

Armed Services Technical Information Agency

Because of our limited supply, you are requested to return this copy WHEN IT HAS SERVED YOUR PURPOSE so that it may be made available to other requesters. Your cooperation will be appreciated.

AD

28572

NOTICE: WHEN GOVERNMENT OR OTHER DRAWINGS, SPECIFICATIONS OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY RELATED GOVERNMENT PROCUREMENT OPERATION, THE U. S. GOVERNMENT THEREBY INCURS NO RESPONSIBILITY, NOR ANY OBLIGATION WHATSOEVER; AND THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED, FURNISHED, OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA IS NOT TO BE REGARDED BY IMPLICATION OR OTHERWISE AS IN ANY MANNER LICENSING THE HOLDER OR ANY OTHER PERSON OR CORPORATION, OR CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

Reproduced by
DOCUMENT SERVICE CENTER
KNOTT BUILDING, DAYTON, 2, OHIO

UNCLASSIFIED

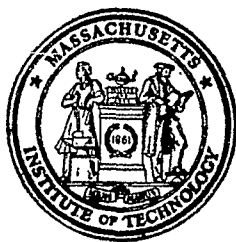
AD No. 28 572

ASTIA FILE COPY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

HYDRODYNAMICS LABORATORY

DEPARTMENT OF CIVIL AND SANITARY ENGINEERING



TECHNICAL REPORT No. 10

RESISTANCE COEFFICIENTS

FOR

ACCELERATED FLOW THROUGH ORIFICES

BY

JAMES W. DAILY AND WILBUR L. HANKEY, JR.

OCTOBER 1953

PREPARED UNDER

CONTRACT N5 ori - 07826

NR-062-047

OFFICE OF NAVAL RESEARCH

U. S. DEPARTMENT OF THE NAVY

WASHINGTON, D. C.

HYDRODYNAMICS LABORATORY
Department of Civil and Sanitary Engineering
Massachusetts Institute of Technology

RESISTANCE COEFFICIENTS FOR ACCELERATED FLOW
THROUGH ORIFICES

by

James W. Daily and Wilbur L. Hankey, Jr.

October 1953

Prepared under

Contract N5ori-07826, NR-062-047
Office of Naval Research
U. S. Department of the Navy
Washington, D. C.

ACKNOWLEDGEMENT

The investigation described in this report has been sponsored by the Mechanics Branch of the Office of Naval Research under Contract No. N5ori-07826, NR-062-047.

The program has been supervised by Professors Arthur T. Ippen and James W. Daily. The experiments were conducted by Mr. Wilbur L. Hankey, Jr., Research Assistant, assisted by Mr. Russell W. Olive, Research Assistant.

ABSTRACT

The investigation of fluid friction in unsteady motion conducted in the M.I.T. Hydrodynamics Laboratory was extended to include frictional resistance caused by orifices in accelerated flow. The objective of this program was to measure the frictional resistance under accelerated conditions along a circular conduit containing an orifice. Two different orifices were investigated, each located in a region of fully developed conduit boundary layer and velocity profile. The results are compared with previous measurements of the resistance of a clear smooth conduit.

The orifices of area ratios 0.5 and 0.7 were installed 38-1/2 diameters from the entrance nozzle in the one-inch diameter tube which forms the working section of the Unsteady Flow Water Tunnel. The velocity and acceleration of flow was programmed by a servomechanism which controls the pressure difference between the supply and receiving tanks of the tunnel. The instantaneous head drop across a foot length of tube containing an orifice was measured with diaphragm differential transformer type differential pressure cells. The velocity head was measured with a similar cell across the metering entrance nozzle and acceleration computed from time incremental changes in the velocity. The tests with orifices covered a conduit Reynolds number range from 5×10^4 to 3×10^5 and accelerations up to 35 ft/sec^2 .

The important conclusions from the orifice tests are:

1. The coefficient of head drop K_a is independent of Reynolds number and is a function of the acceleration parameter $\frac{aL}{V^2}$.
2. The frictional resistance for a given instantaneous velocity of accelerated flow through an orifice in a tube is appreciably less than for steady flow at the same velocity.
3. The frictional resistance for a given instantaneous velocity of accelerated flow through an orifice in a tube decreases with increasing acceleration.

A reanalysis of the previous measurements with a clear conduit shows:

4. The coefficient of head drop K_a is a function of Reynolds number as well as $\frac{aL}{V^2}$.
5. The frictional resistance for a given instantaneous velocity of accelerated flow through a uniform diameter smooth tube is equal to, or possibly slightly greater than, that for steady flow at the same velocity.

TABLE OF CONTENTS

	<u>Page No.</u>
I INTRODUCTION	
A. Background	1
B. Objective of Current Experiments	1
II THEORY	
A. General	1
B. Unsteady Flow Equations	1
III PROCEDURE	
A. Type and Scope of Experiments	6
B. Apparatus	7
1. Tunnel	7
2. Test Section and Orifice	9
C. Test and Computational Procedure	9
IV RESULTS AND CONCLUSIONS	
A. Discussion of Results	12
B. Summary of Conclusions	16
V BIBLIOGRAPHY AND REFERENCES	17

I INTRODUCTION

A. Background

The previously reported measurements (Refs. 1 and 2) of fluid friction for accelerated flow in a circular conduit were made using a one-inch diameter "working section" in the Unsteady Flow Water Tunnel (Ref. 3). This tube has a length of 99 inches (99 diameters) and the tests were performed in a section in which the boundary layer and velocity profile were fully developed for steady flow. The fluid was accelerated from one steady velocity to another with accelerations up to 35 fps^2 between Reynolds numbers from about 7.5×10^4 to 7.5×10^5 . The results showed no appreciable change in the friction factor between steady and unsteady conditions.

B. Objective of Current Experiments

The above measurements have been followed by the investigation of another form of fluid friction loss, that associated with sudden transitions (Ref. 4). The study was concerned with the effect of unsteady motion on the dissipation of energy associated with high shear and turbulence generation accompanying separation and jet formation. Since an orifice plate could be readily installed in the existing tunnel, the investigations described below have been made with sharp-edged orifices of different diameters. The orifices investigated were located in a region along the one-inch diameter tube where the boundary layer and velocity profile were fully developed under conditions of steady flow.

II THEORY

A. General

Considerable information is available on orifice head losses in steady motion. Very little is known pertaining to the evaluation of unsteady orifice losses; however, information has been obtained for the drag on a moving disk under accelerated conditions (Ref. 5). The results relate the unsteady coefficient of drag to the Reynolds number and a correlating modulus, $\frac{ad}{V^2}$ (a = acceleration, d = disk diameter, V = velocity). The force necessary to tow an immersed object is composed of a compound drag term, made up of skin friction drag, a turbulent wake form drag and an accelerative force, comprising the mass of the object and the associated virtual mass. The force necessary to accelerate a fluid through an orifice is composed of a compound frictional term, made up of skin friction and a turbulent wake force, and an accelerative force. By comparison, an analogy between the drag coefficient of an immersed disk and the head loss coefficient for an orifice may be formulated. The following analysis is the derivation of a similar correlating modulus for orifices.

B. Unsteady Flow Equations

The following momentum analysis of the unsteady flow of an incompressible fluid through an orifice in a uniform diameter pipe assumes the motion to be one-dimensional. At any instant only variations in a longitudinal direction are

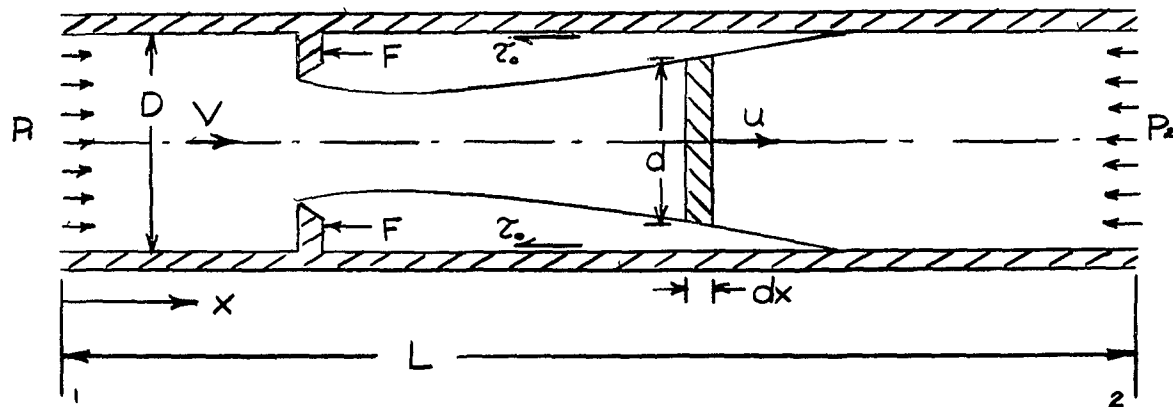
considered, average values of velocity pressure and acceleration being assumed to hold over any normal cross section. Random turbulent fluctuations are not introduced explicitly, but their effects, if any, are absorbed into the overall resistance coefficients employed. For steady motion, the analysis reduces to the conventional energy equation with the resistance coefficients as measures of energy loss. It will be assumed that the differences between coefficients for steady and unsteady motion is a true measure of the transient effects although it is recognized not only that corrections should be made for deviations from one-dimensional flow, but that resistance coefficients from a force-momentum equation may not be equal to the loss coefficients from an energy analysis. (Ref. 6)

The continuity equation retains its usual form,

$$\frac{\partial (Au)}{\partial x} = 0 \quad (\text{Eq. 1})$$

where A, u, and x are defined in the accompanying definition sketch and table of symbols.

Definition Sketch with Notation



A = cross-sectional flow area

t = time

d = jet diameter at any x

u = instantaneous cross-sectional mean velocity of jet at any x

D = conduit diameter

V = instantaneous cross-sectional mean velocity in conduit

F = orifice drag force

x = distance in flow direction

L = conduit test length

m = orifice diameter ratio

ρ = fluid density

p = pressure intensity

τ_o = wall shear

The equation of motion is derived by considering the equilibrium of forces on a differential fluid element. The rate of change of momentum ($\rho A \frac{du}{dt} dx$) is equated to the sum of the normal end forces ($-A \frac{\partial p}{\partial x} dx$), the "x" component of the wall shear ($-\tau_o \pi D dx$) and the portion of the orifice drag force in a length, L, effective on the differential element ($-F \frac{dx}{L}$).

$$\rho A \frac{du}{dt} dx = -A \frac{\partial p}{\partial x} dx - \tau_o \pi D dx - F \frac{dx}{L} \quad (\text{Eq. 2})$$

Expanding and substituting $\tau_o \equiv c_f \rho \frac{u^2}{2}$ (Eq. 3)

$$F \equiv K A \rho \frac{V^2}{2} \quad (\text{Eq. 4})$$

where c_f = coefficient of local wall friction

K = orifice drag coefficient

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} = - \frac{\partial p}{\partial x} - 4c_f \frac{D}{d^2} \rho \frac{u^2}{2} - \frac{K}{L} \rho \frac{V^2}{2} \quad (\text{Eq. 5})$$

Integrating with respect to "x" between points 1 and 2, a length L, such that $u_1 = u_2 = V$, will yield the following equation:

$$p_1 - p_2 = \rho \int_0^L \frac{\partial u}{\partial t} u dx + 2 \rho D \int_0^L \frac{c_f}{d^2} u^2 dx + K \rho \frac{V^2}{2} \quad (\text{Eq. 6})$$

The integral term for the wall friction can be replaced in terms of a mean coefficient so that

$$p_1 - p_2 = \rho \int_0^L \frac{\partial u}{\partial t} dx + K_f \rho \frac{V^2}{2} + K \rho \frac{V^2}{2}$$

or in dimensionless form

$$\frac{p_1 - p_2}{\rho \frac{V^2}{2}} = \frac{2}{V^2} \int_0^L \frac{\partial u}{\partial t} dx + K_f + K \quad (\text{Eq. 7})$$

In order to compare the results of steady and unsteady flow measurements and thus evaluate the effects of unsteadiness, it is convenient to reduce Eq. 7 to another form. First, for this particular problem, let us assume that the ratio $\frac{u}{V}$

for any point along the stream is dependent on x only so that we may write the inertial term in Eq. 7 as

$$\rho \int_0^L \frac{\partial u}{\partial t} dx = \rho \frac{\partial V}{\partial t} \int_0^L \frac{u}{V} dx$$

Next, we will introduce the following definitions and equalities:

1. K_a , coefficient of head drop in accelerated motion,

$$K_a = \frac{p_1 - p_2}{\rho \frac{V^2}{2}} \quad (\text{Eq. 8})$$

2. c_1 , coefficient of inertial head drop,

$$c_1 = \frac{1.0}{L} \int_0^L \frac{u}{V} dx \quad (\text{Eq. 9})$$

c_1 can be evaluated from a flow net of the jet profile through the orifice and is a constant if the jet profile does not change with velocity or acceleration.

3. a , local and, in this case, also the total acceleration in the conduit away from the orifice plate,

$$a = \frac{\partial V}{\partial t} \quad (\text{Eq. 10})$$

4. K_s , coefficient of total resistance (wall and orifice) for steady flow at the instantaneous velocity; and K_t , correcting coefficient which gives a measure of the additional transient effects such that

$$K_s + K_t = K_f + K \quad (\text{Eq. 11})$$

where

$$K_s = \frac{p_1 - p_2}{\rho \frac{V^2}{2}} \bigg|_{a=0} \quad (\text{Eq. 12})$$

Eq. 11 is merely a restatement of the consideration that both K_f and K as defined by their use in Eq. 7 may include steady and unsteady components. In general, K_s is a function of Reynolds number, the orifice-to-conduit diameter ratio, and the absolute roughness of the boundaries.

For unsteady flow through a particular orifice, K_s in the equality given by Eq. 11 is taken as the steady state value corresponding to the

instantaneous Reynolds number of some transient condition. Presumably also, K_t should be a function of Reynolds number as well as an acceleration parameter and the geometric parameters of the test conduit.

Using the above definitions, Eq. 7 is reduced to the following coefficient form:

$$K_a = 2c_1 \frac{aL}{V^2} + K_s + K_t \quad (\text{Eq. 13})$$

in which $\frac{aL}{V^2}$ is an acceleration parameter.

Equation 13 can be further simplified with the aid of an analogy to Schonfeld's analysis for smooth round tubes (Ref. 7). Schonfeld presents the following solution for slowly varied motion in which the resistance dominates (as opposed to quickly varied motion where the inertia dominates).

$$p_1 - p_2 = \frac{\rho g L}{R_h C'^2} \frac{Q^2}{A^2} + N \frac{dQ}{dt} \quad (\text{Eq. 14})$$

where Q = rate of discharge

R_h = hydraulic radius

C' = steady flow Chezy coefficient

$$N = \frac{\rho L}{A} \left[1.0 + \frac{234}{(C' + 14.0)^2} \right] \quad (\text{Eq. 15})$$

By substituting $C' = \sqrt{\frac{8g}{f}}$ (f = steady flow friction factor), $R_h = \frac{D}{4}$ and $Q = AV$, Eq. 14 can be rewritten for the tunnel test section thus

$$\frac{p_1 - p_2}{\rho \frac{V^2}{2}} = \frac{2aL}{V^2} + f \frac{L}{D} + \frac{0.91}{\left(\frac{1}{\sqrt{f}} + 0.87\right)^2} \frac{2aL}{V^2} \quad (\text{Eq. 16})$$

Comparing with Eq. 13 we note that

$$c_1 = 1.00$$

$$K_s = \frac{fL}{D} \quad (\text{Eq. 17})$$

$$K_t = \frac{0.91}{\left(\frac{1}{\sqrt{f}} + 0.87\right)^2} \frac{2aL}{V^2} \quad (\text{Eq. 18})$$

The difference between the resistance for accelerated motion and that for steady motion takes the form of a correction for the inertial term.

Using an analogous treatment for orifice resistance, let

$$K_t = c_2 \frac{2aL}{V^2} \quad (\text{Eq. 19})$$

in which c_2 is a function of the orifice steady flow coefficient, K_s . Then Eq. 13 reduces to the following:

$$K_a = K_s + (c_1 + c_2) \frac{2aL}{V^2} \quad (\text{Eq. 20})$$

with

$$c = c_1 + c_2$$

We can also write this as

$$\frac{K_a}{K_s} = 1 + c \frac{2aL}{K_s V^2} \quad (\text{Eq. 21})$$

Recall now that c_1 is a function of the jet profile and hence for a given orifice area ratio and test length is probably dependent upon Reynolds number R and the acceleration parameter $\frac{aL}{V^2}$. Also, c_2 is assumed to be a function of K_s and hence dependent upon the Reynolds number and m^2 . For one orifice in a velocity and acceleration region where the jet profile and K_s do not change greatly, c is a constant. Using Eq. 21, K_a can be determined for any $\frac{aL}{V^2}$ ratio if c and K_s are known.

For accelerated flow in the positive x-direction, K_s and K_a are both positive with K_a greater than K_s . Thus, c in Eq. 21 is a positive quantity. Of the two terms comprising c , c_1 is 1.00 for an orifice-to-conduit diameter ratio of 1.00 and increases with decreasing diameter ratio (Eq. 9) while c_2 is zero if acceleration does not affect the frictional resistance (Eq. 19). Using Eqs. 11 and 13 together with Eq. 19, the frictional resistance terms can be written as

$$\begin{aligned} (K_f + K) &= K_a - c_1 \frac{2aL}{V^2} \\ &= K_s + c_2 \frac{2aL}{V^2} \end{aligned} \quad (\text{Eq. 22})$$

In this form it is clear that a negative c_2 will indicate less frictional resistance for accelerated than for steady motion and vice versa. The magnitude and sign of these coefficients remain to be experimentally evaluated for each orifice ratio.

III PROCEDURE

A. Type and Scope of Experiments

As indicated by the development in the previous section, the problem was to separate the inertial and frictional components of the "extra" total resistance measured with accelerated flow through a length of pipe containing an orifice.

The basic experimental measurements were total head drop versus velocity for various accelerations from zero upward. The same Reynolds number range (based on the instantaneous mean conduit velocity V) was covered by the steady and unsteady tests. With this data and with c_1 evaluated from a flow net, all the terms in Eqs. 7, 19 and 21 could be determined.

Two orifices of diameter ratios 0.707 and 0.837 (area ratios 0.50 and 0.70) were used in tests covering a conduit Reynolds number range from 5×10^4 to 3×10^5 and accelerations up to 35 ft/sec^2 . This corresponded to a velocity range of about 0 - 40 feet per second and a minimum test duration (for acceleration runs) of about one second. In addition, coefficients for the limiting "orifice," of area ratio equal 1.0, were calculated from the results of the previous investigation of resistance in a uniform conduit (Ref. 1). These uniform conduit tests were made in the R range between $7.5 \times 10^4 \times 7.5 \times 10^5$.

It was desired to have as large a range of the modulus, $\frac{aL}{V^2}$, as possible; therefore it was decided to start from rest or some low steady velocity and accelerate. A range of the modulus, $\frac{aL}{V^2}$, within which an infinite number of values are available, may be obtained from one acceleration of the fluid from rest, thus necessitating only a few test runs.

B. Apparatus

1. Tunnel - The apparatus used for this experiment is a non-return, unsteady flow water tunnel. The same tunnel, control system and recording system were used in the fluid friction investigation of unsteady flow through conduits and are aptly described in Refs. 1, 2 and 3.

The schematic section of the tunnel is shown in Fig. 1. The tunnel consists of two cylindrical tanks mounted one above the other and connected by a vertical pipe or working section which contains the orifice. Water is caused to flow from one tank to the other under pneumatic control. Compressed air in the spaces above the water surfaces in the two tanks is used to provide an adequate driving force for a desired acceleration. To obtain the ranges of acceleration and pressure in the working section, compressed air must be admitted to or rejected from either tank according to some time schedule. A closed loop automatic control for velocity and acceleration is provided, which operates on the "error" between scheduled and actual tank pressure differences (Ref. 8). A cam-driven pressure-programming device drives a control valve, between the high-pressure reservoir and the top tank, through which critical flow is maintained. In order to avoid cavitation and prevent air from entering the piezometric system, the test section is maintained at positive pressure by manually throttling the exhaust from the bottom tank.

Diaphragm differential transformer type differential pressure cells are used as the pressure-sensing devices. An oscillator and preamplifier energize the cell's transformer. Each pressure gage signal is sent through a separate amplifying and detecting unit prior to being recorded on a 10-inch wide roll chart of Hathaway Type S8-C oscillograph.

Natural frequencies, measured with water-filled lead lines, pressure cells and the recording system have exceeded 165 cps.

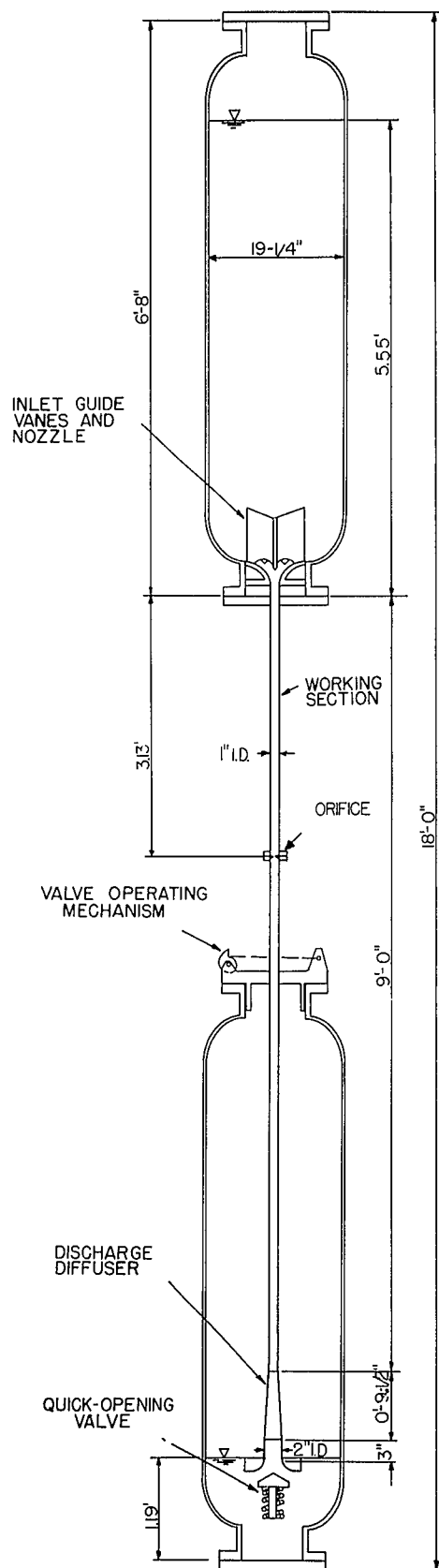


Fig. 1 Schematic Section of the Tunnel

2. Test Section and Orifice - A test section of 1-inch diameter brass tubing 99 inches long contains the orifice. The orifices used were square edged and were constructed of brass according to ASME Standard Specifications (Fig. 2). The orifice plate was enclosed in flanges with corner taps and provided with a vena contracta tap. The lower flange was soldered to the test section while the upper flange, provided with an "O" ring, was left movable to facilitate the exchange of orifice plates. The plate was positioned with dowels and the flanges secured with studs (Figs. 3 and 4).

It was desirable to have the orifice in a fully developed flow region in order to reduce the complexity of the problem. When fluid enters a conduit, a boundary layer develops and grows until the layers meet at the centerline. Beyond this point, the flow is fully developed and the velocity profile is unchanged downstream. For completely turbulent conditions at the conduit entrance, the initial point of fully developed flow, x_c , measured from the conduit inlet, can be determined approximately from the following equation (Ref. 9):

$$x_c = 0.7 D \frac{V x_c}{\nu}^{1/4}$$

For the case of the water tunnel conduit:

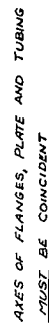
V (fps)	0	10	20	30	40	80
x_c (in.)	0	11.9	14.1	15.6	16.8	20.0

A convenient location for the orifice existed at a distance of 38-1/2 inches from the entrance nozzle. Since the velocities encountered were between 0 and 30 fps, this location was considered to be in a fully developed flow region and was used for the orifice.

The test length L was between piezometer taps located 4-1/2D upstream and 7-1/2D downstream of the orifice plate. These locations bracketed the range of expected influence of the orifice on the local flow conditions. Fink and Pollis (Ref. 10) show longitudinal pressure profiles along a tube for orifice-diameter ratios between 0.3 and 0.7 and pipe Reynolds numbers between 10^4 and 10^5 which indicate that all non-uniform flow conditions are confined to the stretch between 1D upstream and 4D downstream of the orifice plate. In addition, from the previously noted findings (Ref. 2) that the frictional resistance in uniform flow is essentially independent of acceleration, it was inferred that the re-establishment of uniform flow downstream of the orifice should give the same degree of turbulence and rate of turbulent energy dissipation downstream as upstream.

C. Test and Computational Procedure

The general test procedure as described in detail in Refs. 1, 2 and 4 was used. The test data appeared as traces on the oscillograph chart of the differential pressure across the metering entrance nozzle and the pressure drop along the conduit containing the orifice versus time. By referring to static calibrations performed before and after each test run, the instantaneous differential



- 10 -

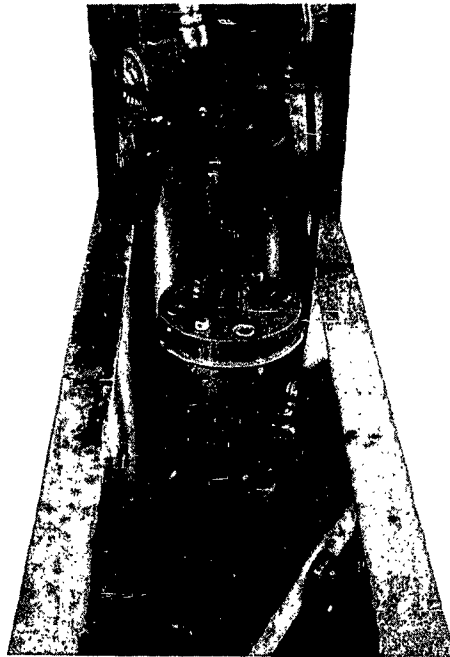


Fig. 3 Installed Orifice

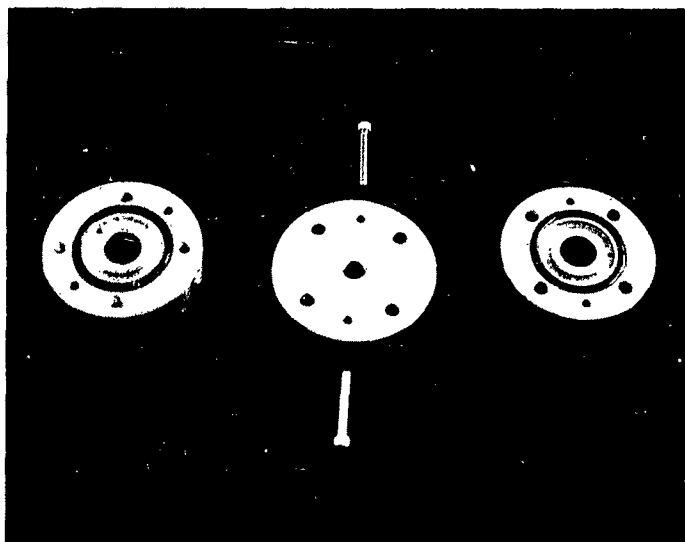


Fig. 4 Orifice and Flange Assembly

pressures were evaluated at time increments. For unsteady flows, the differential pressure head across the nozzle recorded the velocity head and a small inertial head ($\Delta h = \frac{V^2}{2g} + 0.18 \frac{a}{g}$, Ref. 1). The inertial head correction was determined approximately from a potential flow net. Using this correction in a trial and error solution gave values of the instantaneous velocity. The acceleration was calculated by taking time incremental differences of the velocity. For steady flow, of course, the inertial head correction is zero. In all tests two pressure cells were arranged in parallel across the 12 diameter conduit test length to measure the instantaneous head drop. This duplication provided a check on the reliability of the transducing and recording system.

Fig. 5 shows the results of a typical test run with a variable acceleration. The fluid flowing at some low steady velocity, is subjected to a sudden impulse causing a sharp increase in acceleration. The velocity and head drop increase rapidly and continue to rise while the acceleration passes a peak and then falls off. In this example, the accelerated portion of the test run was completed in a two-second interval. From such data, values of K_a versus $\frac{aL}{V^2}$ were obtained for successive time intervals throughout the test.

From steady flow data, values of K_s versus Reynolds number were computed.

IV RESULTS AND CONCLUSIONS

A. Discussion of Results

The experimental relations for the steady flow resistance coefficients are given in Table I.

Table I

Area Ratio (m ²)	Relation for K_s
1.00	$\frac{1}{\sqrt{K_s}} = 0.59 \log_{10} (R \sqrt{K_s}) - 0.54$
0.70	$K_s = 0.91$
0.50	$K_s = 3.68$

For the clear conduit ($m^2 = 1.00$) the pipe friction factor, f , was found equal to that given by the following equation for smooth pipes:

$$\frac{1}{\sqrt{f}} = 2.0 \log_{10} (F \sqrt{f}) - 0.8 \quad (\text{Eq. 23})$$

Substituting $K_s = f \frac{L}{D}$ with $\frac{L}{D} = 12$ for the test length used gives the equation in Table I. With either of the two orifices, the steady flow resistance is dependent primarily on the jet expansion process so that the resistance coefficient is essentially constant, independent of Reynolds number. The tabulated

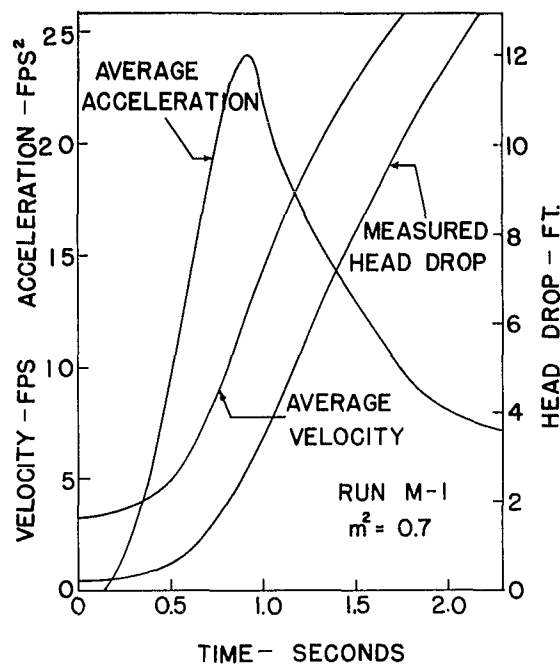


FIG. 5: TYPICAL TEST CURVES

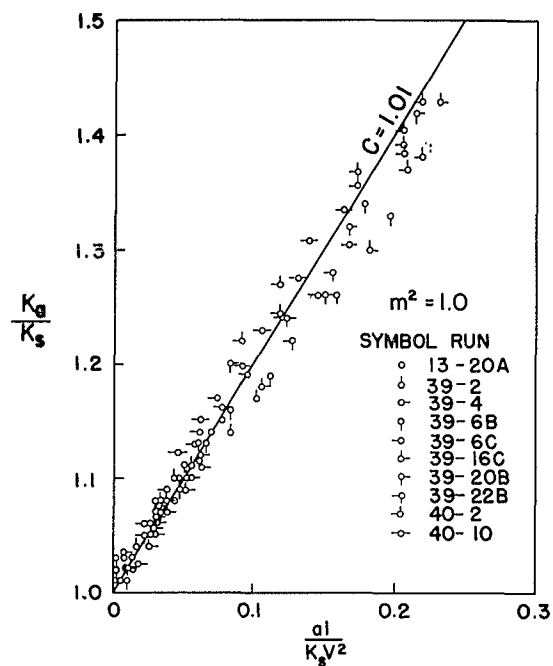


FIG. 6: SMOOTH CONDUIT

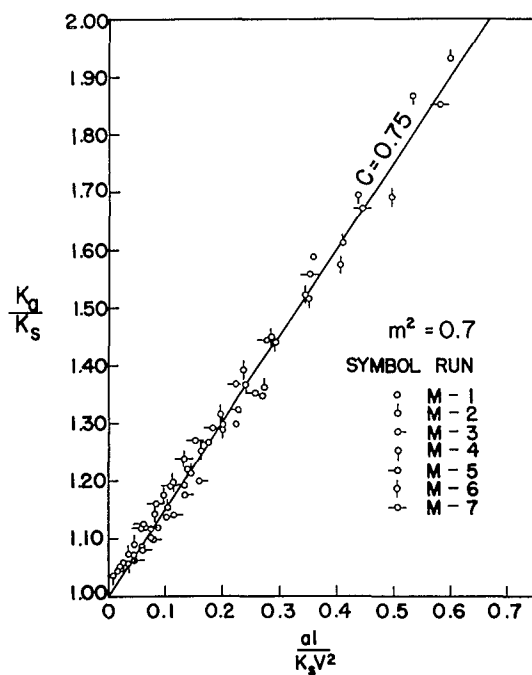


FIG. 7: ORIFICE AREA RATIO = 0.7

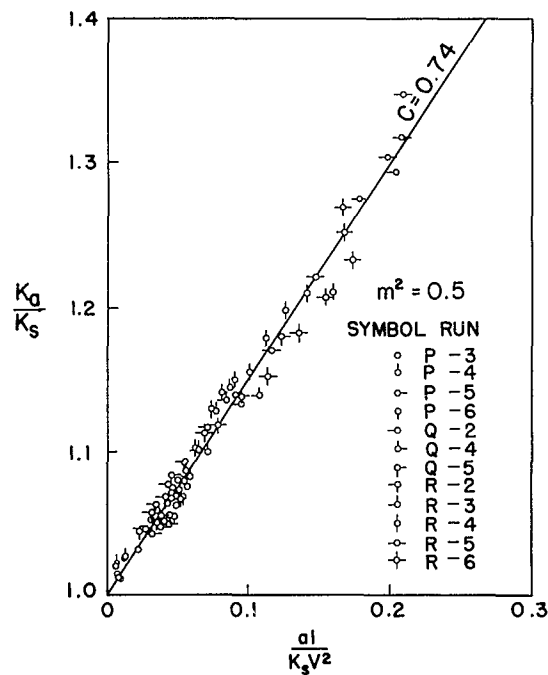


FIG. 8: ORIFICE AREA RATIO = 0.5

FIG. 5 - 8: ACCELERATED FLOW TEST RESULTS

values are the slopes of mean lines drawn through the experimental points of steady flow head drop plotted versus $\frac{V^2}{2g}$.

Using these expressions for K_s , values of $\frac{K_a}{K_s}$ versus $\frac{aL}{K_s V^2}$ were obtained as shown in Figs. 6, 7 and 8. In the case of $m^2 = 1.00$, K_s at the instantaneous Reynolds number of the particular K_a values was used.

In each of the three diagrams of Figs. 6, 7 and 8, a mean straight line is drawn through the experimental data. While the individual points deviate considerably from this line, they can all be banded approximately by parallel straight lines. No other definite trends are indicated by any test run or combination of runs. The scatter is due in large measure to the extreme sensitivity of the ratios plotted to small errors. Of course these lines pass

through the point $(\frac{K_a}{K_s} = 1.00, \frac{aL}{K_s V^2} = 0)$ which any line or curve representing the physical process must do. Consequently, the slope of the line is in each case the value of the coefficient $2c$ in Eq. 21.

Table II gives the values of c , c_1 and c_2 for the three cases. For the clear tube, $c_1 = 1.00$ by definition. As previously noted, c_1 values for the orifices can be determined by numerical integration from a flow net of the jet profile. This profile is known only approximately and in addition is assumed to be essentially constant over the range of velocity and acceleration of the tests. Therefore, while the tabulated values of c_1 are the correct order of magnitude, they are accurate only to within an estimated $\pm 10\%$. The coefficients c_2 were obtained as the differences $(c - c_1)$.

Table II

Area Ratio (m^2)	c	c_1	c_2
1.00	1.01	1.00	+0.01
0.70	0.75	1.15	-0.4
0.50	0.74	1.30	-0.6

Referring to Eq. 20, K_a is a function of Reynolds number as well as the acceleration parameter $\frac{aL}{V^2}$ unless both K_s and $c = c_1 + c_2$ are constants. For orifices K_s and c are in fact constants, so K_a is independent of Reynolds number. However, for the clear tube ($m^2 = 1.00$) the relation in Table I shows K_s to be a function of Reynolds number, while the relations derived from Schonfeld's theory

$$c_1 = 1.00$$

$$c_2 = \frac{0.91}{\left(\frac{1}{\sqrt{f}} + 0.87\right)^2}$$

predicts c_2 and hence c to be also dependent on R . The variation in c is small, however, and the use of a single mean line to represent the data in Fig. 6 is justified as can be shown by numerical example. Using Schonfeld's theory over the range of Reynolds number investigated, c varies only between 1.010 and 1.015. Hence, in Fig 6, a single straight line with a slope indicating a constant $c = 1.01$ is a satisfactory approximation.

This value of $c = 1.01$ makes c_2 positive for the clear conduit and implies a slight increase in pipe flow frictional resistance with acceleration. Expressing the sum of the frictional resistance (from Eq. 22) as a percentage of the steady state value gives

$$\frac{K_f + K}{K_s} = 1 + c_2 \frac{2aL}{K_s V^2} \quad (\text{Eq. 24})$$

With $c_2 = +0.01$, the increase would be less than one percent for $\frac{aL}{K_s V^2}$ less than 0.5. On the other hand, this small value of c_2 could mean very appreciable percentage increases for extreme cases with high values of $\frac{aL}{K_s V^2}$. Actually, the data in Fig. 6 could be represented just as well by a mean line falling slightly below the line shown and hence be in conformance with the previously reported conclusion of an inappreciable effect of acceleration (Refs. 1 and 2).

For both orifices, c_2 is definitely negative implying less frictional resistance at a given flow velocity with acceleration than without. Furthermore, the reduction becomes appreciable. Referring again to Eq. 24 for the frictional resistance as a percentage, it is seen that a negative c_2 also implies that the frictional resistance for a given velocity decreases with increasing acceleration. Thus for the 0.70 area ratio orifice, the resistance would be 60% of the equivalent steady state value for $\frac{aL}{K_s V^2}$ less than 0.5. At the highest values of $\frac{aL}{K_s V^2}$ of the tests (Fig. 7), the resistance is only about 50% of the equivalent steady flow resistance. For the 0.50 area ratio, the reduction is to 40% when $\frac{aL}{K_s V^2} = 0.5$.

It should be noted that the errors probable or possible in the determinations of c and c_1 would not alter these conclusions. The total spread of the plotted data in Figs. 7 and 8 corresponds to only a few percent variation in c , while c_1 must be no less than unity in any case. The combination of the extreme limits would not make c_2 positive for either of these examples.

It should be noted also that while c_1 is taken as a constant independent of Reynolds number and acceleration, this may be only approximately true. In which case c_2 will decrease as c_1 increases and vice versa. However, this would still not alter the previous conclusions.

B. Summary of Conclusions

In summary, these experiments show that the pressure drop and resistance data for accelerated flow through a smooth tube and through orifices in a tube can be represented as functions of the acceleration parameter $\frac{aL}{V^2}$ and in particular the following two equations apply:

$$K_a = K_s + c \frac{2aL}{V^2}$$

$$K_f + K = K_s + c_2 \frac{2aL}{V^2}$$

where for any particular conduit geometry, c is essentially constant and positive, and c_2 is essentially constant with a zero or a slightly positive value for a smooth tube and with negative values for orifices in the tube.

More specifically, it is found for orifices that

1. The coefficient of head drop, K_a , is independent of Reynolds number and dependent on the parameter $\frac{aL}{V^2}$.
2. The frictional resistance for a given instantaneous velocity of accelerated flow through an orifice in a tube is appreciably less than for steady flow at the same velocity.
3. The frictional resistance for a given instantaneous velocity of accelerated flow through an orifice in a tube decreases with increasing acceleration.

Also, a reanalysis of previous measurements with a smooth tube shows that

4. The coefficient of head drop, K_a , is a function of Reynolds number as well as the parameter $\frac{aL}{V^2}$.
5. The frictional resistance for a given instantaneous velocity of accelerated flow through a uniform diameter smooth tube is equal to, or possibly slightly greater than for steady flow at the same velocity.

V BIBLIOGRAPHY AND REFERENCES

1. Deemer, K. C., "Fluid Friction Due to Unsteady Flow in Conduits," Sc. D. Thesis, Course I, M.I.T., 1952.
2. Daily, J. W. and Deemer, K. C., "Measurements of Fluid Friction with Steady and Unsteady Motion," M.I.T. Hydrodynamics Laboratory Report No. 9, July, 1952.
3. Daily, J. W. and Deemer, K. C., "The Unsteady Flow Water Tunnel at the Massachusetts Institute of Technology," Transactions, ASME, Vol. 76, No. 1, 1954, pp. 87-95.
4. Hankey, W. L., Jr., "Head Loss Coefficients for Unsteady Flow through Orifices," S. M. Thesis, Course I, M.I.T., 1953.
5. Iversen, H. W. and Balent, R., "Correlating Modulus for Fluid Resistance in Accelerated Motion," Journal of Applied Physics, Vol. 22, No. 3, March, 1951.
6. Hall, N. A., "Orifice and Flow Coefficients in Pulsating Flow," Transactions, ASME, Vol. 74, No. 6, 1952, pp. 925-929.
7. Schonfeld, J. C., "Resistance and Inertia of the Flow of Liquids in a Tube or Open Canal," Applied Scientific Research, Vol. A 1, 1949.
8. Seaver, W. H., "Redesign of a Water Tunnel Pressure-Control System," M. S. Thesis, Course VI, M.I.T., 1953.
9. Goldstein, S. (ed., Fluid Motion Panel of the Aeronautical Research Committee and Others), Modern Developments in Fluid Dynamics, Vols. I and II, The Clarendon Press, Oxford, 1938.
10. Fink and Pollis, "Further Investigation of Fluid Flow through Orifices in Series," B. S. Thesis, Course XIII, M.I.T., 1950.

TECHNICAL REPORTS
Hydrodynamics Laboratory
Department of Civil and Sanitary Engineering
Massachusetts Institute of Technology

Technical
Report No.

- TR 1. Ippen, A.T., and Harleman, D.R., "Studies on the Validity of the Hydraulic Analogy to Supersonic Flow, Parts I and II," Sponsored by the U.S. Air Force, USAF TR 5985, May, 1950.
- TR 2. Daily, J.W., Deemer, K.C., and Keller, A.L., "The Unsteady Flow Water Tunnel at the Massachusetts Institute of Technology," Sponsored by the Office of Naval Research, May, 1951.
- TR 3. Ippen, A.T., Yoseph, R.S., and Posthill, B.N., "The Continuous Measurement of Oxygen Concentration in Water During Aeration Processes," Sponsored by U.S. Public Health Service, March, 1951.
- TR 4. Ippen, A.T., and Harleman, D.R., "Studies on the Validity of the Hydraulic Analogy to Supersonic Flow, Part III," Sponsored by the U.S. Air Force, USAF TR 5985, October, 1950.
- TR 5. Gifford, A.T., Nece, R.E., and DuBois, R.E., "Water Tests of Eight-Inch Check and Stop Valves," Sponsored by the U.S. Atomic Energy Commission, August, 1953.
- TR 6. Harleman, D.R., and Crossley, H.E., Jr., "Studies on the Validity of the Hydraulic Analogy to Supersonic Flow, Part IV," Sponsored by the U.S. Air Force, USAF TR 5985, February, 1952.
- TR 7. Ippen, A.T., Campbell, L.G., and Carver, C.E., Jr., "Determination of Oxygen Absorption in Aeration Processes," Sponsored by U.S. Public Health Service, May, 1952.
- TR 8. Daily, J.W., and Stephan, S.C., "The Solitary Wave--Its Celerity, Profile, Internal Velocities and Amplitude Attenuation," Sponsored by the Office of Naval Research, July, 1952.
- TR 9. Daily, J.W., and Deemer, K.C., "Measurements of Fluid Friction with Steady and Unsteady Motion," Sponsored by the Office of Naval Research, July, 1952.
- TR 10. Daily, J.W., and Hankey, W.L., Jr., "Resistance Coefficients for Accelerated Flow Through Orifices," Sponsored by the Office of Naval Research, October, 1953.
- TR 11. Crossley, Harry E., Jr., and Harleman, D.R., "Studies on the Validity of the Hydraulic Analogy to Supersonic Flow, Part V - Towed Model Investigation of Transonic Flow," Sponsored by the U.S. Air Force, USAF TR 5985, December, 1952.
- TR 12. Harleman, D.R., and Boedtker, O.A., "Water Table Experiments on Transient Shock Wave Diffraction, Part I, Operation, Instrumentation and Preliminary Experiments," Sponsored by the U.S. Air Force, August, 1953.

Copies of Technical Reports, if available, may be obtained from the Hydrodynamics Laboratory at a charge of \$1.00 per copy.

PUBLICATIONS BY THE STAFF OF THE
Hydrodynamics Laboratory
Department of Civil and Sanitary Engineering
Massachusetts Institute of Technology

- S- 1 Ippen, A.T., "The New Hydrodynamics Laboratory," Preprinted from Technology Review, June, 1951.
- S- 2 Ippen, A.T., and Staff of Hydrodynamics Laboratory, "Hydrodynamics in Modern Technology," A Symposium held at the Dedication of the Hydrodynamics Laboratory, April, 1952, published by the Hydrodynamics Laboratory, M.I.T.
- S- 3 Ippen, A.T., "The Influence of Viscosity on Centrifugal Pump Performance," A.S.M.E. Transactions, November, 1946.
- S- 4 Daily, J.W., "Cavitation Characteristics and Infinite Aspect Ratio Characteristics of Hydrofoil Section," A.S.M.E. Transactions, April, 1949.
- S- 5 Ippen, A.T., "Mechanics of Supercritical Flow," Symposium on High-Velocity Flow in Open Channels, A.S.C.E. Transactions, Vol. 116, 1951.
- S- 6 Ippen, A.T., and Dawson, J.H., "Design of Channel Contractions," Symposium on High-Velocity Flow in Open Channels," A.S.C.E. Transactions, Vol. 116, 1951.
- S- 7 Ippen, A.T., "Channel Transitions and Controls," Chapter VIII, Engineering Hydraulics (ed. by H. Rouse), John Wiley and Sons, 1950.
- S- 8 Daily, J.W., "Hydraulic Machinery," Chapter XIII, Engineering Hydraulics (ed. by H. Rouse), John Wiley and Sons, 1950.
- S- 9 Ippen, A.T., and Harleman, D.R., "Steady State Characteristics of Sub-surface Flow," Symposium on Gravity Waves, National Bureau of Standards, June, 1951.
- S-10 Ippen, A.T., and Harleman, D.R., "Certain Quantitative Results of the Hydraulic Analogy to Supersonic Flow," Second Midwestern Conference on Fluid Mechanics, Ohio State University, March, 1952.
- S-11 Paynter, H.M., "Methods and Results from M.I.T. Studies in Unsteady Flow," Boston Society of Civil Engineers Journal, April, 1952.
- S-12 Daily, J.W., and Stephan, S.C., "Characteristics of the Solitary Wave," A.S.C.E. Transactions, Vol. 118, 1953.
- S-13 Paynter, H.M., "Electrical Analogies and Electrical Computers: Surge and Water Hammer Problems," A.S.C.E. Transactions, Vol. 118, 1953.
- S-14 Daily, J.W., and Deemer, K.C., "The Unsteady Flow Water Tunnel at the Massachusetts Institute of Technology," A.S.M.E. Spring Meeting, April, 1953, Paper No. 53-S-31.
- S-15 Ippen, A.T., and Carver, C.E., Jr., "Continuous Measurement of Dissolved Oxygen with Dropping Mercury and Rotating Platinum Electrodes," Conference on Instrumentation in Water, Sewage and Industrial Waste Treatment, Manhattan College, May, 1953.
- S-16 Ippen, A.T., and Verma, R.P., "The Motion of Discrete Particles Along the Bed of a Turbulent Stream," Proceedings, Minnesota International Hydraulics Convention, September, 1953.

DISTRIBUTION LIST

M. I. T. HYDRODYNAMICS LABORATORY TECHNICAL REPORT NO. 10

RESISTANCE COEFFICIENTS

for

ACCELERATED FLOW THROUGH ORIFICES

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

ONR Contract No. N5ori-07826

October 1953

Chief of Naval Research Department of the Navy Washington 25, D. C. Att.: Code 438	(3)	Director Naval Research Laboratory Washington 25, D. C. Att.: Code 2021	(6)
Commanding Officer Office of Naval Research Branch Office 150 Causeway Street Boston, Massachusetts		Documents Service Center Armed Services Technical Information Agency Knott Building Dayton 2, Ohio	(5)
Commanding Officer Office of Naval Research Branch Office The John Crerar Library Bldg. 86 East Randolph Street Chicago 1, Illinois		Chief, Bureau of Aeronautics Department of the Navy Washington 25, D. C. Att.: Research Division	
Commanding Officer Office of Naval Research Branch Office 346 Broadway New York 13, New York		Chief, Bureau of Ordnance Department of the Navy Washington 25, D. C. Att.: Research and Development Division	
Commanding Officer Office of Naval Research Branch Office 1030 East Green Street Pasadena 1, California		Office of Ordnance Research Department of the Army Washington 25, D. C.	
Commanding Officer Office of Naval Research Branch Office 1000 Geary Street San Francisco 24, California		Commander Air Research and Development Command Office of Scientific Research Post Office Box 1395 Baltimore 18, Maryland Att.: Fluid Mechanics Division	
Commanding Officer Office of Naval Research Navy #100, Fleet Post Office New York, New York	(3)	Director of Research National Advisory Committee for Aeronautics 1724 F Street, Northwest Washington 25, D. C.	

Director
Langley Aeronautical Laboratory
National Advisory Committee
for Aeronautics
Langley Field, Virginia

Director
National Bureau of Standards
Washington 25, D. C.
Att.: Fluid Mechanics Section

Professor R. Courant
Institute for Mathematics and
Mechanics
New York University
45 Fourth Avenue
New York 3, New York

Professor G. Kuerti
Dept. of Mechanical Engineering
Case Institute of Technology
Cleveland, Ohio

Professor W. R. Sears, Director
Graduate School of Aeronautical
Engineering
Cornell University
Ithaca, New York

Chief, Bureau of Yards and Docks
Department of the Navy
Washington 25, D. C.
Att.: Research Division

Director
Underwater Sound Laboratory
Fort Trumbull
New London, Connecticut

Director
Waterways Experiment Station
Box 631
Vicksburg, Mississippi

Office of the Chief of Engineers
Department of the Army
Gravelly Point
Washington 25, D. C.

Beach Erosion Board
U. S. Army Corps of Engineers
Washington 25, D. C.

Commissioner
Bureau of Reclamation
Washington 25, D. C.

Dr. G. H. Keulegan
National Hydraulic Laboratory
National Bureau of Standards
Washington 25, D. C.

Professor V. L. Streeter
The Technology Center
Illinois Institute of Technology
Chicago 16, Illinois

Professor J. B. Wilbur, Head
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

Professor W. W. Hagerty
Mechanical Engineering Department
University of Michigan
Ann Arbor, Michigan

Dr. Andre L. Jorissen
Cornell University
Ithaca, New York

Professor R. C. Binder
Dept. of Mechanical Engineering
Purdue University
Lafayette, Indiana

Mr. J. M. Caldwell
Beach Erosion Board
U. S. Army Corps of Engineers
Washington 25, D. C.

Mr. Joseph B. Tiffany
Assistant to the Director
Waterways Experiment Station
Vicksburg, Mississippi

Mr. Frederick R. Brown
Hydrodynamics Branch
Waterways Experiment Station
Vicksburg, Mississippi

Mr. Harold M. Martin
Hydraulics Laboratory
Bureau of Reclamation
Denver, Colorado

Captain Harold E. Saunders
Asst. to Chief, Bureau of Ships
Department of the Navy
Washington 25, D. C.

J. B. Parkinson, Chief
Hydrodynamics Division
National Advisory Committee
for Aeronautics
Langley Laboratory
Langley Field, Virginia

Chief, Bureau of Ordnance
Department of the Navy
Washington 25, D. C.
Att.: Code Re6a

Chief, Bureau of Ships
Department of the Navy
Washington 25, D. C.
Att.: Ship Design Division
Prop and Shafting Branch
Preliminary Design Branch

Commanding Officer
Naval Ordnance Laboratory
White Oak, Maryland
Att.: Underwater Ordnance Dept.

Commanding Officer
Naval Torpedo Station
Newport, Rhode Island

Professor C. H. Wu
Dept. of Mechanical Engineering
Polytechnic Institute of Brooklyn
99 Livingston Street
Brooklyn 2, New York

California Institute of Technology
Hydrodynamics Laboratory
Pasadena 4, California
Att.: Professor A. Hollander
Professor R. T. Knapp
Professor M. S. Plesset

Professor G. F. Wislicenus
Dept. of Mechanical Engineering
Johns Hopkins University
Baltimore 18, Maryland

Massachusetts Institute of
Technology
Dept. of Naval Architecture
Cambridge 39, Massachusetts

Dr. J. M. Robertson
Ordnance Research Laboratory
Pennsylvania State University
State College, Pennsylvania

Dean K. E. Schoenherr
College of Engineering
University of Notre Dame
Notre Dame, Indiana

Professor J. L. Hooper
Alden Hydraulic Laboratory
Worcester Polytechnic Institute
Worcester, Massachusetts

Professor H. Reissner
Dept. of Aeronautical Engineering
and Applied Mechanics
Polytechnic Institute of Brooklyn
99 Livingston Street
Brooklyn 2, New York

Brown University
Graduate Division of Applied
Mathematics
Providence 12, Rhode Island

Professor G. Birkhoff
Department of Mathematics
Harvard University
Cambridge 38, Massachusetts

Stanford University
Applied Mathematics and Statistics
Laboratory
Stanford, California

Commanding Officer and Director
David Taylor Model Basin
Washington 7, D. C.
Att.: Ship Division

Hydrographer
Department of the Navy
Washington 25, D. C.

Professor V. A. Vanoni
Hydrodynamics Laboratory
California Institute of Technology
Pasadena 4, California

Professor M. L. Albertson
Dept. of Civil Engineering
Colorado A and M College
Fort Collins, Colorado

Professor H. A. Thomas
Pierce Hall
Harvard University
Cambridge 38, Massachusetts

Dr. F. N. Frenkiel
Applied Physics Laboratory
Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland

Dr. R. R. Revelle
Scripps Institute of Oceanography
La Jolla, California

Professor J. K. Vennard
Dept. of Mechanical Engineering
Stanford University
Stanford, California

Professor J. W. Johnson
Fluid Mechanics Laboratory
University of California
Berkeley 4, California

Professor H. A. Einstein
Department of Engineering
University of California
Berkeley 4, California

Professor J. R. Weske
Institute for Fluid Dynamics
University of Maryland
College Park, Maryland

Director
Woods Hole Oceanographic
Institute
Woods Hole, Massachusetts

Chief, Bureau of Ships
Department of the Navy
Washington 25, D. C.
Att.: Research Division

Commander
Naval Ordnance Test Station
3202 E. Foothill Blvd.
Pasadena, California

California Institute of
Technology
Hydrodynamic Laboratory
Pasadena 4, California

Commanding Officer and Director
David Taylor Model Basin
Washington 7, D. C.
Att.: Hydromechanics Laboratory
Hydrodynamics Division
Library

Professor A. T. Ippen
Hydrodynamics Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dr. Hunter Rouse, Director
Iowa Institute of Hydraulic Research
State University of Iowa
Iowa City, Iowa

Stevens Institute of Technology
Experimental Towing Tank
711 Hudson Street
Hoboken, New Jersey

Dr. L. G. Straub
St. Anthony Falls Hydraulic Laboratory
University of Minnesota
Minneapolis 14, Minnesota

Dr. G. H. Hickox
Engineering Experiment Station
University of Tennessee
Knoxville, Tennessee

Mr. C. A. Gongwer
Aerojet General Corporation
6352 N. Irwindale Avenue
Azusa, California

Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D. C.
Att.: Airframe Design Division

Chief, Bureau of Ordnance
Department of the Navy
Washington 25, D. C.
Att.: Code Re9a

Commanding Officer
Naval Ordnance Laboratory
White Oak, Maryland
Att.: Aerophysics Division

Commander
Naval Ordnance Test Station
Inyokern
China Lake, California

Director
Ames Aeronautical Laboratory
National Advisory Committee
for Aeronautics
Moffett Field, California

Director
Lewis Flight Propulsion Lab.
National Advisory Committee
for Aeronautics
21000 Brookpark Road
Cleveland 11, Ohio

Professor A. Ferri
Dept. of Aeronautical Engineering
and Applied Mechanics
Polytechnic Institute of
Brooklyn
99 Livingston Street
Brooklyn 2, New York

Brown University
Graduate Division of Applied
Mathematics
Providence 12, Rhode Island

Professor P. F. Maeder
Division of Engineering
Brown University
Providence 12, Rhode Island

California Institute of
Technology
Guggenheim Aeronautical Lab.
Pasadena 4, California
Att.: Professor P.A. Lagerstrom
Professor L. Lees
Professor H.W. Liepmann

Professor S. Corrsin
Dept. of Aeronautical
Engineering
Johns Hopkins University
Baltimore 18, Maryland

Professor C. C. Lin
Dept. of Mathematics
Massachusetts Institute of
Technology
Cambridge 39, Massachusetts

Stanford University
Guggenheim Aeronautical Lab.
Stanford, California

Massachusetts Institute of Technology
Dept. of Mechanical Engineering
Cambridge 39, Massachusetts
Att.: Professor J. Kaye
Professor A. H. Shapiro
Professor E. S. Taylor

Professor H. G. Lew
Dept. of Aeronautical Engineering
Pennsylvania State University
State College, Pennsylvania

Professor S. A. Schaaf
Low Pressures Research Project
University of California
Berkeley, California

Dean L. M. K. Boelter
University of California
Los Angeles 24, California

Professor George F. Carrier
Dept. of Engineering Sciences
Harvard University
Cambridge 38, Massachusetts

Institute for Fluid Dynamics and
Applied Mathematics
University of Maryland
College Park, Maryland

Professor A. M. Kuethe
Dept. of Aeronautical Engineering
University of Michigan
Ann Arbor, Michigan

Professor J. D. Akerman
Dept. of Aeronautical Engineering
University of Minnesota
Minneapolis 14, Minnesota

University of Washington
Dept. of Aeronautical Engineering
Seattle, Washington

Professor C. H. Fletcher
Dept. of Aeronautical Engineering
University of Illinois
Urbana, Illinois

Professor M. J. Thompson
Defense Research Laboratory
University of Texas
Austin, Texas

Professor R. P. Harrington
Dept. of Aeronautical
Engineering
Rensselaer Polytechnic
Institute
Troy, New York

Director
Jet Propulsion Laboratory
California Institute of
Technology
Pasadena 4, California

Professor J. V. Charyk
Forrestal Research Center
Princeton University
Princeton, New Jersey

Professor S. M. Bogdonoff
Dept. of Aeronautical Engineering
Princeton University
Princeton, New Jersey

Professor M. U. Clauser
Dept. of Aeronautical Engineering
Purdue University
Lafayette, Indiana