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Model Tests Using Low Velocity Air

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WITH DISCUSSION BY
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MODEL TESTS USING LOW VELOCITY AIR

By James W. Ball,[1] A. M. ASCE

With Discussion by Messrs. David W. Appel and James W. Ball

Synopsis

The use of low velocity air in testing closed hydraulic systems, or testing in which air can be substituted for water without introducing any appreciable error due to compressibility, is discussed. The advantages, disadvantages, errors to be expected, and cautions to be observed when the hydraulic engineer employs this method of testing are also introduced.

Introduction

For the purpose of this paper, low velocity air tests will be considered, those that yield, for all practical purposes, the same results as hydraulic tests. Low air velocities usually range up to about 250 ft per sec or about 25% of sonic speed, depending upon the nature of the particular problem.

History of Air Testing.—Air testing, or aerodynamic testing as it is commonly termed, is not new, but the technique of using low velocity air as a fluid to obtain solutions to hydraulic problems is a new development. References[2,3,4] to aerodynamic testing are found in the early part of the twentieth century, but these references usually pertain directly to aircraft research or to fluid mechanics research and not to testing of the type under discussion in this paper. In this early research work the experimental data from tests using different fluids, including air and water, were combined to illustrate a fundamental law or principle rather than to prove that air could be substituted for water in determining the flow characteristics of hydraulic systems. Low velocity air testing is now being used in solving problems of this nature. Among the first to make use of this method, and a pioneer in this field, was C. Keller. Some of Mr. Keller's work was published as early as 1937, and in 1939 he was co-author of an

Note.—Published in June, 1951, as *Proceedings-Separate No. 76*. Positions and titles given are those in effect when the paper or discussion was received for publication.

[1] Hydr. Engr., Bureau of Reclamation, U. S. Dept. of Interior, Denver, Colo.

[2] "Wind Tunnels," by Ludwig Prandtl and Oskar G. Tietjens, *Applied Hydro- and Aeromechanics*, McGraw-Hill Book Co., Inc., New York, N. Y., 1934, pp. 252–265.

[3] "Similarity of Motion in Relation to the Surface Friction of Fluids," by T. E. Stanton and J. R. Pannell, *Philosophical Transactions of the Royal Society of London*, Series A, Vol. 214, 1914, p. 199.

[4] "The Reynolds Number," by Boris A. Bakhmeteff, *Mechanical Engineering*, Vol. 58, 1936, pp. 625–630.

article on air testing of turbines.[5] In the same year another article,[6] which cited some of Mr. Keller's work and discussed low velocity air testing of hydraulic and steam operated machines, was published. Everything set forth in this article is just as applicable today when leading engineering organizations, universities, and private industries are using air testing as a low-cost, useful tool to solve some of their hydraulic problems.

Instruments, test equipment, and measuring techniques are beyond the scope of this paper, but they offer no problem in low velocity air testing because they have been highly developed through the extensive aerodynamic work pertaining to aircraft design. On the other hand, much work still can be done towards defining the limits to which aerodynamic testing can be substituted for hydraulic testing. Some of the limits already established will be discussed subsequently.

Increasing Use and Advantages of Low Velocity Air Testing.—There are numerous reasons why low-velocity air testing is gaining popularity with hydraulic engineers. The following advantages contribute to this popularity:

1. The low density of air minimizes the structural requirements of the test facilities.
2. Power requirements to circulate the test fluid are comparatively low.
3. Absolute fluid tightness is not essential but more easily attained. The wetting problem is nonexistent, permiting use of wide variety of materials.
4. The atmosphere serves both as a supply reservoir and a catch basin.
5. Test procedure is usually greatly simplified but requires certain types of more highly developed and sensitive instruments.
6. Reynolds numbers can be made about the same for either air or water in a given model. Use of a larger model to test at a higher Reynolds number might be advantageous in some cases.
7. The relationships for noncompressible fluids can be applied with negligible error if the air velocities are kept below certain values (less than $\frac{1}{4}$ sonic speed).

All except the last item are advantages that result directly when air is used instead of water for studying the flow characteristics of closed hydraulic systems. However, without proof questions might arise as to whether or not the simple relationships for an incompressible fluid are applicable when air is used in place of water. It will be endeavored to supply this proof without going into extensive mathematical details.

Indicated Disadvantages.—It seems appropriate at this point to mention some of the disadvantages of using air as a test medium and to emphasize that the discussion applies principally to systems of short length where friction is not a major factor. Air has a comparatively low bulk modulus and does not become discontinuous as in the case when the vapor pressures of liquids are reached; and since air is a gas, there is no free surface. From these properties it appears that air could not be used to replace a liquid where effects of compressibility,

[5] "A Method for Determining the Cavitation Factor by Air Tests," by C. Keller and H. Bleuler, *Escher Wyss News*, Zurich, Vol. 1–2, 1939, pp. 19–24.

[6] "New Method of Aerodynamic Research," by C. Keller, *ibid.*, pp. 4–13.

cavitation, and gravity effects are predominating factors. This is not always the case, but it is necessary to be sufficiently familiar with the dynamics of gaseous flow in order to recognize when such studies are applicable. The use of the equations for incompressible flow will indicate the limits where compressibility is of little or no consequence. A logical and valid conclusion without the aid of mathematics would be that the velocity of sound for the test medium should not be exceeded in any event, since beyond this point it is not valid to assume the condition of adiabatic changes. A more elaborate theoretical treatment of the problem is required in such cases.

A pertinent question at this point is "How near can the speed of the air approach sonic velocity without introducing errors of appreciable magnitude?"

Limitations on Use of Compressible Flow

Application and Limitations of Formulas for Incompressible Flow.—It can be shown that large errors are introduced by using near-sonic velocities when the simpler hydraulic relationships are applied. This being the case, it would appear that the first problem of a hydraulic engineer wishing to use air instead of water for testing a hydraulic system would be to determine the maximum air velocity for his particular study.

In most tests, if the velocities are kept low and there are no large changes in pressure or velocity, it will not be necessary to make an evaluation of the compressibility effects. However, if there is some question as to whether or not the compressibility effects should be of concern, this evaluation can be made as will be outlined. The problem may or may not be easy depending upon the difficulty in establishing approximate expressions for the flow conditions in relation to the pressures and velocities for both incompressible and compressible flow. The maximum permissible velocity for any problem can be determined by setting up the expressions for the pressures in incompressible and compressible flow at two carefully selected points, computing the pressure change from one point to the other for both types of flow and plotting these pressure changes against the respective velocities at the reference point.

If the velocity of the air is kept within the range in which the pressure difference between the two selected points is essentially the same for both types of flow, then the simpler hydraulic relationships can be used in analyzing the test data from a hydraulic system using air instead of water as the test medium.

Theoretical Limiting Velocity.—The velocity of the air which will result in a given degree of accuracy in a system can be found by considering two general equations derived from the Bernoulli relationship for incompressible and compressible flow. The equation for incompressible flow is

$$\frac{h_1}{h_0} = 1 - \frac{(V^2{}_1 - V^2{}_0)}{2\,g\,h_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and the equation for compressible flow is

$$\frac{h_1}{h_0} = \left[\, 1 - \frac{(K-1)\,(V^2{}_1 - V^2{}_0)}{2\,C^2{}_0} \,\right]^{\frac{K}{K-1}} \quad \ldots\ldots\ldots\ldots (2)$$

in which h is the pressure head, V is the velocity, g is the acceleration of gravity, K is the gas constant, C is the acoustic velocity, and the subscripts 0 and 1 refer to the reference station and selected station, respectively.

The type of testing under consideration requires all velocities to be much less than sonic and all pressures to be near atmospheric. Therefore, the term $\frac{(K - 1)(V^2_1 - V^2_0)}{2 C^2_0}$ will be less than unity, and the right side of the equation can be expanded into a convergent series by means of the binomial theorem and written:

$$\frac{h_1}{h_0} = 1 - \frac{K (V^2_1 - V^2_0)}{2 C^2_0} \left[1 - \frac{(V^2_1 - V^2_0)}{4 C^2_0} - \frac{(K - 2)(V^2_1 - V^2_0)^2}{24 C^4_0} \cdots \right] \quad (3)$$

V_1 can be expressed in terms of V_0 as

$$V_1 = \beta V_0 \ldots \ldots (4)$$

in which β is the ratio of flow areas $\frac{A_0}{A_1}$. Then

$$\frac{h_1}{h_0} = 1 - \frac{K V^2_0 (\beta^2 - 1)}{2 C^2_0} \left[1 - \frac{V^2_0 (\beta^2 - 1)}{4 C^2_0} - \frac{(K - 2) V^4_0 (\beta^2 - 1)^2}{24 C^4_0} \cdots \right] (5a)$$

or

$$h_1 - h_0 = - \frac{V^2_0 (\beta^2 - 1)}{2 g} \times \left[1 - \frac{V^2_0 (\beta^2 - 1)}{4 C^2_0} - \frac{(K - 2) V^4_0 (\beta^2 - 1)^2}{24 C^4_0} \cdots \right] \ldots (5b)$$

since

$$\frac{h_0 K}{C^2_0} = \frac{1}{g} \ldots \ldots (6)$$

also, for incompressible flow,

$$h_1 - h_0 = - \frac{V^2_0 (\beta^2 - 1)}{2 g} \ldots \ldots (7)$$

Examination of Eqs. 1 to 7 shows that the relative magnitude of the compressibility effects will be reflected only in the second and subsequent terms within the brackets and that this magnitude depends on three factors: (1) The velocity of the air in the test system; (2) the sonic velocity at the pressure in the test system; and (3) the shape of the flow passage.

A quick estimate of the probable error introduced by using air instead of water may be made for a particular test setup by substituting approximate values of V_0, C_0, and β in the second term within the bracket. For example, let $V_0 = 250$ ft per sec, $C_0 = 1{,}000$ ft per sec, and $\beta = 2$. This error would be $\left[\frac{1}{4} \frac{(250)^2}{(1{,}000)} (4 - 1) \right] = 0.047$ or 4.7%. The effect of the third and subsequent terms is insignificant. Examination shows that error would be reduced to about 1% if V_0 was limited to 50 ft per sec. However, at the lower velocity, pressure intensity and pressure differentials might be more difficult to measure, and more precise instruments would be required.

Practical Limiting Velocity.—The use of hydraulic equations for air flow that is actually governed by aerodynamic relations introduces errors in the test results. The magnitude of these errors can be determined in some cases, while in others the limiting velocity can be determined at which the two regimes start to separate.

One of the least complicated examples of the determination of permissible test velocity is that of steady flow past a solid body, such as a pitot tube used in

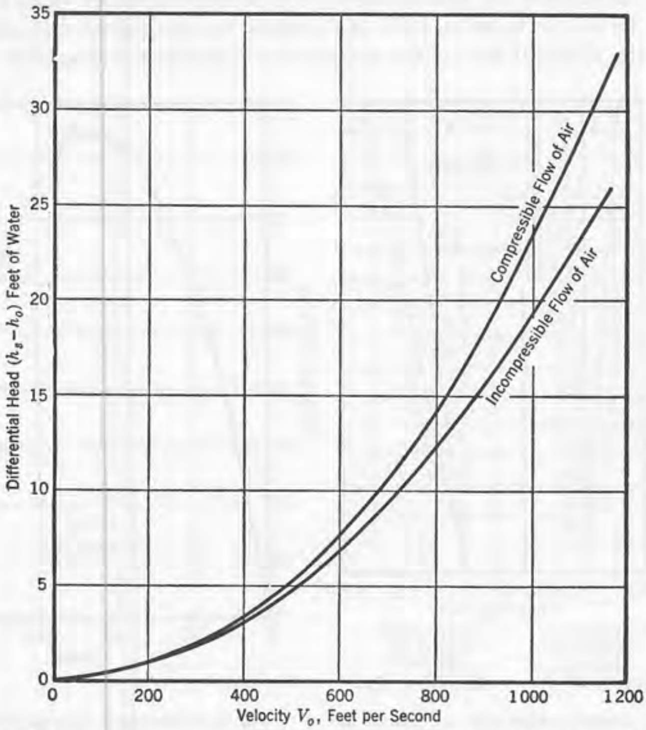

FIG. 1.—PRESSURE DIFFERENTIAL VERSUS VELOCITY CURVES FOR STAGNATION POINT

making a test, held stationary in a uniform stream. In this case the points selected for pressure measurement are in the undisturbed flow upstream from the body and on the leading edge of the body where stagnation pressure exists. The equation for the case of incompressible fluid is

$$h_s - h_0 = \frac{V^2_0}{2\,g} \quad \text{(8)}$$

and for compressible fluid at subsonic velocity:

$$h_s - h_0 = \frac{V^2_0}{2\,g}\left[1 + \frac{V^2_0}{4\,C^2_0} - \frac{(k-2)\,V^4_0}{24\,C^4_0}\cdots\right] \quad \text{(9)}$$

The subscripts 0 and s refer to the station in the undisturbed flow and at the stagnation point, respectively. By assuming various values (less than sonic) for V_0, computing values of $h_s - h_0$ and plotting the $(h_s - h_0)$ versus V_0 terms for both cases, Fig. 1 is obtained. An examination of the graph discloses that the values for both conditions are essentially the same for velocities up to about 250 ft per sec. For this type of study then, one would conclude that results comparable to hydraulic tests could be obtained with air, providing the value of V_0 was kept below about 250 ft per sec. Reliable results could be expected from a pitot tube for this velocity range. However, if other points in such a system are selected for measurement, it is possible that the value of V_0 would have to be less in order to hold the error to an equivalent minimum. Compressibility effects influence the accuracy of many test instruments.

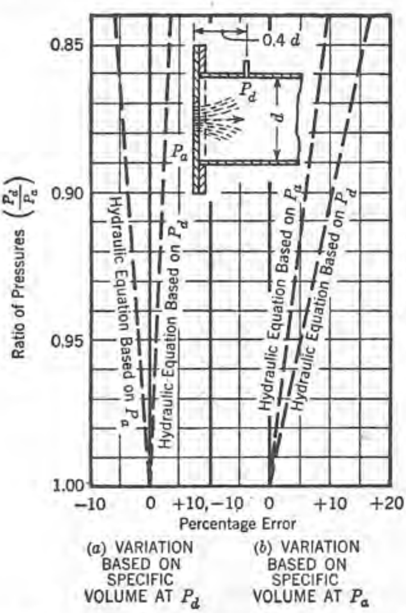

FIG. 2.—ERROR INTRODUCED BY USING HYDRAULIC INSTEAD OF AERODYNAMIC EQUATION FOR AN INTAKE ORIFICE

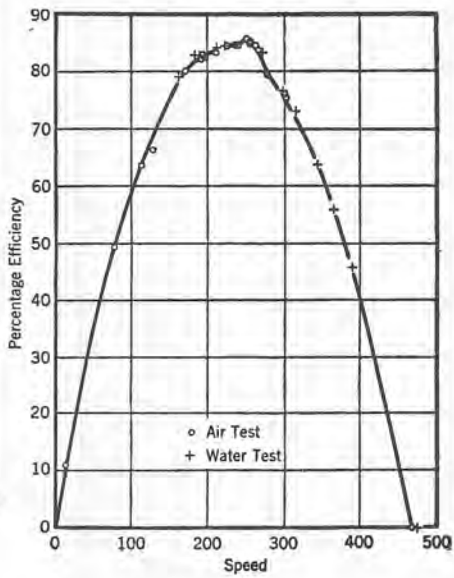

FIG. 3.—EFFICIENCY CURVES MEASURED ON A MODEL TURBINE

Flow through an orifice is an example of the determination of the magnitude of error introduced. The accuracy of the formula for incompressible flow through an intake orifice will vary depending on the pressures at which it operates and the reference pressure used in making the computation. The four lines in Fig. 2 show the percentage error introduced by using the hydraulic equation instead of thermodynamic relations for the four possible conditions based on the different reference points. The error is a minimum when the base pressure used is that in the pipe downstream, and results are compared with those obtained by the equation for compressible flow using the specific volume for the downstream pressure. With the low velocities suggested for the air tests, the pressure differentials are small and the ratio of downstream pressure to upstream pressure so near unity that the error is small in any case. The use of the mean pressure would result in even less error if the quantity were based on the specific volume at the downstream pressure. It may be concluded from this illustration that the equation for incompressible flow for an intake orifice may be used without introducing serious error if the pressure differential across the orifice is kept small (not more than 1 ft of water).

Examples for stream tubes in general and for flow in a venturi meter may be found in standard texts.[7] The evaluation of the compressibility effects on the accuracy of data taken from the test structure and on any instruments that are to be used in making the tests might be only the initial phase of a study in which air is substituted for water. In most cases the need for this initial work can be eliminated by maintaining the test velocities as low as possible while still providing accurately measurable quantities. With a little experience the hydraulic engineer is able to recognize whether or not the initial investigation of the compressibility effects is necessary.

There are other factors not apparent in the equations that might influence the accuracy of the results or make them qualitative only. Specific examples will be cited later to illustrate some of these factors which have been discovered mainly through experience.

Hydraulic Problems Studied

Air has been used successfully in hydraulic problems of the following nature: (*a*) Design of water passages, runners, and impellers of hydraulic turbines and pumps; (*b*) study of operating characteristics of hydraulic turbines and pumps including the efficiency and cavitation factor; (*c*) study and determination of losses and capacities of water distribution systems; (*d*) determination of losses and capacity of comparatively large water tunnels; (*e*) study of the mechanics of turbulent flow and its application to liquids (turbulence loss, development, and decay below screens); (*f*) study of the hydraulic characteristics of large outlet valves; (*g*) study of the hydraulic characteristics of complex passages such as those of hydraulic operating systems of large valves; (*h*) study of the pressure distribution and losses for various shapes of penstock inlets; (*i*) capacities and hydraulic characteristics of certain types of fluid meters (nozzles, orifices, etc.); and (*j*) study of the diffusion of air jets and its application to such structures as submerged sluice gates.

Turbine and Pump Design.—Air testing in connection with turbine design seems to have been done mainly by German and Swiss engineers in the late 1930's. A great deal of their work was published in Swiss technical papers,[8] that contained the comparison between aerodynamic and hydraulic tests shown in Fig. 3. The method has not been adopted by manufacturers in the United States, for these companies still use water for testing their models. The same is true of United States pump manufacturers.

Large Water Tunnel Design.—An unusual instance in which air has been used in place of water to determine the flow characteristics of a system of water

[7] "Fluid Mechanics," by Russell A. Dodge and Milton J. Thompson, McGraw-Hill Book Co., Inc., New York, N. Y., 1st Ed., 1937.

[8] "Aerodynamische Versuchsanlagen für Hydraulische Maschinen," by C. Keller, *Schweizerische Bauzeitung*, Vol. 110, 1937, p. 203.

tunnels was discussed in papers[9,10] given by two French engineers, G. Remenieras and P. Bourguignon at the 1949 meeting of the International Association for Hydraulic Structures Research in Grenoble, France. These tests were made before the tunnels were placed in operation and later checked by hydraulic tests. The test was performed by passing air through the tunnels while taking measurements of pressure changes, ascertaining the loss coefficients, and computing the tunnel capacities. Good agreement was found when the results were checked hydraulically after the system was placed in operation. The air tests in this case actually proved the adequacy of parts of the system before construction of the entire system was completed as is necessary for water tests. Such air tests permit an on-the-spot check of a system before the contractor has moved from the site and any deficiency could still be corrected at a minimum cost.

Turbulence Testing.—Work is being done at the State University of Iowa (at Iowa City) laboratory to study fundamental laws dealing with turbulence. Air is used instead of water because suitable instruments have been developed for measuring turbulence in air while instruments for measuring turbulence in water are still in the experimental stage. The diffusion of an air jet and its application to submerged sluice gates is another of this university's projects.

Characteristisc of Hydraulic Outlet Structures.—The Bureau of Reclamation Hydraulic Laboratory at the Denver (Colo.) Federal Center first employed this type of testing to study the flow characteristics of a diffuser cone. Later it was used to investigate the hydraulic properties of outlet valves to determine the deficiencies or advantages of the existing and proposed physical arrangement and dimensions of the water passages in regard to the capacity and possible occurrence of cavitation.

In one case the time required for the closing and opening cycle of an outlet needle valve when operated hydraulically was under study. The speed of the cycle was governed mainly by the capacity of the flow passages of the operating mechanism. A very simple representation of this mechanism was constructed of wood and sheet metal and tested with air. The results proved very satisfactory, and required less work and a fraction of the time required for hydraulic tests. Tests in the laboratory have included the study of the pressure distribution in the rectangular entrance to a conduit having a radial gate for regulation and the determination of loss coefficients for a complicated system of branching penstocks. Comparison of the results of these air studies with water studies have not been made available.

Miscellaneous Factors Affecting Low Velocity Air Tests

Turbulence.—Some very interesting facts pertinent to air testing were brought to light during the studies just discussed.

In the initial air tests on diffusers an unexpected discrepancy was noted in the results when compared with the results of water tests. Fig. 4 is a plot of this

[9] "Prédétermination de la perte de charge dans une canalisation d'eau sous pression à partir de celle mesurée sur la même canalisation parcourue par de l'air," by G. Remenieras, *Paper III-2*, Third Meeting of International Assn. for Hydraulic Structures Research, Grenoble, France, 1949.

[10] "Prédétermination de la perte de charge dans une canalisation d'eau sous pression à partir de celle mesurée sur la même canalisation parcourue par de l'air; contrôle de la validité de la méthode sur la Galerie d'Amenée, R. G. de l'usine hydro-eléctrique de Pont-Escoffier," by P. Bourguignon, *Paper III-9* Third Meeting of International Assn. for Hydraulic Structures Research, Grenoble, France, 1949.

test. The air tests indicated considerably more loss in the diffusers than did the water tests. In an attempt to introduce an additional loss ahead of the diffuser to study the effect of such loss on the action of the diffuser, a wire mesh waste-

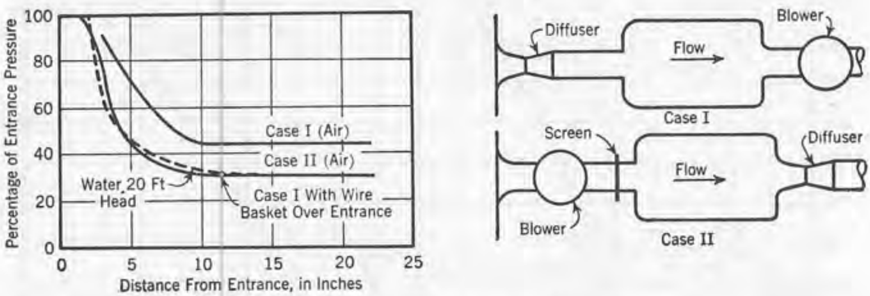

FIG. 4.—EFFECT OF TURBULENCE ON AIR TEST

basket was held over the inlet to the test apparatus shown as Case I in Fig. 4. A decrease in loss was indicated immediately. It was concluded that turbulence was almost nonexistent without the basket in the incoming air stream because

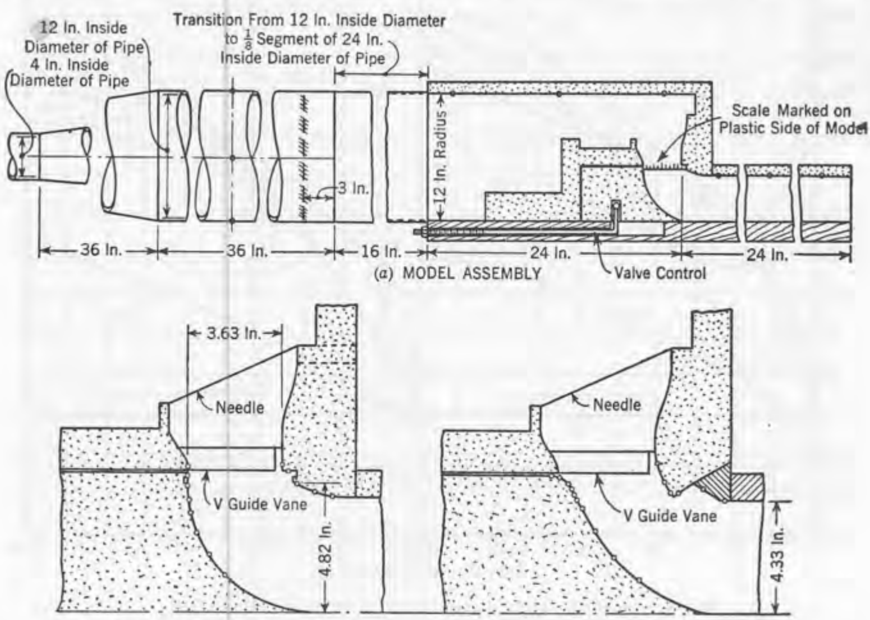

FIG. 5.—SHOSHONE DAM AERODYNAMIC MODEL

of the arrangement that used the entire volume of the laboratory as a supply reservoir. Thus, flow conditions were not correctly represented. The apparatus was rearranged as shown for Case II, and the tests repeated.

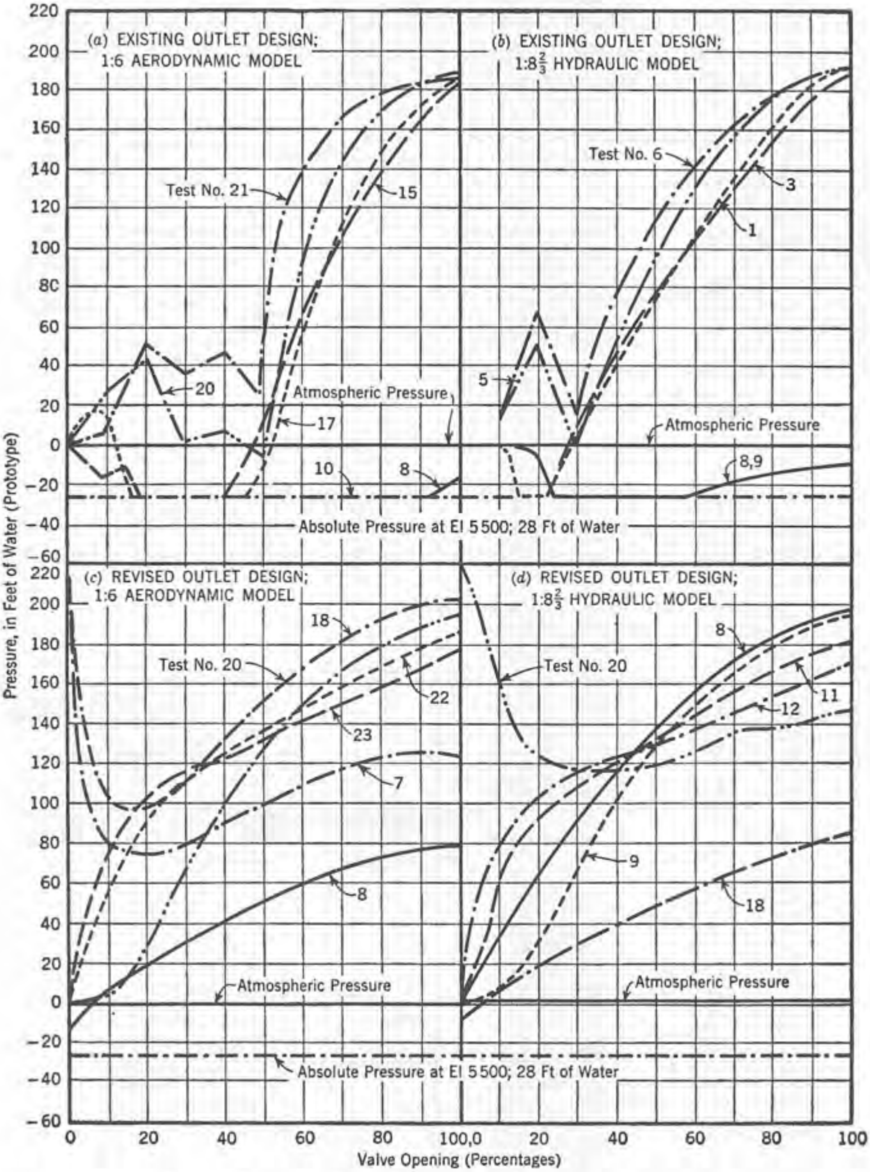

FIG. 6.—SHOSHONE DAM—PRESSURES IN VALVES AND CONDUITS

With the new arrangement of the air supply passing through the screen before flowing through the diffusers, there was a marked change in the results, and good agreement between the aerodynamic and hydraulic tests ensued. The situation of a virtually turbulence-free fluid at the beginning of the model, which first occurred inadvertently in the air test, rarely, if ever, is encountered in a hydraulic problem. This is the reverse of the case in aerodynamic works where the turbulence-free conditions of the atmosphere can best be approximated only in wind tunnels. The plot of Fig. 4 illustrates the error which might be introduced by improper turbulence.

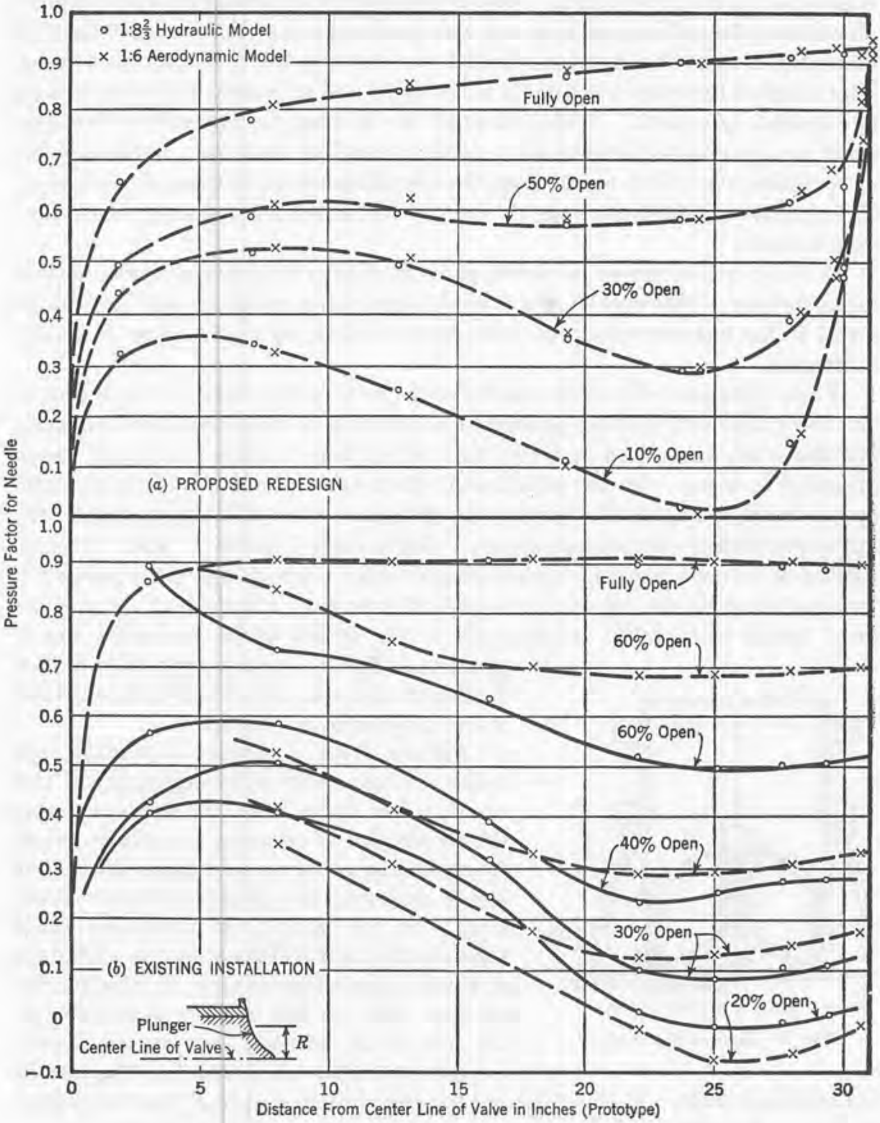

FIG. 7.—SHOSHONE DAM—COMPARISON OF PRESSURE FACTORS

Cavitation.—Several items of interest were discovered in the Bureau of Reclamation Laboratory during the air tests pertaining to the design of outlet valves. The tests were conducted on the Ensign balanced valve, needle valves, and the more recent development, the hollow-jet valve. In the case of the balanced valve extensive air tests were made on the existing design and proposed alterations to eliminate cavitation. Fig. 5 shows the general dimensions of the aerodynamic model for a 58 in.-balanced valve in the outlet chamber of Shoshone Dam in Wyoming. The air tests were completed before a hydraulic model could be put in operation and were used as an expedient to obtain design information until the hydraulic model was constructed. The air tests were later checked by water testing of a scale model and in general were found to be in excellent agreement. When materials for making the indicated alterations could not be obtained because of war restrictions, the tests were used as a guide in operating the valves at openings that would cause a minimum of cavitation. The operation at these openings proved highly successful in reducing the cavitation damage.

It is not within the scope of this paper to discuss the construction of models for air testing. However, it is pertinent to note that modeling clay is as useful a tool to the engineer using low velocity air techniques as the eraser is to the draftsman.

Vapor Pressure.—From the results of the tests on the balanced valve, it may be shown that very reliable quantitative data will be obtained from hydraulic systems when air is used as a test fluid, when there is little chance for vapor pressures to occur. On the other hand, when vapor pressure is likely to occur in the prototype hydraulic system, the data are not so reliable quantitatively but are extremely useful qualitatively. Figs. 6 and 7 illustrate this. A comparison of pressure factors for computing pressure intensities at given points for various operating conditions show excellent agreement in the case of the streamlined design and sizable discrepancies in the design where cavitation was a problem. The more general condition of flow leading to discrepancies of this nature is that where separation is present.

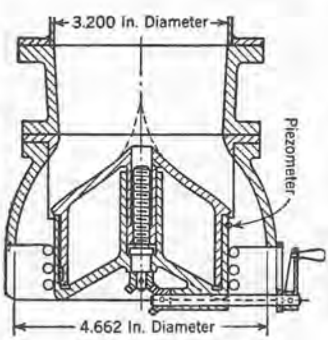

FIG. 8—HOLLOW-JET VALVE

Effective Head.—Another interesting fact noted during a study of the calibration of two small valves using both air and water was the importance of selecting the correct points for measuring pressures or pressure drops that would represent the actual hydraulic conditions. In the case of the hollow-jet valve shown in Fig. 8 it was necessary to install an additional piezometer in order to measure the effective head on the valve, mainly because the use of air actually represented a submerged condition which was not the case in the hydraulic tests. Without this piezometer the results would have been misleading and would not have compared with those from the water tests.

In another instance it was found necessary to remove an apparently essential part of the test valve in order to make it represent the hydraulic conditions which would be present in the field structure.

Conclusion

No doubt there are other factors involved in the proper representation of boundary conditions influencing the application and accuracy of air test results that have not been discussed in this paper: The factors presented here are either readily apparent from an examination of the physical relationships involved or those encountered by the Bureau of Reclamation Laboratory or other engineers who have conducted low velocity air tests for solving problems of a hydraulic nature. It would be interesting to hear from others who have had experience with or have knowledge of hydraulic problems being solved by low velocity air testing.

Although low velocity air testing of hydraulic systems is a very useful, expeditious, and economical method of solving many hydraulic problems, it is doubtful if it will ever be used extensively or result in accomplishments of a sensational nature. It is used mainly as a substitute for hydraulic tests and serves as an expedient for urgent or preliminary studies. The final proof of the design of a hydraulic system will, therefore, in most cases still be its successful operation under hydraulic conditions.

DISCUSSION

DAVID W. APPEL,[11] J. M. ASCE.—Although the author emphasizes the use of air tests in problems of hydraulic design rather than in fundamental hydraulic research, it is still difficult to justify the indecisive nature of his conclusions. His discussion of the limitations on the use of air for hydraulic model tests, although incomplete, is more detailed than necessary, since the general principles of hydraulic similitude—which apply to any fluid—have long since been verified and are now generally accepted. In particular, the "miscellaneous factors" which he lists as affecting air tests are all embodied in the general requirements for similitude and in themselves introduce no uncertainties in the air-test results. In every case where discrepancies in test results were observed, one of these requirements was not met. After removing this uncertainty as to the existence of unaccountable factors which may affect air-test results, one can only conclude that air tests should play an ever-growing role in hydraulic design as well as research.

The general principles of hydraulic similitude were established, confirmed, and accepted by the profession a long time ago. The author's assertion that these do not prove that air can be substituted for water in determining the characteristics of specific hydraulic systems is untenable; the use of air in place of water is as fully warranted and fully prescribed as merely the change in boundary scale and rate of flow. To establish similtude, certainly it is necessary to consider those properties of air, as a gas, which differ from those of water, as a liquid. These differences were given in the first part of the paper: Air is compressible, cannot maintain a free surface, and cannot become discontinuous; whereas water is assumed to be incompressible, can maintain a free surface, and becomes discontinuous when the vapor pressure is reached. The limitations due to each of these differences were considered. The compressibility effect was then found to be negligible for low to moderate velocities; closed systems were assumed in order to avoid free-surface effects; and it was indicated that only qualitative results can be obtained when cavitation occurs in the prototype. In other words, for tests of closed systems, where air velocities in the model are not high and pressures in the prototype are above the vapor pressure, the well-known principles of hydraulic similitude should be sufficient to establish practically perfect similarity between model and prototype.

The discrepancies noted in the particular tests described can now be explained in terms of well-established limitations. For example, the hollow-jet valve tests represent a case in which a free surface exists in the prototype which cannot be reproduced in the model using air. It is significant that comparable results were obtained in spite of this by selecting suitable points (using the principles of fluid mechanics) for measuring the effective head. The difference

[11] Research Associate, Iowa Inst. of Hydr. Research, State Univ. of Iowa, Iowa City, Iowa.

in results in the tests on diffusors, although caused by a difference in turbulence in the flow, should be attributed to geometric dissimilarity between the model and prototype. The results, using nonturbulent flow of air in Case I, could be reproduced equally well using water, by having the diffuser supplied directly from a large tank, thus eliminating turbulence from the approaching flow. The selection of the proper arrangement of equipment depends on the arrangement in the prototype. Geometric similitude requires that the flow system on either side of the test section be similar, or at least equivalent, in the model and prototype. This will be sufficient to make sure of correct results in nearly all tests of hydraulic models. The exception will be the case in which viscous effects are not negligible, as was assumed by Mr. Ball, and similitude of the Reynolds type would be required.

It is evident from these examples that careful consideration must be given to all factors that may influence the flow in a particular model. Similitude in all models—whether tested in air or in water—is usually only approximate due to the practical necessity of ignoring various secondary requirements. A comparison of the precision desired in the results with estimates of the probable deviations from perfect similitude should indicate whether additional tests are necessary under conditions more closely approximating those in the prototype. The model turbine test cited by the author is an example of the excellent degree of similitude that often can be obtained.

The advantages of using air instead of water in model tests were cited in a paper by Hunter Rouse, M. ASCE, in 1947,[12] which emphasized in particular the simplification of many phases of instrumentation which the use of air permits. The availability of more highly developed and sensitive instruments is an advantage in favor of using air, rather than just a requirement to be met as the author suggests. This is especially true in basic research where instruments such as the hot-wire anemometer can be used to make measurements in air that cannot readily be obtained in water at the present time.

The list, given by Mr. Ball, of the types of hydraulic problems studied emphasizes the uses of air in model tests for the design of hydraulic structures. The importance of the uses of air in fundamental hydraulic research warrants more attention to this phase of air testing. To indicate the wide variety of research problems that have been studied in air, examples of investigations conducted at the Iowa Institute of Hydraulic Research, in Iowa City, will be given.

The early experiences of the staff of the Iowa Institute with air tests during World War II have been described.[12] The relative ease of conducting the air tests compared with similar water tests was so apparent that air-flow equipment has since been explained and applied to many other problems. Two of these were mentioned in the paper: The investigation of flow through screens and baffles,[13] and the investigation of the diffusion of submerged jets.[14] One sig-

[12] "Use of the Low-Velocity Air Tunnel in Hydraulic Research," by Hunter Rouse, *Bulletin No. 31*, Studies in Engineering, State Univ. of Iowa, Iowa City, Iowa, 1947 (*Proceedings*, Third Hydraulic Conference).

[13] "An Investigation of Flow Through Screens," by W. D. Baines and E. G. Peterson, *Transactions* ASME, Vol. 73, July, 1951, p. 467.

[14] "Diffusion of Submerged Jets," by M. L. Albertson, Y. B. Dai, R. A. Jensen, and Hunter Rouse, *Transactions*, ASCE, Vol. 115, 1950, p. 639

nificant fact about these investigations is that the results are applicable whereever these flow situations are encountered, in the flow of water just as much as in the flow of air. The results obtained give hydraulic engineers all the basic information they are likely to need for flow of these two types without recourse to supplementary tests with water.

Another extensive investigation has been made of the development of the boundary layer on both smooth and rough surfaces.[15,16] Here again the experimental results are being obtained from air tests. These are of immediate importance in the problem of predicting the underwater drag of ship hulls and will undoubtedly be applied in the design of hydraulic structures in the future. The results of the air tests have already been used by William J. Bauer,[17] J. M. ASCE, in an investigation of the growth of the boundary layer in the accelerated flow of water in steeply inclined channels.

In connection with another project at the Iowa Institute, it was necessary to determine, experimentally, the best head form for a cylindrical body which would make possible a simple indication of the magnitude and inclination of the velocity of flowing water by measurements of pressures at suitable locations. A large number of head forms, such as blunt, partly rounded, hemispherical, ellipsoidal, ogival, and conical, were tested in a small open-throat air tunnel to obtain the pressure distributions around the head forms at different angles to the flow. The work in running the tests in air was only a small fraction of what would have been required for tests in a water tunnel, and the results agreed with the few data that were available from earlier water-tunnel tests.

The usefulness of air tests for the prediction and elimination of cavatition is illustrated well by the tests on outlet valves described by the author. Often, advantage can be taken of larger models for this type of test. At the Iowa Institute, water-tunnel tests on the occurrence of cavitation at gate slots[18] were supplemented by air-tunnel tests at a greatly enlarged scale to permit not only much finer detail in the local pressure measurements but also a relatively convenient control of the velocity distribution in the boundary layer to determine its effect on the pressure distribution.

Air tests have also been used to obtain data about gravitational phenomena in which the Froude criterion for similitude is just as applicable as it is to flow problems involving a free liquid-gas interface. In several instances the free convection above sources of heat was studied, for convenience, in air,[19,20,21]

[15] "An Exploratory Investigation of Boundary-Layer Development on Smooth and Rough Surfaces," by W. D. Baines, thesis presented to the State University of Iowa, at Iowa City, Iowa, in August, 1950, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

[16] "An Experimental Investigation of the Boundary-Layer Development Along a Rough Surface," by Walter L. Moore, thesis presented to the State University of Iowa, at Iowa City, Iowa, in August, 1951, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

[17] "The Development of the Turbulent Boundary Layer on Steep Slopes," by William J. Bauer, thesis presented to the State University of Iowa, at Iowa City, Iowa, in August, 1951, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

[18] "Cavitation and Pressure Distribution at Gate Slots," by Aristokli Spengo, thesis presented to the State University of Iowa, at Iowa City, Iowa, in June, 1949, in partial fulfilment of the requirements for the degree of Master of Science.

[19] "Gravitational Diffusion From a Boundary Scource in Two-Dimensional Flow," by Hunter Rouse, *Journal of Applied Mechanics*, Vol. 14, September, 1947, p. A225.

[20] "Free Convection Due to a Point Source of Heat," by Chia-Shuen Yih, thesis presented to the State University of Iowa, at Iowa City, Iowa, in August, 1948, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

[21] "Gravitational Convection from Line Sources," by Harold W. Humphreys, thesis presented to the State University of Iowa, at Iowa City, Iowa, in February, 1950, in partial fulfilment of the requirements for the degree of Master of Science.

the results being applicable as well to convection in water, whether produced by the addition of heat or (inversely) of sediment-laden liquid. In another instance, the fall velocity of spherical particles in a cylindrical container of liquid was being studied as the ratio of the particle diameter to the diameter of the container was varied. Practical difficulties were met in these fall-velocity experiments when relatively large spheres were used. Therefore, dynamically similar air tests were made with the spheres fixed in an air stream passing through a short cylindrical duct. Instead of measuring the fall velocity, pressure measurements were made to determine the drag of the spheres, which in turn could be related to their fall velocities.[22] A large scale was chosen for the air-test model for convenience in construction and to obtain high Reynolds numbers, an advantage in the use of air tests noted by Mr. Ball.

In one current thesis project air flow is actually used to simulate the non-uniform flow of water with a free surface. Impossible as it may seem at first, the distribution of turbulence in the hydraulic jump is being studied in this manner. This is done by shaping a closed-conduit transition according to the profile of the jump at each of a series of Froude numbers. The similarity of the flow pattern is checked by measuring the pressure distribution on the boundary representing the free surface and comparing this with the distribution corresponding to the assumed hydrostatic conditions within the jump. Pitot traverses will be used to verify the mean velocity distribution at various sections and, finally, hot-wire anemometer measurements will give the distribution of turbulence. The extra work involved in using air in this case is warranted only because a reliable instrument is not yet available for measuring the various components of turbulence in water.

Besides these examples of the use of air tests in research, it is obvious that air flow may be very convenient for demonstrations, student instruction, and the preparation of motion pictures, particularly when the flow pattern is to be observed by means of foreign agents. Disposing of air containing smoke, heat, or chemicals is no problem, whereas cleaning or disposing of contaminated water may be very difficult or uneconomical. The student laboratory equipment at the institute includes a small air tunnel and an air-pipe assembly for the purpose of familiarizing students with the advantages of air tests and their applications in hydraulic problems. Two other air tunnels and supplementary blower systems are available for more extensive applications.

It is evident from the tests cited in the paper, as well as from the investigations mentioned in this discussion, that the use of air as a model fluid provides a convenient and economical means of solving many problems in hydraulic design and in hydraulic research. These examples are in accord with the established fact that practically perfect similitude can be obtained in a large number of problems in which there are no free-surface or cavitation effects. Moreover, even when such close similarity is not a practical possibility, the use of air for qualitative or exploratory studies is advantageous. The availability of highly developed, sensitive instruments permits measurements to be made quite simply in air and, furthermore, makes possible studies of turbulence

[22] "Drag of Spheres Within Cylindrical Boundaries," by John S. McNown and John T. Newlin, *Proceedings*, First U. S. National Cong. of Applied Mechanics (publication pending).

in air that cannot be made in water at the present time. In spite of the author's conclusions to the contrary, the writer predicts that the many advantages accruing from the use of air will result in its playing an increasingly important role in the solution of hydraulic problems.

JAMES W. BALL,[23] A. M. ASCE.—Many excellent examples of low velocity air testing have been presented by Mr. Appel. The work cited is extremely interesting and indicative of the many outstanding facts and principles in fluid mechanics that can be established by this type of testing. The introduction of similitude increases the scope of the paper to include the fluid mechanics viewpoint. The paper is not a dissertation on similitude; neither does it misuse or advocate the misuse of this most valuable tool. The proper representation of boundary conditions is stressed as these are very important in attaining similitude in low velocity air testing as in hydraulic testing. Some boundary conditions are negligible whereas others are absolutely essential, but even these can often be represented artificially as illustrated in the paper.

Although not stated explicitly, the paper was written from the hydraulic point of view for engineers who are fearful of using compressible fluid data for solving problems relating to incompressible flow. There is no intention of implying that the results of air tests on hydraulic systems must be regarded with suspicion; rather, it is intended to encourage the use of air tests, but to caution that boundary conditions must be selected carefully. One of the most important factors retarding the use of low velocity air testing of models or full-size hydraulic structures is the problem of persuading hydraulic and design engineers to apply compressible fluid test data, confidently, to problems involving incompressible fluids. This reticence results from unfamiliarity with fluid mechanics and compressible fluids. A definite effort must be made to offset this factor when introducing air testing in laboratories where most of the problems concern incompressible flow. The paper represents such an effort.

In such laboratories (including those confined to pumps or turbines alone) it is not expected that outstanding hydraulic designs will be developed by direct testing with a low velocity compressible fluid, although the designs might be influenced considerably by similar tests which have established certain fundamental principles. Until the hydraulic engineers and designers are convinced that tests with low velocity air are as reliable as tests with water, they will insist on a check in the field of work with which they are familiar.

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[23] Hydr. Engr., Bureau of Reclamation, U. S. Dept. of Interior, Denver, Colo.