However, both pressures and shears have been determined satisfactorily in this way—the precision evidently increasing as the uniformity of stress distribution permits larger and larger portions of the boundary to be included. By far the most common method, of course, is that involving manometry. Mention has already been made of the need for care in the construction of piezometer openings, so that attention can now be concentrated on the manometer itself [9] (T).

The simplest manometer consists merely of a glass tube and a scale. The tube should preferably be straight, of clear glass and constant bore, clean, and large enough in section to be free from capillary effects. All of these criteria are obviously relative rather than absolute. Since every manometer scale must be zeroed before use, any means of eliminating capillary errors—whether cleanliness or addition of a wetting agent (U)—makes the bore size of little import so long as it is constant. So far as the scale itself is concerned, tubes are often mounted in front of coordinate paper having the desired fineness of division; the danger of damage from spilled water is only partially obviated by shellacking or varnishing the coordinate paper to a sheet of plywood or hardboard. A grid of parallel lines 0.01 foot apart can be drawn with a ruling pen and ink or thin paint.
on a panel that has been given several coats of a flat white paint, and the whole finally varnished. Still further improvement is obtained through use of a graduated (preferably Wyteface) tape, the divisions of which are sufficiently accurate to permit further precision to be gained by means of a vernier. The latter is mounted on a small spring-loaded slide (Fig. 28)

![Diagram of Simple and Differential Manometers](https://ir.uiowa.edu/uisie/41)

**Fig. 28. Simple and Differential Manometers.**

running on a bar of cold-rolled steel. A fine wire loop surrounding the glass tube, or the combination of a wire in front and a small mirror behind, or even a mirror alone with a fine horizontal line ruled in the silver coating—each of which guides the eye to the same level as the meniscus—will enable the observer to make readings with a precision of 0.001 foot. Banks of tubes can likewise be mounted in front of a large stationary mirror, and placement of the guide bar at one side (Fig. 29) or at the center will permit a single or double cantilever support for a cross-wire to extend across as many as six to twelve tubes. The final refinement is a double guide with interconnected rack-and-pinion drive at either side—the net result, of course, still being the simple indication of water-column height.

Single-column manometers of the type just described are necessarily restricted to the measurement of liquid level or pressure head relative to some arbitrary datum. There are, of course, many cases in which it is the difference between two levels or heads that is to be measured. Then, rather than make two separate readings and subtract one from the other, the manometer can be arranged to yield a single differential reading. The two water columns are placed either side of the same guide bar, separate slides are provided for each column, and the graduated scale is fixed to
one (Fig. 28) and read by vernier on the other; the scale can be rigid, but it is generally more convenient to make it of flexible tape passing around pulleys at top and bottom and spring-connected at the rear of the panel. As in all manometers, combined shut-off and drain cocks should be provided at the bottom and bleeder cocks at the top. The pressure of the air above the liquid columns has no influence on the differential reading, since it is essentially the same at each liquid surface; as a result, the mean level can be adjusted arbitrarily for convenience in reading (the differential manometer for a Pitot tube, in fact, is often placed on a gage carriage above the flume).

Because the air in the passage connecting such liquid columns changes in volume with the absolute pressure load of the liquid system, the foregoing differential pressure must always be measured as such. In a two-liquid system (for example, water and mercury) this is not true, and it is therefore necessary to measure the displacement of only one column and then multiply it by two. This presumes, of course, that the two tubes have identical bores. To minimize the error that would result from slightly dif-

![Fig. 29. Multiple Manometer.](http://ir.uiowa.edu/uisie/41)
the gage liquid is confined by the measured liquid on both sides (or if the pot is not used), but the specific gravity of the gage liquid itself if the other liquid is on only the pot side (for example, if such a mercury gage is used to measure changes in water level or pressure).

Either the liquid-air type of manometer or the two-liquid type can easily be set as accurately as one can read the normal vernier—that is, to 0.001 foot, 0.01 inch, or 0.1 millimeter. Augmentation of sensitivity is frequently attempted by choosing a gage liquid that closely approaches in specific gravity the liquid under test, but usually the anticipated improvement is offset by increased sluggishness, errors due to interfacial contamination, and difficulty of handling. Fully as much is gained by utilizing a sloping manometer to magnify the displacement of the meniscus. Instead of inclining the entire manometer (a frequent practice, but one which requires extreme straightness of tube, precision of mounting, and constancy of bore), only a small segment need be given the desired slope, and this (or the pot) is then mounted on the vertical slide; the reading is made when the meniscus coincides with a mark on the sloping segment. Use of this “zero-displacement” feature (Fig. 31) obviates difficulties resulting from variation in bore, inclination, and nonuniform cleanliness of manometer; unless the pot is large, however, the flexible connecting tube must be of sufficient cross-sectional rigidity to change only inappreciably in volume as the indicator is moved over the scale range.

Although there is a constant striving toward the measurement of smaller
and smaller liquid pressures, it is in the measurement of gas pressures
that small readings are most frequently encountered. The Prandtl type
of manometer [9] relies for its precision on the optical magnification of
an alcohol-air meniscus in a vertical tube, with a vernier reading to 1/20
millimeter. However, essentially the same results can be obtained by an
adaptation of the zero-displacement type of manometer just described
for two liquids. Methyl alcohol is used as the gage liquid (because of its
relatively low viscosity and excellent wetting properties), with a touch
of dye (such as methyl red or orange) to make it more visible. It is
actually as much the mechanical drive as the displacement of the meniscus
that is involved in the refinement of a gage of this nature; the combination
of rack-and-pinion control and either foot or inch scale with vernier is
usually limited to 0.001-foot or 0.01-inch precision, and this can be im-
proved upon only by combining a precision lead-screw control with a
fractional-turn indicator. A gage used by the Institute (Fig. 32) combines

![Fig. 32. Precision Manometer.](http://ir.uiowa.edu/uisie/41)

the worm drive of such a lead screw with a mechanical revolution counter,
the result being the direct reading of vertical displacement to 0.001 inch.
For air pressures of greater magnitude, of course, the water-air type of
manometer previously described (but now in inverted position) is ap-
propriate.

Live-rubber tubing, long the most common form of manometer con-
nection, has recently given way to transparent or translucent plastic (M),
which is of particular convenience in the detection of air bubbles. Mul-
tiple plastic tubing in clusters of as many as twenty parallel passages per-
mits ready identification of individual leads. While this type of substance is considerably less flexible than rubber, application of heat will permit it to be enlarged or otherwise deformed to an extreme degree.

The measurement of viscosity is based upon one or another flow phenomenon involving viscous resistance to deformation—generally classed as Couette, Stokes, or Poiseuille motion. Each can readily be reproduced in the laboratory with ordinary equipment, though special apparatus is on the market (Q) which permits the control of temperature and the convenient attainment of rather precise observations through use of only small quantities of fluid. Couette flow is exemplified by the Stormer or rotating-cylinder type of viscometer (or viscosimeter), but the prospective user should recall that rotation of the inner rather than the outer cylinder produces an early onset of centrifugal instability. The large quantity of liquid necessary to permit the settlement of spheres without appreciable influence of the container walls has led to the use of a relatively small tube with either calibration curves for spheres of different diameters and specific gravities, or additional tubes filled with standard liquids and spheres (or bubbles) for comparative measurements. The Hoeppler apparatus consists of a steeply inclined tube with spheres nearly as large in diameter so that the viscosity of gases as well as of liquids can be determined. The Saybolt, Engler, and similar temperature-controlled viscometers involve the timing of the efflux of a specific volume of the liquid from a small reservoir through a short tube of standardized form. Somewhat related is the simpler and cheaper Ostwald device of blown glass (Fig. 33) which is based upon the time required for the head to change a specified amount as the liquid passes through a capillary tube between two bulbs. Both types, of course, also require calibration. Because the Stormer unit does not subject the fluid to gravitational action, it measures the dynamic viscosity, whereas those involving a falling sphere or flow under a differential head indicate the kinematic viscosity.

**INSTRUCTIONAL PROCEDURES**

**Elementary Experiments**

Even the simplest of demonstration or group-exercise programs should include experiments aptly illustrating the principles of continuity, momentum, and energy, and conditions of inertial, gravitational, viscous, and elastic similarity. This can be accomplished in many ways. Indeed, laboratory exercises which are not stereotyped but vary from year to
year (or, better still, from class to class) are effective indications of the generality of the science. It has been mentioned before that time spent in devising the experiments is far more important than money spent in the purchase of equipment, and the following paragraphs have the purpose of stimulating the ingenuity of the instructor rather than providing finished directions for a specific group of experiments.

Various simple demonstrations of the basic principles are used in high-school and college physics, and some of these might well be discussed if not performed in the beginning fluids course. Most of them involve a combination of continuity and energy effects. Thus, the local constriction of a rubber tube carrying either air or water produces an increase of velocity, a decrease of pressure, and a tendency of the tube to constrict still further; complete stoppage of flow produces a reversal in trend, and the cycle rapidly repeats itself. The same phenomenon results from forcing air or water through a tube inserted in the center of one of two parallel disks; since the radial decrease in velocity is accompanied by a radial increase in pressure toward the atmospheric limit, the lower central pressure causes the disks to move together till the flow is stopped and then be forced apart repeatedly. Two light mailing tubes or balloons suspended side by side in the stream of air from an ordinary fan will produce a similar occurrence. The fan itself permits the demonstration of Pitot and Venturi effects with simple cardboard or plastic models. One of the balloons, in turn, becomes a very convenient demonstrator of the momentum principle when released as a jet-propelled body. Further experiments of this nature are described by Eck [3].

To illustrate details of the flow pattern, the Hele Shaw method (flow with dye or smoke streamers (V) between closely spaced glass plates containing the desired boundary profile) is sometimes used. A simple substitute is the water table—a very gently sloping plate of glass over which a thin sheet of water flows from a small supply reservoir (Fig. 34):
the boundary profile (for example, a foil or Venturi section) of plastic or metal is laid on the glass and a small amount of coarse potassium permanganate powder is applied with a salt shaker to show the lines of irrotational flow. Flows with separation are best demonstrated with a smoke tunnel or towing tank (Fig. 35), though it must be noted that the corresponding Reynolds numbers are of necessity very low and the patterns hence of limited significance.

Qualitative experiments like these have a very evident value, but it is their quantitative counterparts that are essential to effective instruction in an engineering course. The simplest combination of the three principles is found in a rounded orifice at the end of a pipe. A piezometer connection in the uniform approach section, and a stagnation tube in the initially almost uniform jet, will permit calculation of the rate of flow (of either air or water) and the force on the orifice plate. Ingenuity of construction would permit the latter force to be measured directly to yield the necessary check. As an alternative, the force exerted on a plate held across the jet could be measured and the check obtained by calculation. This is, in brief, the fundamental continuity-momentum-energy experiment, and it has many variants. The nozzle could be placed at the end of a duct containing a fan to supply the flow (or in the wall of a tank of water), and suspension of the unit (of known weight) on wires would then permit the net force to be evaluated from the angular displacement. Or the nozzle could follow a bend at the end of a radial duct (like one arm of a lawn sprinkler), the torque then being the measured quantity.

Careful planning will permit the foregoing to be combined with one or more of the similarity demonstrations, in case circumstances require that the number of experiments be a minimum. This is particularly easy in the illustration of inertial similarity, for the nondimensional discharge or pressure coefficient of the orifice just discussed (one form or another

Fig. 35. Karman Vortex Trail in Wake of Moving Cylinder.
of the Euler number \( [10] \) can be shown by runs at widely different rates of flow to have very nearly identical magnitudes for both. The same would be true of any section change in a pipe such that boundary geometry rather than boundary-layer growth is primarily responsible for the pressure distribution. This is, of course, the basis of the performance diagrams of most flow machinery, which can readily be demonstrated with an ordinary electric fan—preferably, but not necessarily, housed in a convergent shroud. The thrust of the fan can be indicated by wire suspension and measurement of angular displacement (Fig. 36); control of the speed by rheostat would then permit the thrust coefficient to be evaluated (and found to be practically the same) at various speeds. Comparable studies can be carried out on a pump by evaluating head and discharge coefficients under dynamically similar conditions.

Gravitational similarity is frequently illustrated by flow over weirs and under gates. The latter are the more convenient, in that a simple change in the gate opening permits a change in linear scale to be simulated and the discharge coefficient shown thereby to remain essentially constant. However, it should be emphasized that weirs and gates are not proper illustrations of devices for which the Froude number is an independent parameter, for it is usually controlled in magnitude by the pertinent geometric parameter—i.e., the ratio of head to weir height or gate opening; only for very low weirs and sills can the Froude number be changed, once the regime of gravity overflow has been exceeded, without changing the upstream depth. On the other hand, use of a broad-crested weir with well-faired upstream and downstream slopes will show a variation of the Froude number with position—a matter of significance, since (as in Fig. 37) it can be made to pass through unity over the crest. A radically different illustration is the liquid jet issuing horizontally from a tank with a free surface [10]. The Froude number is written in terms of the orifice

Fig. 36. Measurement of Fan Thrust.
diameter and the efflux velocity head. The additional relationship between the geometry of the line of total head and the jet axis and the kinematics of the flow is an excellent supplement to the basic similarity requirements.

![Fig. 37. Transition from Subcritical to Supercritical Open-Channel Flow.](image)

Now, however, the use of the Froude number is unorthodox rather than misleading. By far the most appropriate phenomenon for this purpose is the hydraulic jump (particularly one below a sluice gate, as in Fig. 38). Not only can the relative change in depth easily be shown to be a function of the Froude number, but the principles of continuity, momentum, and energy (not to mention that of relative motion) are readily applied.

Probably the simplest way of demonstrating viscous similarity is by timing the descent (or rise) of spheres of various sizes and densities in liquids of various viscosities. For true similarity it is necessary that the ratio of sphere diameter to container diameter, as well as the Reynolds number, remain the same. However, the effect of disregarding this requirement is as instructive as it is appreciable, and the two functional trends can be profitably and simply evaluated [11]. Three glass jars from 3 to

![Fig. 38. Profile of Hydraulic Jump Below a Sluice Gate.](image)
10 inches in diameter and about 12 inches in depth can readily be contained within a water bath (for constancy of temperature) consisting of an ordinary aquarium; either three different colorless mineral oils (W) or water and two oils, and an assortment of spheres of lead, steel, glass, and plastic will permit a range of Reynolds numbers from 0.001 to 1000 to be investigated (Fig. 39). For ease in timing, two sets of horizontal wires a fixed distance (say 6 inches) apart should be mounted at the front and rear of the tank, and a sheet of rear-lighted tracing paper used as background. Spheres are best released by tweezers (below the surface, to avoid air entrainment) and recovered in groups with a screen basket resting on the bottom.

A somewhat indirect though nonetheless instructive means of investigating viscous similarity is that of comparing measurements on the resistance of a smooth pipe with the Prandtl-Kármán equation for \( f \) as a function of \( R \). With little more than the usual student care, test data can be obtained that reproduce the functional curve quite satisfactorily. Much can be gained, however, if the facilities are not limited to a single pipe and a single fluid. Rather, various sizes of pipes, from fine capillaries to ducts commensurate in diameter with the length that can be accommodated, and fluids including air, water, and at least one oil (W) should be at hand. It is not intended that each group use more than one such facility, but that the results of various groups be shown to fit different parts of the
same relationship. Careful combination of pipe size and fluid will permit not only very small and very large Reynolds numbers to be attained but also several that straddle the critical (Fig. 40). In the latter connection,

![Graph](http://ir.uiowa.edu/uisie/41)

Fig. 40. Measurements of Resistance to Uniform Flow in Pipes.

it should be remarked that the free liquid jet at the end of a pipe—see Frontispiece—provides a far more convenient and effective means of demonstrating the onset of turbulence [12] than the so-called Reynolds apparatus.

Somewhat of an orphan in this series—but nonetheless relevant—is the pipe fitting. Though flow through it is essentially free from viscous (and gravitational) effects, which makes it properly an example of inertial similarity, it is perhaps more instructive to show again by means of it, while dealing with viscous similarity, that form effects often obliterate those of viscosity. A small (1- or 2-inch) line can readily be assembled to include an abrupt inlet, enlargement, contraction, diaphragm orifice, bend, valve, tee, and submerged and free outlets. A sufficient number of appropriately located piezometers (at the midpoint and end of each uniform reach between fittings) with leads to a petcock manifold and manometer, together with a triangular-weir tank or other means of flow measurement, will yield sufficient data to permit plotting the lines of total and piezometric heads and calculating loss and discharge coefficients for the fittings. The truly instructive unit, however, is one consisting of
two parallel systems, the fittings in the one involving abrupt changes in section and those in the other being streamlined. The vast difference in flow characteristics makes an impression that is not soon forgotten.

Because of their rather slow inclusion in the curriculum of fluids courses, demonstrations of elastic effects in terms of the Mach number will still seem foreign to many instructors of the subject. Studies of flow at supersonic speed, moreover, are known to involve rather complex and costly equipment. Fortunately, several elementary experiments can be rather simply planned and equipped. The very simplest demonstration of an elastic phenomenon lies in the generation of a sound wave and the measurement of its celerity of propagation—preferably in both air and water. Sonar gear has seen many refinements since the war, marine fathometers now have their laboratory versions, and other items as well can be adapted to experimental purposes. However, their use under otherwise stagnant conditions does not take advantage of the added interest of propagation in a moving medium [13]. With some ingenuity the generating and receiving elements can be mounted in a pipe or duct (preferably receivers equal distances upstream and downstream from the sender) so that—at least in air—the added effect of flow can be shown. On the other hand, installation of a quick-acting valve at the end of such a pipe or duct will permit the pressure and celerity of a water-hammer wave to be determined, a sensitive pressure recorder (X) now being necessary in place of the sonar type of device. To avoid the secondary effect of the boundary elasticity it is suggested that a heavy-walled pipe be used; effects of resistance and energy dissipation can also be ignored in the basic course, with only the initial pressure rise considered.

Three phenomena already discussed in connection with inertial, gravitational, and viscous similarity can also be adapted to the illustration of elastic effects as well, to great pedagogical advantage. The combination with viscous resistance is effected by use of a relatively long metal pipe of small diameter through which air is passed at such a rate that the density will change appreciably from end to end. The flow may be produced by supply from a pressure tank at one end, to a vacuum tank at the other, or both together. In any event, pressure measurement at successive sections will indicate a continuously variable Mach number yet a constant Reynolds number and a correspondingly variable resistance yet constant resistance coefficient. As the difference in pressure between the two ends is steadily increased, the Mach number will approach unity at the downstream end, and thenceforth only the pressure at the upstream end will control the flow. Recourse to the inertial phenomenon of efflux from a well-rounded pipe orifice (preferably at small scale) permits the replacement of the foregoing condition of isothermal flow with an equally
instructive case of adiabatic flow. As the pressure drop is increased, a condition of sonic flow is eventually established at the parallel section of the outlet. Thereafter the external pressure will have no further effect on the rate of efflux. Continued increase in the base pressure will cause the efflux rate to increase, but without exceeding the sonic velocity, by virtue of the continued change in jet characteristics. The constancy of the Mach number (essentially unity) can readily be verified quantitatively by measuring the jet pressure, jet temperature, and efflux rate. The gravitational phenomenon of significance is the passage of water over the low, broad-crested weir already mentioned (Fig. 37). With depth replacing pressure, it represents the direct counterpart of the sonic effects just described, for the flow attains the critical (i.e., gravity-wave) celerity with a Froude number of unity at the contracted section, and the conditions downstream have no further influence so long as backwater greater than the critical depth does not occur.

Intermediate Experiments

Essentially all of the phenomena described in the foregoing section are subject to the one-dimensional type of analysis, and the relatively simple observations involved render them suitable to the "quantitative-demonstration" type of exercise. Herein either the instructor or a selected member of the class performs the experiment before the others, calling out the readings for them to record and subsequently analyze. Such a method is not, to be sure, preferable to the performance of tests by small groups, but in circumstances of large numbers and limited time and space it is an acceptable substitute, at least in the elementary course. In the intermediate type of course—that in which the students go well beyond the basic concepts—it is essential that they handle the equipment and carry out the measurements themselves in groups of two or three. Many of the following experiments will be seen to involve much the same equipment as before, but it is now the details of the flow pattern rather than their one-dimensional approximation that receive the major attention. These are, it should be understood, replacements for the elementary experiments rather than merely supplements, for they contain everything that is of importance in their simpler counterparts.

The situation under discussion is best illustrated by the orifice and deflected jet previously discussed. Now, however, it is not the average conditions over the cross section that are of interest but their spatial variation. The force on the orifice plate is evaluated by integrating the measured pressure, determined from a series of well-placed piezometers, over the plate surface, for comparison with the computed value. The force on the deflector plate (preferably inclined or even curved) is likewise ob-
tained by integration of the measured pressure distribution (ignoring, to be sure, the relatively small contribution of the viscous shear). By far the best, however, is the use of a two-dimensional orifice (i.e., a slot) spanning two parallel walls of glass or plastic. It is now possible [10] to construct the corresponding flow net (or at least interpret a net furnished by the instructor), to measure the pressure distribution through the jet in the plane of the slot, and then to compare the velocities thus indicated and integrate to check the measured rate of flow. Such a procedure is highly recommended at some part of the course, although it may be introduced if preferred in connection with other equipment.

If a water tunnel is available, a somewhat similar sort of exercise can be performed—without a continuous free surface, to be sure, but with the possibility instead of introducing cavitation. The two-dimensional profile may be in the form of a rounded orifice, a Venturi throat, a streamlined strut, or many variants thereof. It is preferable that the profile be sufficiently well streamlined for the flow net to indicate both an extensive zone of approximate irrotationality and some departure therefrom because of separation. One transparent wall should contain a series of piezometers (see Fig. 41) yielding at least centerline and boundary pressure distributions (a petcock manifold and a single Bourdon gage permitting the most rapid measurements). The best sequence of runs is one at high pressure, one at the point of incipient cavitation, and two at successively more severe stages—all at the same rate of flow. The most in-
structive handling of the data is the preparation of a series of nondimensional pressure diagrams (Fig. 42) for comparison with that obtained from the flow net itself.

Whereas these two experiments are specifically planned to illustrate the continuity-momentum and the continuity-energy relationships for curvilinear flow, further illustrations are obtained repeatedly in experiments actually intended for other purposes. Two of these might well be introduced at this point, however, because of the fundamental nature of the principles involved. One is the submerged jet—water in water or, more conveniently, air in air. The fact that the pressure is nearly hydrostatic throughout the zone of turbulent diffusion renders the momentum principle very simply applicable: beyond the zone of flow establishment all velocity-distribution curves (see Fig. 43) can be shown to be similar in form, so that integration of the momentum flux will yield the same value at every section [14]. Integration of the increasing volume flux will show the rate of lateral entrainment, whereas that of the decreasing energy flux will show the rate of energy loss. An air jet, a stagnation tube, and a manometer are the only equipment needed for this very instructive exercise. The other experiment requires an air (or water) tunnel of sufficient length to permit the wake of a cylinder to be traversed with a stagnation tube [15]. From the resulting velocity distribution the change in

Fig. 42. **Pressure Measurements at a Constriction for Successive Stages of Cavitation.**

http://ir.uiowa.edu/uisie/41
momentum flux, equal to the force on the cylinder, is evaluated. The experiment is completed, if no dynamometer is available, by measuring and integrating the pressure around the cylinder to obtain the corresponding force (a single piezometer on a cylinder that can be rotated through 360° simplifies this aspect of the equipment).

The role of gravity in free-surface flow is best shown in the glass-walled flume by means of an underflow or overflow structure—a sluice gate, sharp-crested weir, or one or another of their variants. Either the gate or weir should be provided with piezometers over its face, and there should be means of continuing the pressure measurements through the flow in the same plane (most simply, with wall piezometers; alternatively, with a thin disk held tight against the wall by a metal piezometer tube sliding in the gate slot and connected to a hole in the center of the disk). Measurements involve the surface profile and pressure distribution; the evaluated velocity distribution (Fig. 44) is compared with that for the flow.
net and used to compute the integral of volume flux $q$ to compare with the measured discharge or that of momentum flux $m$ to compare with the pressure integral. In the case of the ventilated weir, calculation of the height of backwater under the nappe necessary to produce the measured nappe deflection provides a significant value to compare with that observed. If an ogee spillway is used for the study, comparison of the measured pressure distribution around the bucket to that required for equilibrium with the measured velocity change is both informative and convincing.

Wave experiments, an essential part of gravitational phenomena, can be arranged in a variety of ways depending on the facilities available. The solitary wave can be produced in a long flume of standing water simply by lowering a concrete block nearly as wide as the flume into the water; the speed of lowering and the immersed volume of the block control the amplitude and the superposed volume of the wave. If the end of the block (like the other end of the flume) is plane and vertical, the wave can be permitted to pass back and forth repeatedly and its change in celerity with relative amplitude determined. A hinged wall spanning the flume and driven by a motor in simple harmonic motion (see Fig. 19) will permit oscillatory waves to be studied in place of the solitary, but a gently sloping, permeable beach must be installed at the opposite end.

Fig. 45. Above: Hydraulic Jump in Water under Air. Below: Hydraulic Jump in Dyed Salt Water under Clear Fresh Water.
to absorb the wave energy and minimize disturbances due to reflection. The change in celerity with relative depth, wave length, and amplitude can now be determined. To study the surge the flume must be connected to either a large forebay or a pumping system. The surge can be formed in various ways: by suddenly admitting water to a stagnant pool; by suddenly changing the rate of inflow to a uniform stream, say by altering the setting of a head gate; or by suddenly changing the rate of outflow, with a tailgate. Because depths and velocities will change continuously as the surge advances along the channel, observations must be made at sections fairly close together; however, the results should agree quite satisfactorily with those obtained from the hydraulic-jump equation by the principle of relative motion. If at all possible, one or more of the foregoing phenomena should also be produced at the interface between fresh and saline water (as in Fig. 45) to illustrate the role of the effective gravitational acceleration $g' = g \frac{\Delta \rho}{\rho}$ [10].

Adaptation of the elementary pipe-flow experiments to the intermediate course involves primarily the addition of velocity traverses at various Reynolds numbers. This requires only a stagnation-tube traversing mechanism at the end of the pipe (Fig. 46), for the corresponding pressure can be determined by extending the line of piezometric head. The resulting data are used for both discharge integrals and shear gradients. Although the elementary exercises should be limited to smooth pipes, it is desirable in the intermediate series to include either a natural or an artificial roughness—preferably one which can be reproduced to the same absolute
degree in two different pipe sizes—say ½ inch and 2 inches (refer to Fig. 40); velocity traverses might well then be made in both smooth and rough pipes of the same diameter at the same Reynolds number.

Boundary-layer measurements should also be included in the intermediate grade of laboratory course. The most straightforward boundary-layer study, to be sure, involves simply a smooth flat plate in an air- or water-tunnel test section that is either open or slightly flared to maintain essentially zero pressure gradient. However, an even more effective experiment can be accomplished in a uniform section of 10- or 12-inch air duct with rounded inlet connected to the suction side of a centrifugal fan. Not only is the expanding boundary layer along the wall directly observable by stagnation-tube traverses at successive sections, but the accompanying longitudinal pressure drop observable with wall piezometers can be correlated instructively with the measured displacement thickness of the boundary layer and the computed acceleration of the central core of the flow. Essentially the same exercise (though without the benefit of velocity traverses) can be performed at the rounded inlet of a 1-inch pipe containing a light oil (one of the resistance units already discussed) if piezometers are suitably placed along the initial zone of establishment. The longitudinal variation of piezometric head (and total head), in terms of the velocity head, will be a unique function of the Reynolds number (see Fig. 47) so long as the latter does not exceed the critical; the coefficient

![Fig. 47. Establishment of Flow at a Pipe Inlet.](http://ir.uiowa.edu/uisie/41)
of entrance loss can be evaluated and the length of the zone of establishment shown to vary systematically from a fraction of a diameter to many hundred diameters.

Mention has already been made in this section of the indirect measurement of drag in an air (or water) tunnel through the integration of pressure measurements on a cylinder. This method is to be recommended for a variety of profile forms that produce separation: a thin plate, an elliptical cylinder, and a streamlined foil, among the two-dimensional bodies; and a disk, a sphere, and a streamlined body of revolution, among the axisymmetric. (The infinite limit of two-dimensional forms can be simulated, it should be noted, either by causing them to span the fixed boundaries of a stream or—as in Fig. 27—by placing thin disks perhaps twice as great in diameter at their ends to minimize three-dimensionality of the flow; otherwise any desired aspect ratio can be studied, whether in half or full section—i.e., one or both ends being free). Although a single piezometer can no longer be brought to various points around the circumference by rotating the profile, it is usually feasible to place piezometers at enough key points to permit a satisfactory plot of the pressure distribution to be made (plotting pressure—or $2\pi rp$, for axial symmetry—in the longitudinal direction from the body profile permits the longitudinal force component to be obtained directly by integration). Mounting an elliptical cylinder on springs of the proper elasticity (for the given mass and test velocity) permits a striking demonstration [16] to be made of the oscillating cross thrust in connection with the foregoing drag experiments: with the major axis of the cross section horizontal, the oscillation is held to a minimum through self-damping; but if the cylinder is rotated through 90° the movement will be amplified “catastrophically”—or at least as much as the mounting will permit.

Unfortunately, without a dynamometer the influence of viscous shear cannot be investigated. Although the foregoing studies of form effects are perhaps more important, and though an indication of viscous action can be obtained if the Reynolds number for the sphere is made to pass through the critical (or if boundary-layer turbulence is induced by surface roughness), it is quite desirable that drag measurements be made independently for comparison with pressure-distribution evaluations. Fall-velocity measurements in water and viscous oils—and perhaps also in air—should now be extended to other forms than spheres (disks and streamlined bodies of revolution [17]). However, instructive as these may be at low Reynolds numbers, they cannot easily be carried high enough to replace dynamometer indications in an air or water tunnel. Even the simplest of dynamometers (a wire-parallelogram suspension indicating
through angular deflection against gravity) is far preferable to none at all.

Qualitative studies of the effect of circulation can be made by observing surface patterns in a small towing tank, whether for a rotating cylinder or (Fig. 48) a simple foil. With an air-tunnel dynamometer of sufficient flexibility, of course, both lift and drag measurements can be conducted on the rotating cylinder at various relative speeds. On the other hand, even the simple dynamometer just recommended for drag studies will also serve for determining the lift as well as the drag of a foil. If the thin, longitudinal plate on which the foil is mounted is so suspended as to deflect in one plane only (see Fig. 49a) measurements of drag versus angle of attack can first be made with the plane of deflection parallel to the air stream, and the unit then turned (Fig. 49b) till the plane is normal to the stream for the corresponding series of lift indications. The results are best plotted to form a polar diagram—that is, $C_L$ versus $C_D$, with angle of attack as parameter. However, unless some imagination is used in the selection of foil profile and in the variation of profile and aspect ratio from one class or group to another, such dynamometer experiments are not far removed from the calibration category. Therefore, no foil experiment should be considered complete without direct measurement of the pressure distribution (by means of piezometers set into the foil surface) and calculation therefrom of at least the lift for comparison with the dynamometer indications.

Without rather special equipment, it is more difficult to raise fluid-machinery experiments out of the calibration category. Nevertheless, if imagination is again drawn upon, the addition of a small variable-speed motor to the simple dynamometer just discussed will permit a most instructive series of studies to be made upon a propeller having elements patterned after the foils previously investigated. Even if the dynamom-
eter is of the very simple one-component type that must be turned through 90° to yield a second component, the lift position will permit the torque to be measured almost as readily as the other position will yield the thrust. Step application of the blade-element theory will permit the thrust and torque coefficients to be approximated for comparison with measured values. The use of flat blades of adjustable pitch will make it possible for still another aspect of the theory to be checked in first approximation.

Intermediate experiments on the effect of fluid elasticity can fruitfully extend the water-hammer measurements to include the additional effects of pipe elasticity and resistance to flow. Such other factors as the influence of section changes, branches, and air chambers, and—in particular—the occurrence of cavitation downstream from a quick-acting valve are worthy of consideration. If a supersonic air tunnel is available at least for demonstration purposes, the basic relation between Mach number, profile form, and shock-wave generation can profitably be observed. If no such facility is at hand, essentially the same relation can be shown by means of the gravity-wave analogy (Fig. 50) on a water table similar to

![Diagram](http://ir.uiowa.edu/uisie/41)

Fig. 49. **Adaptation of Simple Dynamometer to Indicate Lift As Well As Drag.**

that suggested for the demonstration of irrotational-flow patterns: a glass plate that can now be given sufficient slope (actually only a few degrees) to produce supercritical flow at moderately small depth; the boundary profiles are formed of metal and simply laid on the glass as desired. For the intermediate series of experiments the observations might best be limited to qualitative ones involving wave generation, reflection, and su-
perposition at various Froude numbers. For the advanced series, the experiment might be extended to quantitative verification of the method of characteristics, in departments where this is taught.

Advanced Experiments

So extensive are the possibilities of devising experimental studies for graduate students specializing in the subject, and so greatly does the choice of direction depend upon the available facilities and current activities of the particular laboratory, that only a half dozen suggestions are given at this point. These, on the other hand, are almost mandatory, since they embody the very essence of advanced experimentation.

The first of these is the construction of the pattern of streamlines from a series of velocity measurements—for two-dimensional flow around or through a simple boundary configuration, at the very least, but preferably for axisymmetric flow (see Fig. 51) past a boundary that produces separation. The use of axial symmetry emphasizes the role of the annular element of cross section, and the zone of separation illustrates the distinction between the fields of primary and secondary flow. In any event, the evaluation of the flow rate by integration of the velocity data, and the subsequent spacing of the stream surfaces to enclose increments of flow that are equal or systematically varied, will give an appreciation for the stream function that can be acquired in no other way.

The second in the series is the determination of the velocity potential, and thence the velocity and pressure distribution, for a case of irrotational flow in three dimensions. There are several optional ways of proceeding: use of an electrolytic tank shaped like the flow passage to be studied is the most common; however, the electrolyte can be replaced by a solid conductor—or even by a bed of porous material. Of most general interest
would be the transition from a reservoir to a conduit of square or triangular cross section. The nonconducting tank boundaries would then be shaped just like the walls of the transition (but closed at either end), and current would be passed through the conducting liquid (an aqueous solution, say, of copper sulfate) between a hemispherical terminal (of copper screen) in the reservoir and a plane terminal in the conduit; the change in electrical potential could be measured either with wire electrodes mounted permanently in the boundaries or with an insulated probe on a traversing device, the exposed tip of which could be placed at desired locations within the bath. The solid conductor—made of a substance like carbon—would be handled in much the same way, except for the fact that only surface measurements could be made. The percolation analogy would also require a tank, filled now with a uniform sand and provided with boundary piezometers, the potential gradient of a flowing gas or liquid being proportional to that of pressure or piezometric head. (It should be noted that in the case of symmetry [15] only one of the repeating parts need be reproduced—say one-eighth of a passage of rectangular cross section.) In each instance measurement of the relative change in potential per unit distance in the desired direction will yield the relative velocity in that direction. Not only will due care result in satisfactory accuracy of measurement, but comparison (and explanation) of the pressure distributions along the edges of the transition and the median lines of symmetry for various degrees of curvature will prove most beneficial.

Fig. 51. Pattern of Streamlines [18] at the Nose of a Blunt Cylinder.

A third, but somewhat less definite, experiment is one which combines viscous and inertial effects that play mutually opposing roles as laminar flow becomes unstable. The usual transition to turbulent flow in a pipe is both hackneyed and inconclusive—the latter because of the difficulty in controlling quantitatively the disturbance that leads to the breakdown. Much the same situation prevails in the case of the boundary layer, at least so far as the instructional laboratory is concerned. However, develop-
ment of the Taylor type of instability [19, 15] is only a step removed from the actual formation of turbulence, and it is a phenomenon that is readily reproduced. If a cylinder is made to rotate at constant speed in a container of liquid (preferably a light oil), a secondary flow will develop once the Reynolds number becomes sufficiently great for inertial effects of a centrifugal nature to set in. (At this point it might well be noted that the flow patterns obtained in paint or oil applied to fixed boundaries in zones of nonuniformity reveal the same sort of viscosity-inertia interplay—but in the boundary layer rather than in the flow as a whole as is sometimes falsely assumed.) So long as the depth and radius of the container are of about the same magnitude, a single ring vortex will form, as can be seen by the addition of dye. A considerable increase in depth or decrease in annular clearance will cause a series of Taylor vortices, alternating in sense, to appear. Inflow at one end of the container and outflow at the other will result in a multiple spiral formation. The use of two parallel cylinders in a container permits a series of related occurrences to be studied. Rotation in the same direction will produce a doubling of the foregoing pattern with a further tendency toward instability. Rotation in opposite directions will result in the production of a jet, the free stream surfaces of which will illustrate the rolling up of a vortex sheet. Ingenuity in planning will permit numerous variations of the foregoing basic effects to be carried out, and still further thought will carry them from the qualitative realm into the quantitative.

Fourth in the series is the measurement of turbulence. This is best carried out in the air jet previously used for the measurement of mean-flow characteristics. Unfortunately, the hot-wire anemometer [20] (Y) is usually not only expensive but almost the only instrument capable of re-

Fig. 52. Characteristics of Turbulence in the Jet of Fig. 43.
sponding to high-frequency velocity fluctuations with sufficient rapidity. However, a satisfactory unit for instructional purposes can be made much more cheaply than one for research, and through its use such quantities as the root-mean-square of one component (the intensity) and the mean product of two (the shear) can be obtained with sufficient accuracy. In the simplest experiment radial traverses at different longitudinal distances from the nozzle or at different efflux velocities would be used to show (Fig. 52) that the condition of similarity prevails in the secondary pattern as in the primary [21]. In a considerably more sophisticated analysis the mean-flow and turbulent-flow data could be used to calculate each of the terms in the mean-flow energy equation [18] with the goal of showing that they are indeed in balance.

Equally instructive is a fifth advanced experiment, but this can be carried out with the most commonplace of equipment. A sluice gate in a flume with a plane bottom is used to produce a smooth sheet of high-velocity flow which expands as the developing boundary layer retards the flow above. Measurements of the surface elevation with either point gage or floor piezometers and of the velocity distribution with stagnation tube at successive sections (see Fig. 53) will then permit the boundary-

![Fig. 53. Boundary-Layer Development Below a Sluice Gate.](http://ir.uiowa.edu/uisie/41)

layer thickness, displacement thickness, momentum flux, energy flux, bed shear, and loss of head to be computed and shown to satisfy the detailed continuity, momentum, and energy equations.

The last of this series, while almost the most important in the broad sense, must remain the most indefinite. Cases of unsteady flow have been examined heretofore only under rather restricted conditions—that is, either those in which no nonuniformities occur, or else those which can be reduced to steady flow by the principle of relative motion. The advanced
student should be faced at some point with conditions that are less restricted, but these are usually either so complex or so difficult to instrument that—aside from general suggestions—they must be left to the instructor to devise as the situation permits. Historically, the damping of a solitary or standing wave with distance or time is one of the earliest inherently unsteady effects to be measured, though only recently have the results been properly analyzed [4, 22]. A step beyond simple water hammer or flow establishment is the damped pendulation in U-tubes of liquids covering a sufficient range of viscosity for the damping to vary from a secondary to the primary effect [4]. Closely related is the establishment of the terminal velocity of fall of various bodies; however, since this can require only a few diameters, the matter of instrumentation is a difficult one for the instructional laboratory. Less complex, but perhaps also less significant, is the drag of an immersed body of elementary form mounted on a pendulum having little drag itself but a considerable moment of inertia; the resistance is evaluated from the gradual reduction of amplitude of swing (the mean drag coefficient, it should be noted, becomes surprisingly high as the angular displacement decreases, due to the residual effect of the previous wake). Also instructive is the vibration of a cylindrical body in an ambient flow of constant velocity, as exemplified by a taut wire in a stream of air or water [2]. Whatever the choice may be, it is probably here that the ability that has been acquired by the instructor to devise a worthwhile experiment will be put most effectively to the test.

ACKNOWLEDGMENTS

Early outlines of the foregoing manuscript were discussed in detail with Mr. Arthur Toch, Research Engineer of the Institute, who had been invited to be a coauthor but was prevented from actively participating by a serious illness. Later versions of the manuscript were critically reviewed by Dr. E. O. Macagno, Research Engineer and Assistant Professor of Fluid Mechanics. Professor J. W. Howe, who as Head of the Department of Mechanics and Hydraulics has remained a staunch supporter of the writer's efforts from the time of the first laboratory revision in 1940, also read both manuscript and proof. The majority of the photographs used as illustrations were made by Mr. James A. Kent of the University Photographic Service. Experimental data appearing in the figures were taken from student reports. In addition to the writer and Messrs. Toch and Macagno, those who have had a part in the laboratory instruction at Iowa during the past two decades include Messrs. D. W. Appel, T. J. Carmody, C. G. DeHaven, E. M. Laursen, D. E. Metzler, and T. E. Strelkoff, each of whom left his mark upon either equipment or procedure. Through most of this period the construction and maintenance of the Iowa equipment have been the responsibility of Mr. D. C. Harris, Shop Supervisor of the Institute.
REFERENCES


SUGGESTED VENDORS OF LABORATORY EQUIPMENT AND SUPPLIES

A. Equipment of this nature has been fabricated according to Institute designs for a number of American and foreign laboratories by the Hawkeye Company, 1807 Rockingham Road, Davenport, Iowa, under William F. Bieg, proprietor.


C. Light-weight piping and fittings are supplied by the Naylor Pipe Company, 1230 E. 92nd St., Chicago, Illinois; Taylor Forge & Pipe Works, P.O. Box 485, Chicago; and Steel and Tubes Division, Republic Steel Company, 224 E. 131st St., Cleveland Ohio. Special fittings are made by the Victaulic Company of America, Elizabeth, New Jersey.

D. Prior to the war the apparatus described in the Bruno Eck book [3] was manufactured by a German firm; the writer was recently assured by Professor Eck (Geisbergstrasse 24, Köln-Klettenberg, Germany) that plans were being made to resume fabrication. Equipment of a similar nature, as well as many other laboratory items, is produced by the Ann Arbor Instrument Works, 725 Packard St., Ann Arbor, Michigan.

E. Variable-speed drives are made by the American Blower Corporation, Detroit, Michigan; U.S. Electrical Motors, Inc., Milford, Connecticut; and Vickers Incorporated, Detroit, Michigan.

F. Closed-circuit water tunnels (as well as other special items of equipment) are available in several sizes from Kempf & Remmers, Danzigerstrasse 35a, Hamburg, Germany.

G. Propellor pumps with especially low susceptibility to cavitation are manufactured by the Peerless Pump Division, Food Machinery and Chemical Corporation, 2005 Northwestern Ave., Indianapolis, Indiana.

H. Clear plastic (methacrylate resin) is available in sheets of various thicknesses under the trade name of Plexiglass or Lucite from Cope Plastics, 1157 So. Kingshighway Blvd., St. Louis, Missouri. Chloroform is a solvent and may be used (preferably applied with a fine hypodermic needle) to join finished surfaces.

I. Air tunnels (as well as pertinent equipment) for the instructional laboratory are made in several sizes by the Aerolab Supply Company, 3411 Chatham Road, Hyattsville, Maryland, and by the Ann Arbor Instrument Works (D).

J. Corner vanes can be obtained under the trade name “Ducturns” from Tuttle & Bailey, New Britain, Connecticut.

K. By far the best modeling clay known to the writer is made by Harbutt’s Plasticine Limited, Bathampton, Bath, England, and is available in America from the firm of J. L. Hammett Company, 290 Main St., Cambridge, Massachusetts.


M. Plexiglass or Lucite pipe is available in diameters from ⅛ to 6 inches from Cope...
Plastics (H). Transparent plastic tubing for piezometer leads can be obtained in the multiple form known as "Stripatube" from Jessal Plastics, Inc., Kensington, Connecticut.

N. Wyteface tape is supplied in ¼ - to ½-inch widths by the Keuffel & Esser Company, 520 South Dearborn, Chicago, Illinois.

O. Point and hook gages of various lengths are manufactured as follows: with rack-and-pinion drive, by the Lory Company, Davis, California; with friction drive, by Leopold and Stevens Instruments, Inc., 4445 N. E. Glisan St., Portland, Oregon; and with limited screw drive by Keuffel & Esser (N).


Q. Laboratory equipment of this nature can be obtained from the Chicago Apparatus Company, 1735 N. Ashland Ave., and the Central Scientific Company, 1700 Irving Park Road, both of Chicago, Illinois.

R. Strain gages with a wide range of characteristics are sold by the Baldwin-Lima-Hamilton Corporation, Waltham 54, Massachusetts.

S. Sensitive differential transformers are a specialty of Schaevitz Engineering, P.O. Box 505, Camden, New Jersey; they are also made by the Sanborn Company, Waltham 54, Massachusetts, whose specialty is recording galvanometers.

T. Manometers of various types are supplied by the F. W. Dwyer Manufacturing Company, Michigan City, Indiana; the Flow Corporation, 85 Mystic St., Arlington, Massachusetts; the Dynametrics Corporation, Burlington, Massachusetts; and Kempf & Remmers (F).

U. A useful wetting agent is Photo-Flo Solution sold by the Eastman Kodak Company, Rochester, New York.

V. For infrequent use as a tracer in low-velocity air flow, smoke from a cigarette or smoldering rag will suffice. The combination of acid and ammonia fumes is sometimes used, and a few drops of titanium tetrachloride will yield a very dense smoke; these are both highly corrosive, however, and the air-smoke mixture must be discharged outside the laboratory. Smoke-producing units involving the vaporization of oil are available commercially (I). The best dye for use in water is ordinary food coloring; it is concentrated, comes in various colors, is not much denser than water, and can be made neutrally buoyant by the addition of alcohol. Potassium permanganate has the advantage of changing composition after use and thus leaving the laboratory water uncolored.

W. Mineral oils of various viscosities, when used in small quantities, can be of the medicinal quality obtainable from a wholesale druggist. The grade used for the Frontispiece experiment is sold by the Standard Oil Company under the name "Eureka White" with a viscosity about fifteen times that of water. Glycerine-water mixtures yield a thousandfold variation in viscosity, but they attract atmospheric moisture and seep through the finest cracks. The glycols (automobile antifreeze is one) are nonseepers and—like the silicones—provide a large viscosity range.

X. For information on pressure cells write to Statham Instruments, Inc., 12401 W. Olympic Blvd., Los Angeles, California, or Consolidated Electrodynamics Corporation, 1025 E. Green St., Pasadena, California.

Y. Hot-wire anemometers of the constant-current type are manufactured by the Flow Corporation, Arlington, Massachusetts; and of the constant-temperature type by the Hubbard Instrument Company, Iowa City.
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Bulletin 33. "Third Decade of Hydraulics at the State University of Iowa," edited by M. C. Boyer, 1949. 84 pages, 8 figures, price $0.50.


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