For item 3, any effects of acceleration on the inception of cavitation can be an important key to the unsolved question of scale effects with cavitating flows.

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Discussion

J. O. Jones.[5] This paper describes a remarkable achievement. The solution of a difficult problem was boldly conceived and carried to a convincing conclusion. The detailed description of the means employed emphasizes the promise of success that can be achieved in microtechnic by utilizing all scientific equipment available; but, in turn, this demands that the experimenter have an ever-wider knowledge of the tools of modern research. In short, the emphasis nowadays must be on instrumentation.

In laboratory work in all fields, always there is the question: Are the measurements accurate or merely consistent? In this instance the remarkable agreement of the pipe-friction measurements with the von Kármán-Prandtl equation for steady flow in smooth pipes gives confidence that the measurements are not only consistent, but also are as precise as can be desired. In view of the fact that the measurements are practically instantaneous, the agreement is amazing.

The writer hopes that future experiments will include measurements of pipe friction for values of Reynolds numbers as great as 10^7 and even greater.

R. W. Powell.[6] Since the writer recommended Professor Deemer for this research job at M.I.T., he naturally read this paper with great interest, and rates it as very important. For years we have been collecting data as to the resistance to flow in pipes and channels when the flow was steady. Flow in nature and in the works of man is seldom steady, but in our designs and investigations we have said "in the absence of any data as to resistance to unsteady flow, we will assume that the resistance will be the same as for steady flow at the same velocity." At last, in this paper we have data on the resistance to accelerated flow.

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There is much in the paper which the writer will not attempt to discuss. He freely admits that the instrumentation is too complicated for one trained in the old school to understand. The writer can contemplate it only with awe and amazement. It is clear that most of the 4 years were spent in designing and constructing the apparatus, and little time was left for using it. But some worth-while data were obtained.

The runs at zero acceleration give us no new information, but give us confidence that the complicated mechanism actually is measuring what it is supposed to. Considering the extremely short duration of the runs, and that the length of pipe over which the pressure drop was measured was only 39 diam, the agreement, shown in Fig. 9 of the paper, is remarkable. It may be noted that although the von Kármán-Prandtl formula plotted in that figure is regarded by most as the best available for smooth pipes, there is some disagreement. For example, refer to the formulas proposed by Harris[7] and some of the discussers of his paper, and that of Chu and Streeter.[8] It should be added that most of these formulas also agree well with the authors' data.

Figs. 10, 11, and 12 are only samples of ten such figures given in the more complete papers (5 and 6 of the authors' Bibliography). They are typical samples, however. From all their data the authors conclude that when the acceleration is constant, or approximately so, the shearing resistance indicated (after correction for the force necessary to produce the acceleration) is the same as for steady flow at that instantaneous velocity. The authors say, "only in the region of initial impulse, Fig. 10, does the head loss differ from what would be calculated by using the instantaneous velocity and the steady-velocity friction factor." Their explanation for the difference is that with rapidly increasing acceleration the increase in mechanical viscosity of the turbulent flow in the central core of the pipe does not keep pace with the increase in the velocity of flow, and that, therefore, the resistance to flow is less than for steady flow at the same velocity.

Fig. 11 does not bear out the authors' statement because there is a large difference at the very point where the rate of change of acceleration is zero. But perhaps this was a purely instrumental difficulty. In the thesis (5 of the Bibliography), it is stated that it was "difficult to attain a high degree of accuracy in the early portions of the unsteady-flow runs." It would be interesting to know if subsequent tests have been made with negative acceleration, and, if so, whether the authors' theory was verified by the resistance to unsteady flow being greater than for steady flow.

One other minor point is that, with rapidly changing pressure difference, it is important that the pressures on the two sides of the differential gage represent simultaneous pressures at the two ends of the test length, and the velocity measurements correspond to that same time. It would seem that the leads to the differential gage should have been of equal length, and that the leads from the measuring nozzle should have been longer than these by about 90 in. Actually, they were somewhat shorter. As the velocity of pressure waves in copper pipe is of the order of 3700 fps, this might have put the pressure and velocity measurements some 0.003 sec out of phase. This is probably negligible in these experiments, but should be considered if further refinements are made.

Authors' Closure

The authors are grateful to Professors Jones and Powell for their objective discussions. In particular, they have raised certain questions regarding the test results which the following paragraphs will attempt to answer.

[7] "An Engineering Concept of Flow in Pipes," by C. W. Harris, Trans. ASCE, vol. 115, 1950, pp. 909–958.

[8] "Fluid Flow and Heat Transfer in Artificially Roughened Pipes," by H. Chu and V. L. Streeter, Final Report of Project No. 4918, Illinois Institute of Technology, 1949.

Accuracy in measurement of the difference between the pipe-friction factor for steady flow and that for unsteady flow depends on the ratio of acceleration head to total head drop. In order to keep this ratio reasonably high, the experimental program did not include unsteady flow velocities above approximately 75 ft per sec; consequently, inasmuch as the steady-flow results were considered only a necessary part of the unsteady-flow data, the steady-flow measurements did not extend far beyond those velocities.

Professor Jones' suggestion that more complete steady-flow pipe-friction data, especially at higher Reynolds numbers, should be obtained with the DDT cell, may be followed. Certainly, extensive high-caliber experimental work has been done on steady flow, but it would be interesting to see how rapidly an entire set of experiments could be run and still maintain a fair degree of accuracy.

Professor Powell is justified in pointing out the discrepancy in Fig. 11, but there appears to be ample evidence that the discrepancy is an experimental error rather than a phenomenon of the flow. As mentioned in Bibliography (5) and (6), the ranges of the electronic cells were set to give full-scale oscillograph chart deflection for the range of differential pressures desired in a given group of runs. In setting these ranges, the amplifiers and power supplies used in this experimental work frequently approached saturation at the extreme signals (at zero and max differential pressures). During runs, the extreme signals did cause some saturation, but no such saturation occurred in the central portions of the set ranges. In addition, as mentioned in this paper and in greater detail in Bibliography (5) and (6), the overall error in converting data from the oscillograph chart to numerical quantities is approximately $^2/_3$ per cent of full-scale deflection. The "fat and wiggly" nature of the line accounts for most of this error. Of course, the lower the differential pressure, the greater the actual error in converting data. Hence both the saturation and the data-conversion factors indicate that more weight should be given to data obtained in the central regions of the test range (such as shown in the central regions of Fig. 10) than that obtained in the lower ranges (such as in the early portions of Fig. 11). It might be noted that the power supplies and amplifiers have been redesigned recently to give greater capacity and to have more stability. The authors wish to emphasize that the experimental work reported herein was exploratory and the results were meant to be preliminary.

It is true that an impulse traveling through two different lengths of lead line will arrive at the cell diaphragm at different times and the magnitude of the possible error should be checked. In this work the precision with which the data could be obtained and plotted was not of sufficient order as to make a time delay of 0.003 sec significant. The cells were mounted on a sturdy framework independent of the tunnel structure, and the lead lines were made as short as possible to minimize inertial effects and difficulties arising from air entrainment.