PAP 213

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UNITED STATES GOVERNMENT

Memorandum

HYDRAULICS BRANCH
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Memorandum

Denver, Colorado

TO : Files

DATE: October 28, 1964

Through: Chief, Hydraulics Branch

FROM : Henry T. Falvey

BUREAU OF RECLAMATION
HYDRAULIC LABORATORY
OFFICE
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SUBJECT: Critique of three exotic proposals intended to reduce friction losses in large conduits

In the daily notes of the Hydraulics Branch for June 9, 1964, three proposals were listed to reduce the friction losses in large conduits. (See Appendix.) These proposals were:

1. Using a gas film in the boundary layer
2. Using annular grooves filled with air over which the transported fluid passes
3. Applying suction to the porous inner wall of a double walled pipe

This memorandum presents a critique of these methods which is based on established hydraulic principles. In each case the effect of these proposals on the friction loss is given and an estimate of magnitude of the effect is included when possible.

Introduction

These proposals represent two of the several methods which have already been developed experimentally to control the boundary layer. A more complete list includes the following:

1. Motion of solid walls
2. Acceleration of the boundary layer
3. Removal of the decelerated fluid particles from the boundary layer by suction
4. Prevention of transition to turbulent flow by suitable shapes (laminar airfoils)
5. The use of a gas film in the boundary layer

The primary purpose of boundary layer control is to reduce losses by either retarding, and in some cases preventing, separation of the flow from the flow surface, or by retarding the formation of the turbulent boundary layer for some particular value of the Reynolds number. Boundary layer control can also be used to increase the thickness of the laminar sublayer thus covering up surface roughnesses.

The retardation of separation is important in the cases of bodies with blunt or rounded stems. For these cases, the form drag

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decreases suddenly as the point of flow separation moves farther downstream on the body as the Reynolds number is increased (Figure 1). With a cylinder this occurs with a Reynolds number of about 4×10^5 and is due to the formation of a turbulent boundary layer. This turbulence brings high energy fluid particles in the boundary layer, thereby retarding separation and causing the point of separation to occur farther downstream. Since the point of separation is farther

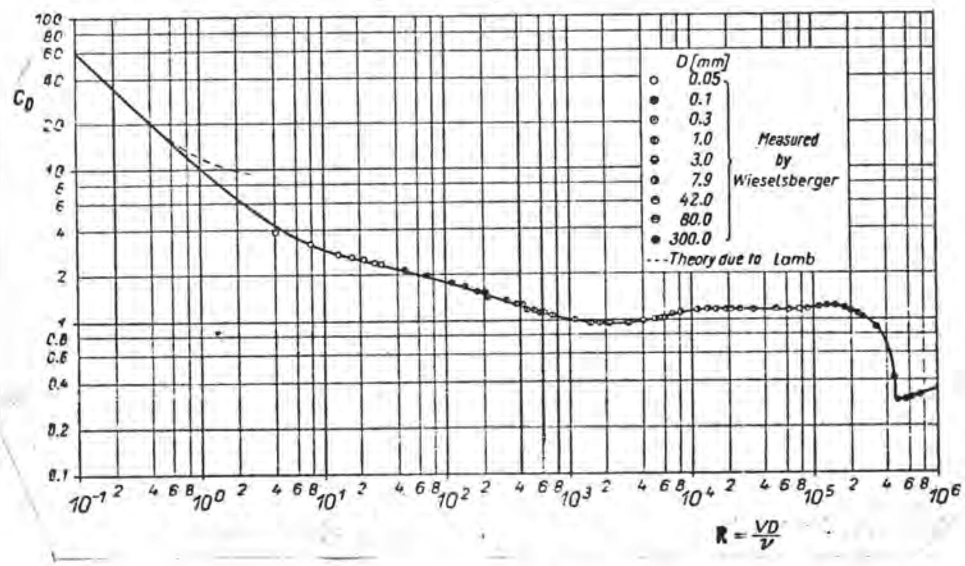

Figure 1. Drag Coefficient for Circular Cylinders[1]

$C_D = \frac{F/A}{\rho V_o^2/2}$ where F = force, A = cylinder diameter x length

ρ = fluid density, V = velocity, ν = fluid viscosity

downstream, the wake of the cylinder or of even other relatively blunt forms is smaller. This results in an increased pressure on the downstream side of the body (Figure 2). The increased pressure which acts over a large portion of the downstream area produces a force which is directed upstream. This upstream force acting opposite to the direction of the drag force explains the lower net drag on the body when the point of separation has moved downstream.

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[1] Rouse, H., Engineering Hydraulics, Wiley and Sons, 1949.

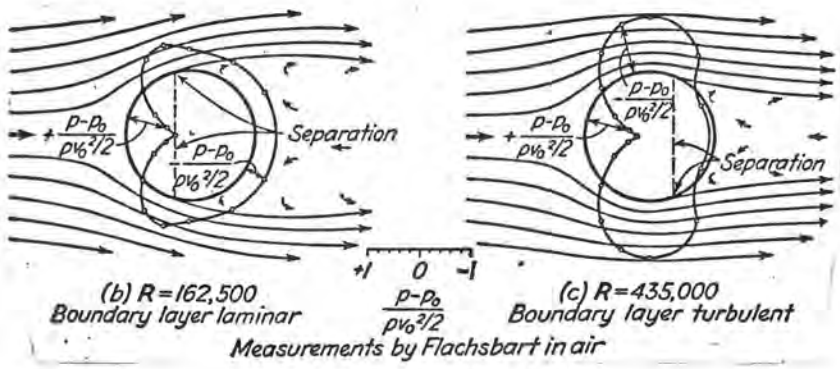

Figure 2. Effect of Boundary Layer on Point of Separation for Circular Cylinder[1]

where P = pressure on the body

Po = free stream pressure

For slenderer body forms, the sudden jump in the drag curve becomes less pronounced. With streamlined bodies, the sudden change in the drag curve disappears completely because separation does not occur. For these cases, the skin friction or surface resistance has a greater effect on the resistance to flow than the form drag. Thus, where form drag is small, further reducing the loss becomes a problem of retarding or eliminating the formation of a turbulent boundary. The effect of a turbulent and a laminar boundary layer on the friction loss coefficient can be seen in Figure 3. The objection might be made that laminar flow does not exist for a Reynolds number (based on the distance from the beginning of the flat plate) higher than 5×10^5. This objection is valid under most circumstances. However, a method will be discussed in a subsequent section which describes a procedure to maintain laminar flow for very large Reynolds numbers.

[1] See page 2.

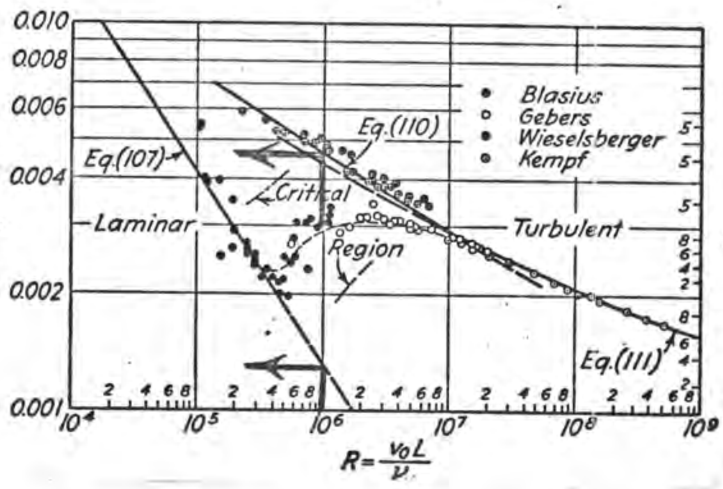

Figure 3. Effect of Boundary Layer on Surface Resistance[1]

$$C_f = \frac{F/BL}{\rho V_o^2/2}$$ where F = force, B = width of surface,

L = length of surface

Since flow in a pipe is primarily a function of surface resistance, the problem of reducing losses is one of either retarding the formation of the turbulent boundary layer or increasing the thickness of the laminar sublayer to cover up the surface irregularities. The specific manner in which each of the three proposals achieves either of these results is discussed in the following sections.

Use of a Gas Film in the Boundary Layer of the Flow

a. Motion of bodies through a fluid

Laminar flow can be considered as the flow condition which exists whenever a disturbance of any magnitude or frequency is completely damped. The opposite condition in which a disturbance of any magnitude or frequency was not damped or perhaps even amplified is turbulent flow. Between these two extremes exists a condition for which the flow is on the brink of becoming unstable. This condition is known as the "limit of stability" and is generally

[1] See page 2.

regarded as the largest Reynolds number for which disturbances of any wave length are still damped. With airfoil sections it is desirable to move the point at which the limit of stability occurs as far downstream on the airfoil as possible and at the same time keep the Reynolds number as small as possible. Figure 4 shows the location for the limit of stability for a laminar airfoil shape as a function of the Reynolds number.

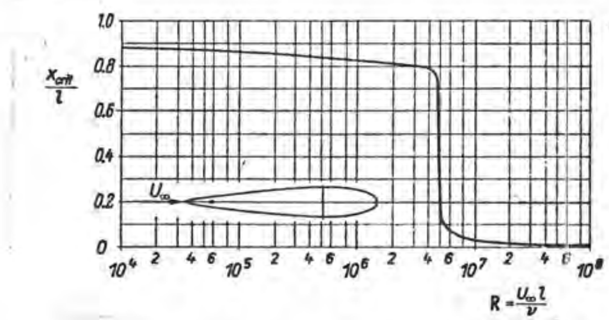

Figure 4. Location of Limit of Stability for a Laminar Airfoil[2]

l = arc length of airfoil, X_{crit} = distance along airfoil surface to point of transition from a laminar to a turbulent boundary layer, U_∞ = free stream velocity

The drag coefficient for a slightly different laminar airfoil is given in Figure 5.

[2] Schlichting, H., Boundary Layer Theory, McGraw-Hill, 1955.

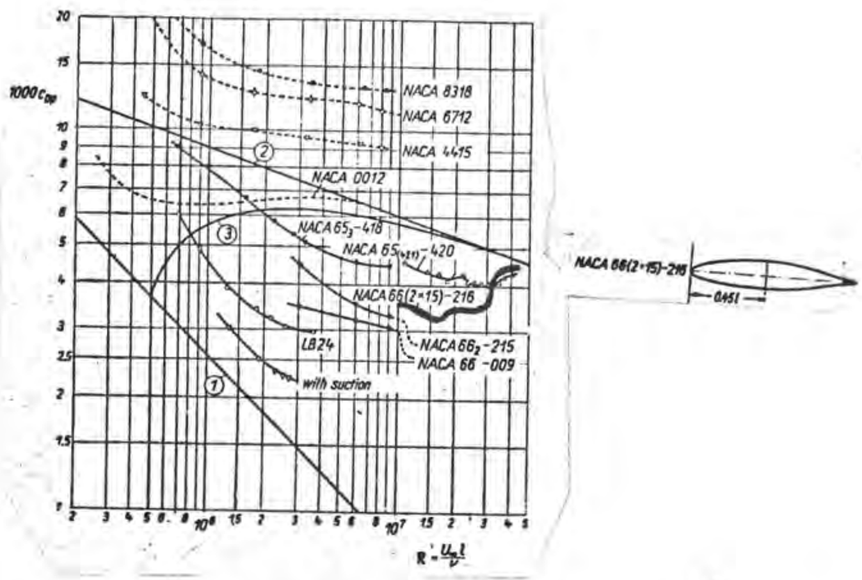

Figure 5. Drag Coefficient for a Laminar Airfoil[2]

$$C_{DP} = \frac{F/B}{\rho V_o^2/2}$$ where F = force, B = width of airfoil,

l = arc length of airfoil

The minimum loss for the NACA 216 airfoil is seen to appear in the range of Reynolds numbers from 1.5×10^7 to 1.7×10^7. This range represents that range of the minimum Reynolds numbers for which the limit of stability is still toward the downstream end of the airfoil. If the operating conditions for this airfoil result in Reynolds numbers which lie outside of this range, the losses will be greater. One method to force the Reynolds numbers back into the optimum range is through the injection of a fluid with the correct viscosity into the boundary layer. Thus it can be seen that the losses for the NACA 216 airfoil operating in water at a Reynolds number of 2×10^8 could be reduced by injecting air, which has a kinematic viscosity of about 10 times that of water, Figure 6, into the boundary layer. This would bring the effective Reynolds number back into the 2×10^7 range.

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[2] See page 5.

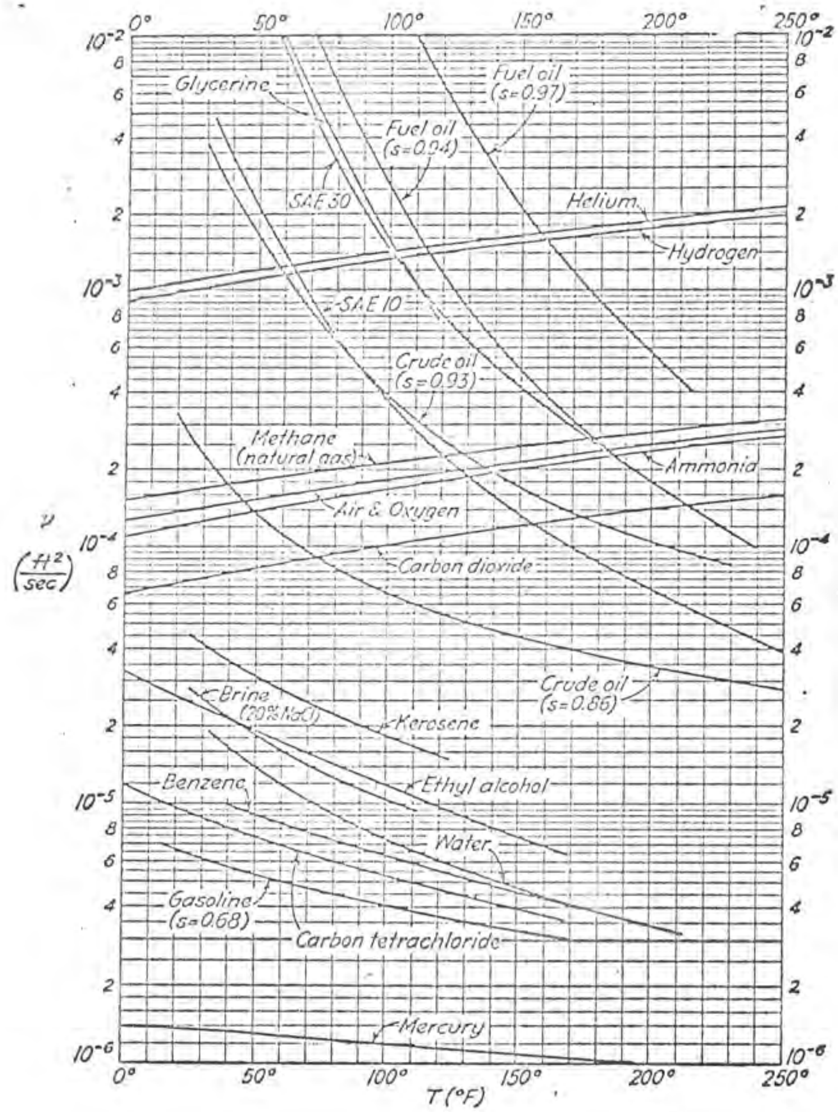

Figure 6. Kinematic Viscosity Versus Temperature for Various Fluids1/

One important factor which comes into play with the use of gas films in the boundary layer is the effect of the density gradient on the limit of stability. If the density decreases vertically upward, the arrangement can be stable. Thus, stable conditions may result when air is used in the boundary layer and water is used in the main flow beneath a horizontal plate. The relationship which governs the stability of moving fluids with a density which decreases vertically upward is given in Figure 7.

1/See page 2.

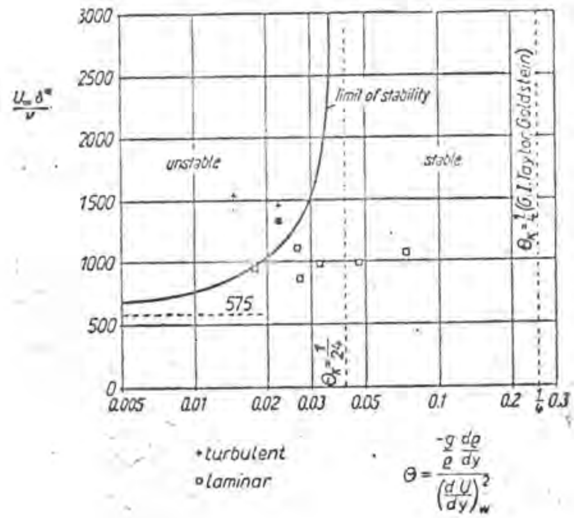

Figure 7. Stability of Moving Fluids with Density Gradients 2/

δ^* = displacement thickness, $\frac{d\rho}{dy}$ = density gradient

$\frac{dU}{dy}$ = velocity gradient at the wall

With a density gradient which decreases vertically downward the arrangement is always unstable, even for motionless fluids. An example of this is a fluid which is heated from below. Thus unstable conditions result when using air in the boundary layer and water in the main flow on top of a plate, or between parallel walls. This instability could defeat the purpose of injecting gas or other fluids into the boundary layer.

Thus from the previous considerations about the location of the limit of stability and the effect of density gradients on the limit of stability it has been shown that under certain conditions injection of gas into the boundary layer can be used to reduce drag on hydrofoils, submarines, and possibly subsurface drag on surface ships. The reduction in the loss is due to the downstream shift in the point of the limit of stability.

b. Movement of fluids through a pipe

The use of gases in a pipe to reduce the drag and, hence, the loss is due to an entirely different phenomenon. This reduction is due

2/See page 5.

to the enclosing of the boundary roughnesses by the laminar sublayer. For instance, experiments have shown that when the laminar sublayer is larger than 4K, where K = the sand grain roughness, the boundary can be considered smooth. However, when the laminar sublayer is less than 1/8K, the boundary can be considered rough.[2] Thus a change in the boundary layer thickness by a factor of 32 (Schlichting gives 35) can produce a change in the flow regime from flow characterized by a rough pipe to flow characterized by a smooth pipe.

The thickness of the laminar sublayer, δ', is given by approximately

$$\delta' \approx \sqrt{\frac{5\nu}{V_*}}$$

where V_* is the shear or friction velocity.

This equation indicates that an increase in the viscosity of the laminar sublayer will result in an increase of the laminar sublayer thickness. If this increase is enough to partially enclose the pipe roughness, then the loss coefficient will decrease. A decrease in the loss coefficient has the effect of reducing V_*, since

$$V_* = \sqrt{\frac{\lambda\rho}{\delta}}\ \overline{U}$$

where λ = the loss coefficient

ρ = the density of the fluid in the sublayer

$\overline{U}$ = the average velocity in the pipe

This will also tend to increase the sublayer thickness, δ', further reducing the loss coefficient. The ultimate decrease in the loss coefficient must be determined by successive approximations, but cannot be less than the loss coefficient for a smooth pipe with turbulent flow.

If, on the other hand, an increase in the laminar sublayer is insufficient to significantly enclose the pipe roughness, then the injection of gas will have a negligible effect in reducing the loss.

As mentioned previously, the stability of the laminar sublayer is dependent upon the density gradient in the layer. The only case

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[2] See page 5.

for which this layer could remain stable in a pipe is one in which the densities of the injected fluid and the transported fluid are approximately equal. Thus, a fuel oil whose density is 61 lb per ft^3 and whose viscosity is about 1,000 times that of water could conceivably be used to reduce the friction losses (Figure 6).

Experiments by Mavis and Bustamante tentatively confirmed the above considerations.[3] In their tests air was injected along the top of a conduit carrying water (a stable condition) and the experimenters observed a slight increase in the velocity (hence discharge) for a given slope.

From a practical standpoint, the mechanics of injecting a fluid into the laminar sublayer may present some insurmountable problems. Since the laminar sublayer is very thin (about the order of magnitude of the pipe roughness), the velocity of the injected fluid must be very small to prevent the fluid from passing through the sublayer. If the injected fluid did pass through the sublayer, the friction loss might be increased instead of decreased due to the added disturbance on the pipe wall. This problem can only be resolved through experimental investigations.

Conclusions

1. The decrease in drag as a result of injecting a gas into the boundary layer of airfoil or hydrofoil shapes (e.g., a submarine) is caused by a downstream shift in the point of stability.

2. The decrease in drag and, hence, the loss as result of injecting gas into the boundary layer of a pipe is caused by a covering up or enclosing of the surface roughness.

3. The ultimate decrease in the loss of a pipe with the injection of a fluid into the boundary layer is governed by the law of resistance with smooth pipes.

4. For a maximum reduction in the loss, the fluid which is to be injected into the laminar sublayer of a pipe must be more viscous than the fluid transported, but should have a density almost the same as the fluid transported.

5. The mechanics of injecting a fluid into the laminar sublayer may present some insurmountable problems. The investigation of this aspect must be done experimentally.

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[3] Mavis, F. T., Bustamante, F., A Basic Model Study Simulating Effects of Air Entrapment in Unlined Water Tunnels through Rock, IAHR, Sixth Meeting, 1957, Paper C6.

Use of Annular Grooves in Which Air is Maintained and Over Which the Flow Passes

Experiments by Falvey indicate that the only proportion of groove for which air might be maintained in the groove is one in which the depth equals the length.[4] However, this groove resulted in a loss that was greater than that of a section of pipe without the groove. In addition, the effect of these grooves is to increase, not decrease, the boundary layer thickness. In the tests, no significant difference in the head loss was observed between the grooves when they were filled with air and when they were filled with water. In addition, tests by Streeter[5] with a spiral groove of the above configuration along the entire length of the pipe resulted in a loss which was greater than the loss for a pipe without the grooves. However, in these tests no effort was made to maintain air in the grooves.

Conclusion

This proposal probably results in greater, not smaller, losses.

Use of Suction to Reduce Friction Drag

The effect of suction on reducing the friction drag has been investigated for flow along a flat plate.[1] These results when applied to a pipe will not give exact numerical values, but the results can be used to determine the order of magnitude of the reduced friction drag. This proposal is based on the fact that the suction alters the patterns of the flow lines (Figure 8).

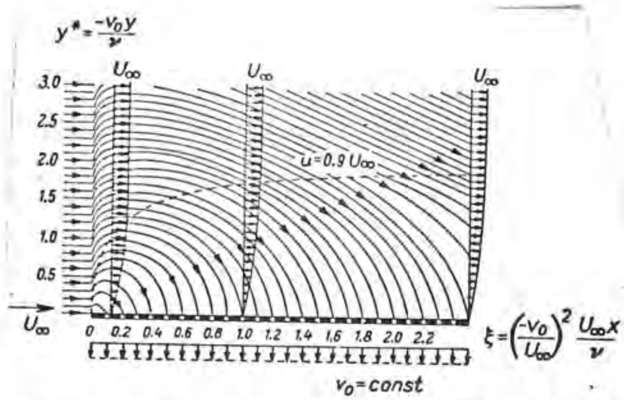

Figure 8. Streamline Pattern for a Flat Plate with Uniform Suction[2]

[4] Falvey, H. T., Strömungsvorgänge und Energieverluste bei Nischen, Doctorial Thesis, Technische Hochschule, Karlsrule, Germany.

[5] Streeter, V., Frictional Resistance in Artificially Roughened Pipes, Trans. ASCE, Vol. 101, 1936.

[1] See page 2.

[2] See page 5.

If the suction is large enough, the turbulent boundary layer is effectively eliminated and essentially laminar flow conditions exist is the pipe. If the suction is too great, the laminar flow conditions still exist, but the system is inefficient because more flow than necessary is removed from the pipe. Thus, a suction exists which is just sufficient to maintain the laminar flow condition. This is called "optimum suction." The discharge through the wall that is required to maintain optimum suction is given by

where $Q_w = C_q A V_\infty$

Q_w = discharge through the wall

C_q = volume coefficient = 1.18×10^{-4} for a flat plate

A = wetted area

V_∞ = free stream velocity. In a pipe this would be the centerline velocity and is approximately equal to $\frac{2Q}{A}$ with fully developed laminar flow

With optimum suction, the resistance to flow is roughly equal to the resistance with laminar flow, Figure 9.

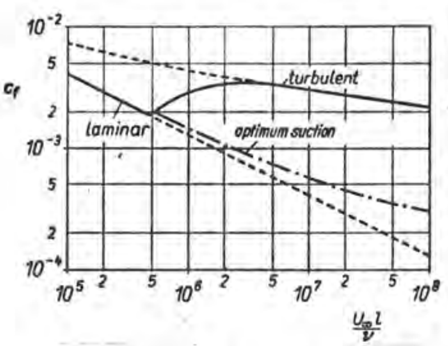

Figure 9. Effect of Optimum Suction on the Resistance to Flow Along a Flat Plate[2]

Since the flow in a pipe remains laminar up to a pipe Reynolds number of roughly 2100, optimum suction is beneficial only at

[2] See page 5.

higher Reynolds numbers. The advantage of using the optimum suction in reducing the friction loss is evident in a plot of the percent reduction versus the Reynolds number, Figure 10.

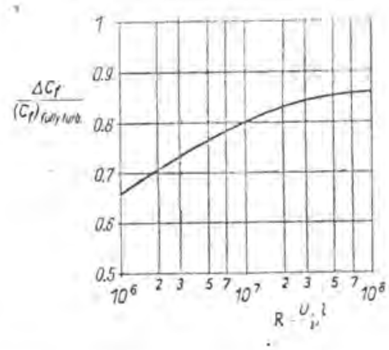

Figure 10. Percent Reduction in the Friction Loss Along a Flat Plate with Optimum Suction[2]

where $\Delta C_f = C_f$ turb - C_f with optimum suction

Although the suction tends to retard the turbulent boundary from forming, the flow never completely attains the laminar flow condition. Because of this, the percent reduction in the friction loss approaches some limit which is less than unity.

The maintenance of a uniform suction which is required to have optimum suction may present practical problems in a pipeline due to the pressure gradient. These might be solved through the use of variable-sized pores in the pipe or even by maintaining an equal gradient but of a smaller magnitude around the porous pipe.

The amount of water required to maintain the optimum suction can become a significant percentage of the total inflow into the pipe. For instance, the discharge which passes through the pipe is given approximately by

$$Q = VA = V\pi r^2$$

[2] See page 5.

The discharge through the wall, as given previously, is

$$Q_w = C_q AV$$

or for a pipe

$$Q_w = C_q \pi dL \, 2V$$

The percentage outflow to maintain optimum suction given approximately by

$$\frac{Q_w}{Q} = \frac{C_q \pi dL \, 2V}{\pi d^2 V/4}$$

$$= 8C_q \frac{L}{d}$$

Therefore, with large L/d ratios, that is long pipelines, the required outflow will be large.

These considerations are illustrated through the following practical example:

Example

Assume that the optimum suction is applied to 2,000 feet of straight, new, 36-inch-diameter, continuous, porous pipe, carrying 150 cubic feet per second of water at 40° F. The problem is to find the amount of discharge required to produce this optimum suction and the head loss when optimum suction is applied. These values are to be compared to the head loss in an equivalent concrete pipe without suction.

Discharge Computations

Using the results of flow over flat plates, the discharge through the pipe wall can be found from the equation

$$Q_w = C_q \, dL \, 2 \, \frac{Q}{A} \cdot$$

$$Q_w = \frac{(1.18)(3\pi)(2)(2)(150)(4) \times 10^{-1}}{9\pi} = 47.2 \text{ cfs}$$

Head Loss Computations

The Reynolds number for flow in the pipe is

$$R = \frac{VD}{\nu} = \frac{(42.5)(3)}{1.8 \times 10^{-5}} = 7.1 \times 10^6$$

The equivalent Reynolds number for a flat plate can be computed by assuming the pipe radius is equal to the boundary layer thickness. Thus

$$\frac{V_\infty}{\nu} = \frac{(7.1 \times 10^6)}{2} \approx 5\sqrt{\frac{V_\infty X}{\nu}}$$

or

$$\frac{V_\infty X}{\nu} \approx 5 \times 10^{11}$$

From extrapolating Figure 10 for this Reynolds number the relative savings in drag on a flat plate with optimum suction is

$$\frac{\Delta C_f}{C_f} = 86 \text{ percent}$$

The rugosity for the porous concrete pipe would probably be about 0.001 foot. Thus

$$\frac{\epsilon}{D} = \frac{0.001}{3.0} = 0.0003$$

From a Moody diagram[6] using

$$\frac{\epsilon}{D} = 0.0003 \text{ and } Re = 7 \times 10^6$$

[6] USBR Monograph No. 7, Friction Factors for Large Conduits Flowing Full.

The friction factor is

$$f = 0.0103$$

The friction factor with optimum suction would thus be

$$f \text{ feet} = (0.0103)(1.00 - 0.86) = 0.00144$$

The head loss with optimum suction is

$$h_L = \frac{fL}{D}\frac{V^2}{2g} = \frac{(0.00144)(2{,}000)}{(3)(64.4)} \; \frac{\left(150 + \frac{47.2}{2}\right)^2}{(7.07)^2}$$

$$= 9.0 \text{ feet}$$

Using the example in Reference 6, the equivalent loss in head using continuous interior steel pipe, factory dipped in hot asphalt, is

$$= 57.8 \text{ feet}$$

The diameter of pipe with optimum suction which has the same head loss as an equivalent steel pipe is given by

$$d = 5\sqrt{\frac{fLQ^2}{h_L\ 39.6}} = 5\sqrt{\frac{(1.44)(2)(3.02) \times 10^4}{(5.78)(3.96) \times 10^2}}$$

$$= 2.08 \text{ feet}$$

Conclusions Based on a Reynolds Number $> 2 \times 10^5$

1. The loss in a pipe can be reduced by a factor of about 80 percent by application of the optimum suction; that is, just enough suction to maintain laminar flow in the pipe.

2. The amount of discharge through the pipe walls that is required to maintain optimum suction can become a significant part of the total discharge for pipes that have large length to diameter ratios. For the example, Q_w/Q was about 24 percent.

3. The pipe diameter can be reduced about 25 percent with optimum suction, and the system will have the same magnitude of head loss as the original pipe without optimum suction.

4. Maintaining a uniform flow out of the conduit will present many difficulties in practice since the pressure head decreases along the conduit.

Summary of Proposals to Reduce Friction Losses in Large Conduits

The usefulness of the three proposals in reducing the friction losses in large conduits can be summarized as follows:

1. The use of a gas film in the boundary layer can be used to reduce friction losses in rough pipes. The minimum friction loss attainable is characterized by the loss in smooth pipes. Experiments must be performed to develop means of injecting the gas film into the boundary layer and to find a gas or fluid which could be satisfactorily used with water.

2. The use of annular grooves filled with an air over which the transported fluid passes will result in increased friction losses. Therefore, this proposal is not applicable as a means to reduce losses in conduits.

3. The use of suction to reduce friction losses in large conduits appears feasible for pipelines with small length to diameter ratios. Experiments must be performed to determine the optimum suction discharge rate, as well as, to obtain the required physical characteristics of the porous pipe and configuration of the suction system.

Henry T. Falvey

APPENDIX

Form DFC-11
(12-61)
Bureau of Reclamation

INFORMATIONAL ROUTING

Memorandum

G. E. Burnett

H. M. Martin

Denver, Colorado
June 10, 1964

Daily Record--Hydraulics Branch

June 8, 1964

Granby Dam Spillway

Jabara and Wentz came to the laboratory to see the operation of the model with the pad height in the transition section increased to 16 inches. The flow distribution in the jet was improved for free flow; however, it was noted that for gate-controlled flows the concentration of water was greater on the left-hand side of the jet. Jabara proposed installing an additional pad farther downstream on the right-hand side of the chute.

June 9, 1964

Granby Dam Spillway

Jabara and Wentz came to the laboratory to view the operation of the model with a 12-inch-high triangular shaped pad installed on the right-hand side of the chute in the panel upstream from the P.C. of the vertical curve. This pad was in addition to the 16-inch pad and the performance for gate-controlled flows was quite good. While the designers were here, the upstream pad was removed which improved the flow distribution in the jet still further for gate-controlled flows in the vicinity of 1,200 cfs. The model was operated also with this pad removed. This arrangement produced heavy concentration of water on the right-hand side of the jet for all flows whether gate controlled or not. Jabara said that he would show the one 12-inch-high pad on the right-hand side in the revised spec drawings and that he would compute velocities at the beginning of the bucket for flows of 1,200 and 500 cfs using roughness coefficients of n=0.008 and n=0.013. We will then operate the model regulating the velocities as close to these values as possible for a further check on this latest pad design.

Friction Losses in Large Conduits

I had a call from Mr. John Carlson of the Franklin Institute, Philadelphia, who inquired about the possibility of implementing several ideas developed by Dr. George P. Wachtell of that institution. Mr. Carlson had talked to T. W. Mermel recently who referred Mr. Carlson to the Chief Engineer's Office. Dr. Wachtell explained that he proposed using a gas film in the boundary layer of flow in large conduits to modify the velocity gradient and reduce friction losses from roughness. He recalled that this idea has been used experimentally on ship hulls and particularly on submarines. Dr. Wachtell recognized, of course, that to inject a gas at frequent intervals in a conduit would risk the possibility of reducing the flow due to the accumulation of gas. A further development utilizes a conduit made with annular grooves in which air is maintained. In effect, the flow of fluid passes over a series of air pockets supported by annular ridges. A further thought included a double-walled pipe, the inner pipe being porous. A suction would be applied to the annular space between the concentric pipes to control the boundary layer of the inner pipe which conveys the fluid. He reasoned that with a nominal amount of power required to convert the flow from turbulent regime to laminar the boundary layer losses could be greatly reduced, thereby reducing the head losses.

It was explained to Mr. Carlson and Dr. Wachtell that the Bureau of Reclamation design and construction responsibilities lie largely in the field of irrigation water distribution and hydropower. Offhand, it was difficult to recognize any ready application of these ideas in irrigation and power engineering. Mr. Carlson and Dr. Wachtell explained then that they visualized application of these ideas in the transport of demineralized sea water where pumping costs would be high and research may very well be justified by operating costs. They were referred to the Office of Saline Water, particularly Dr. W. S. Gillam, Chief, Division of Research, Office of Saline Water.

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