The Effect of Viscosity on Orifice Flows

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1920 Proc. Phys. Soc. London 33 225

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XIX. *The Effect of Viscosity on Orifice Flows.* By W. N. BOND, B.Sc. (Engineering), M.Sc. (Lond.), A.R.C.S., A.Inst.P.

RECEIVED NOVEMBER 16, 1921.

ABSTRACT.

Determinations were made of the coefficient of discharge through an orifice 0.1469 cm. in diameter of solutions of glycerine and water, varying in kinematic viscosity from 0.01 to 7. The results are plotted in a manner which combines both purely viscous and purely turbulent flows in one graph. It is shown that the effect of slight viscosity is to increase the coefficient of discharge.

A LARGE number of experiments have been carried out by different workers on the flow through orifices when the effect of viscosity can be neglected. When viscosity has to be taken into account, the value of the coefficient of discharge C , given by $C=Q/(A\sqrt{2gh})$, should be the same for all cases having the same value of $vl\rho/\mu$,

where Q =observed volume passing per second.

h =the difference of "head" between the two sides of the orifice.

A =the area of the orifice.

$v=Q/A$ =the average velocity at the orifice.

l =the diameter of the orifice.

ρ =the density of the liquid.

μ =the viscosity of the liquid.

The kinematic viscosity μ/ρ may be denoted by ν .

The following experiments were carried out for J. L. Hodgson, Esq., B.Sc., A.M.I.C.E., of Messrs. Geo. Kent, Ltd.; the object of the investigation being to obtain the values of C for lower values of $vl\rho/\mu$ than were previously available, in the case of a circular sharp-edged orifice in a thin plate, having liquid on both sides of it.

It was known from previous experiments that as viscosity becomes more important the value of C is at first increased; and it is necessary that for yet more viscous liquids C should decrease to zero. Since the completion of these experiments the author has found that G. F. Davidson* had previously attempted to obtain similar information in the case of a round edged orifice. For his experiments a thick engine oil was used, the viscosity being varied at will by changing the temperature.

* Proc. Roy. Soc., A., Vol. LXXXIX., 1913-14, pp. 91-99

The values obtained for the coefficient of discharge were not constant for any one value of $\nu l \rho / \mu$, and he traced the cause of the discrepancy to the fact that the oil he was using had not a definite value of ν independent of the rate of shear. The value of ν was found to decrease for an increase in the rate of shear. Similarly an increase in the value of ν when the rate of shear is made small has been found by Kurt Molin,* using Searle's viscosity apparatus.

In the present experiments, at Mr. J. L. Hodgson's suggestion, mixtures of glycerine and water were used, the value of ν being thus varied from about 0.01 to 7.

The viscosity of each mixture used was determined by the capillary tube method, the capillary tube being placed in a

FIG. 1.

water bath. The values obtained were consistent and agreed in the cases of water and pure glycerine with the values usually accepted.

The density of each mixture was determined by means of a hydrometer.

The orifice was made by clamping a piece of thin hard-rolled sheet German silver between two gunmetal plates and drilling through the three together. After unclamping, the

* Kurt Molin, Proc. Camb. Phil. Soc., Vol. XX., Pt. I., pp. 23-34, 1920.

orifice plate was polished on both sides to ensure the edge being right-angled. This plate was then soldered to a small gunmetal ring, which in its turn was fastened to one end of a wide glass tube with plasticine. The wide glass tube, which was about 76 cm. long by 2.85 cm. diameter, was clamped vertically with the orifice at the lower end. This end was arranged to dip into a large beaker containing some of the liquid being used. A scale divided in millimetres was pasted along the length of the tube. The area of cross-section of the tube at different points was obtained by closing the lower end, pouring in successive known volumes of water and noting the corresponding rise in level.

The diameter of the orifice was measured by means of a microscope fitted with an eyepiece scale micrometer. Check measurements were obtained by other means. The mean of the determinations was 0.1469 cm. diameter. The thickness of the orifice plate was obtained by means of a micrometer screw gauge, which gave a value of approximately 0.0075 cm.

In the flow experiments the vertical tube was filled with liquid, the orifice being meanwhile closed by one finger. An air-tight cover was placed on the top of the tube to prevent flow taking place till desired. The beaker was put in position and any air bubbles removed from the orifice plate. Time was allowed to let any bubbles in the liquid rise to the surface. On removing the top cover the time was noted when the falling liquid surface in the tube passed suitable divisions on the scale. The level in the beaker was read when desired, and a correction for its rise applied to the value of the "head." The temperature of the liquid was observed and a viscosity test carried out at the same temperature.

From the determinations of the time of passing successive divisions on the tube scale, the rate of flow could be deduced, since the area of cross-section of the tube had been obtained by the preliminary experiment. This very convenient method of experimenting was suggested by Mr. F. Gray.

For the timing in the case of the less viscous mixtures a chronoscope reading to 1/50 sec. was used; and it was found that successive readings could be taken satisfactorily at intervals of as little as six seconds, the observing and writing being carried out by two observers.

In all the more viscous mixtures, great care had to be taken to remove air bubbles. Also in the case of the most viscous liquids there was an appreciable quantity of liquid left clinging

to the inside of the glass tube. The error this would cause was made small by the use of the small size of orifice adopted.

The space between the orifice and the bottom of the beaker was varied in the case when $\nu=0.35$ from 2.2 cm. to 4 cm., and no measurable change in C occurred. For most of the experiments the length of this free downstream was 2.2 cm. which is about 15 times the orifice diameter.

At the end of this set of experiments the orifice plate was fitted into a pipe line and the value of C obtained for larger water flows.

In plotting the results, instead of plotting the values of C

FIG. 2.

against those of $\nu l \rho / \mu$ or its equivalent $4 Q \rho / \pi l \mu$, it was found better to plot against $\sqrt{Q \rho / l \mu}$ in order to obtain a more convenient representation of both viscous and turbulent portions of the curve on a single graph. This method of plotting has also the advantage that it causes both the purely viscous and the purely turbulent portions of the graph to become straight lines.

Fig. 1 shows the curve obtained by plotting the results on this basis. In Fig. 2 the portion corresponding to viscous

flow is plotted on a larger scale. The curves given by C. F. Davidson* in Fig. 2 of his Paper have been reduced to the same basis and are indicated by the broken curves in Fig. 2. The values of the kinematic viscosity $\nu = \mu/\rho$ are given by each curve. The figures above refer to Davidson's experiments; those below to the present results. The points obtained with different values of ν are distinguished by plotting successive sets with dots, crosses, circles, and so on. In Fig. 2 the viscous flow determinations (shown in detail in Fig. 2) are for simplicity indicated entirely by dots.

It will be noted that the extreme values of ν used are in ratio of about 1 to 700 (cf. Davidson's 1 to 1,000). Moreover, the results obtained with the more viscous mixtures lie extremely closely along a straight line through the origin. This indicates that true viscous flow is obtained; and further that under the conditions of these more viscous experiments the viscosity of the mixtures is to a close degree independent of the rate of shear. However, when less viscous mixtures were used, there are indications of successive experiments with different amounts of dilution showing slight disagreement; and it is probable that for the less viscous mixtures (and consequently greater rates of flow) the value of ν is no longer independent of the rate of shear. Thus though the left-hand end of the curve is probably determined with fair accuracy, the shape of the apex may be slightly in error, due to variations in ν similar to those observed by Davidson. Any error due to this cause is probably confined to the portion of the curve near the apex, since the linear law agreement obtained for purely viscous flows renders error there improbable; and for purely turbulent flows any variation in ν with rate of shear can have no effect on the resultant curve.

The fact that viscosity, when its effect is small, produces an increase in the coefficient of discharge (perhaps due to its causing an increase in the coefficient of contraction) is in agreement with previous experiments carried out at Messrs. Geo. Kent's, and with the results obtained by Davidson in the case of water. The results obtained by Osborne Reynolds† and subsequent experimenters for the pressure gradient in the case of flow in pipes, show a similar increase in the discharge caused by slight viscosity. Another set of experiments showing a similar result is the determination at the National Physical

* Proc. Roy. Soc., A., Vol. LXXXIX., 1913-14, p. 94.

† Osborne Reynolds, Phil. Trans. Roy. Soc., 1883.

Laboratory of the force exerted on a cable by a transverse air current.*

In conclusion the author would like to thank Messrs. Geo. Kent, Ltd., for the facilities that have made these experiments possible; Mr. J. L. Hodgson, at whose instance the experiments were made, for his kindness in suggesting such an interesting problem for investigation; and Mr. F. Gray, conjointly with whom the tests were made, for his kindly co-operation throughout the progress of the work.

DISCUSSION.

Mr. A. S. E. ACKERMANN said he had made experiments of a similar character in which the substance tested was clay. The clay was packed in a box with an orifice of from 3 to 20 millimeters diameter in the bottom. The space above the clay contained air, and the pressure was raised by means of a pump.

The speaker then drew curves on the board to show his main results. With any particular orifice a certain initial pressure is required before any clay is forced out. As the pressure increases the rate of the flow becomes more rapid, and finally becomes very rapid indeed. The critical pressures and the orifice diameters were connected by the law $pd^{0.833}=5408$ for a clay with 29 per cent. water. Similar results are obtained in forcing a disc through clay. The speaker mentioned that these and other results were given in a Paper by him to the Society of Engineers, which was at present in the Press.

Mr. BOND said the phenomena described by Mr. Ackermann were probably due to plasticity, rather than viscosity.

* Report of the Advisory Committee on Aeronautics, 1912-14.