FLUID MECHANICS (DYNAMIC)

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LECTURE 1

Elementary Fluid Dynamics.
Newton’s Second Law.
The Bernoulli Equation.
Static, Stagnation, Dynamic, and Total Pressure.

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Newton's Second Law

As a fluid particle moves from one location to another, it usually experiences an ***acceleration*** or ***deceleration***. According to Newton's second law of motion, the net force acting on the fluid particle under consideration must equal its mass times its acceleration,

$$F = m\,a \quad \text{..................(1)}$$

We consider the motion of inviscid fluids. That is, the fluid is assumed to have zero viscosity. If the viscosity is zero, then the thermal conductivity of the fluid is also zero and there can be no heat transfer (except by radiation).

In practice there are no inviscid fluids, since every fluid supports shear stresses when it is subjected to a rate of strain displacement.
For many flow situations the viscous effects are relatively small compared with other effects.

We assume that the fluid motion is governed by pressure and gravity forces only and examine Newton's second law as it applies to a fluid particle in the form:

(Net pressure force on particle) + (net gravity force on particle)=
(Particle mass) x (particle acceleration)

The results of the interaction between the **pressure**, **gravity**, and **acceleration** provide numerous useful applications in fluid mechanics.

Inviscid fluid flow is governed by pressure and gravity forces.

Steady flow: The velocity at a given point in space does not vary with time,

$$\frac{\partial V}{\partial t} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Unsteady flow: The velocity at given point in space does changing with time.

$$\frac{\partial V}{\partial t} \neq 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

In reality, almost all flows are unsteady in some sense.

Here, we will be concerned with two-dimensional motion like that confined to the x–z plane as is shown in Fig. A. Clearly we could choose to describe the flow in terms of the components of acceleration and forces in the **x** and **z** coordinate directions.

The resulting equations are frequently referred to as a two-dimensional form of the ***Euler equations of motion*** in rectangular Cartesian coordinates.

Σ Force = Mass * Acceleration

$$d\left(\frac{P}{\gamma}+\frac{V^2}{2g}+z\right)=0$$

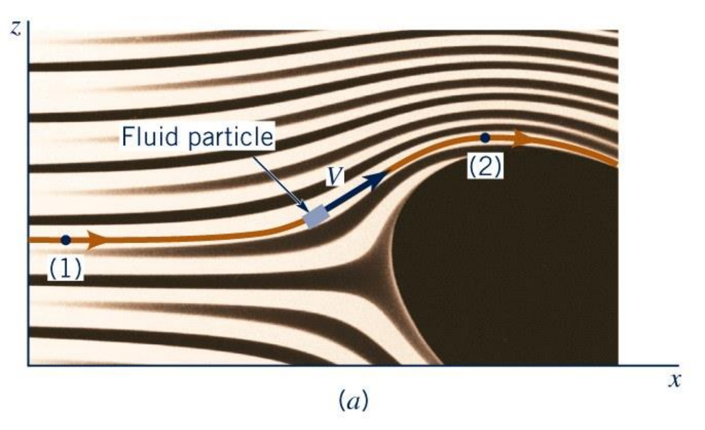


Figure (A)

The motion of each fluid particle is described in terms of its **velocity vector, V**, which is defined as the time rate of change of the position of the particle. The particle's velocity is a vector quantity with a magnitude (the speed, **V= |V|**) and direction.

As the particle moves about, it follows a particular path, the shape of which is governed by the velocity of the particle. The location of the particle along the path is a function of where the particle started at the initial time and its velocity along the path.

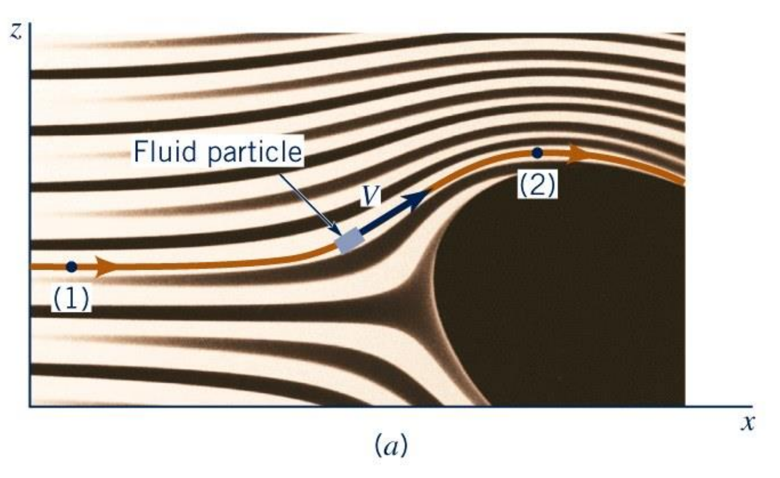


Figure (A)

If it is **steady flow** (i.e., nothing changes with time at a given location in the flow field), each successive particle that passes through a given point [such as point (1) in Fig. A] will follow the same path. For such cases the path is a fixed line in the x–z plane. Neighboring particles that pass on either side of point (1) follow their own paths, which may be of a different shape than the one passing through (1). The entire x–z plane is filled with such paths.

For **steady flows** each particle slides along its path, and its velocity vector is everywhere tangent to the path. The lines that are tangent to the velocity vectors throughout the flow field are called ***streamlines***.

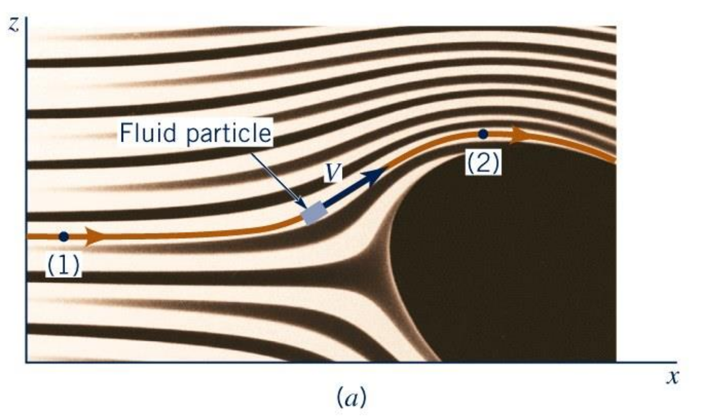


Figure (A)

Bernoull's Equation

Bernoulli equation—a very powerful tool in fluid mechanics. In 1738 Daniel Bernoulli 1(700–1782) published his Hydrodynamics in which an equivalent of this famous equation first appeared.

$$p + \frac{1}{2}\rho V^2 + \gamma z = \text{constant along the streamline} \quad ...(4)$$

$$p + \rho \int \frac{V^2}{\mathcal{R}} dn + \gamma z = \text{constant across the streamline} \quad ...(5)$$

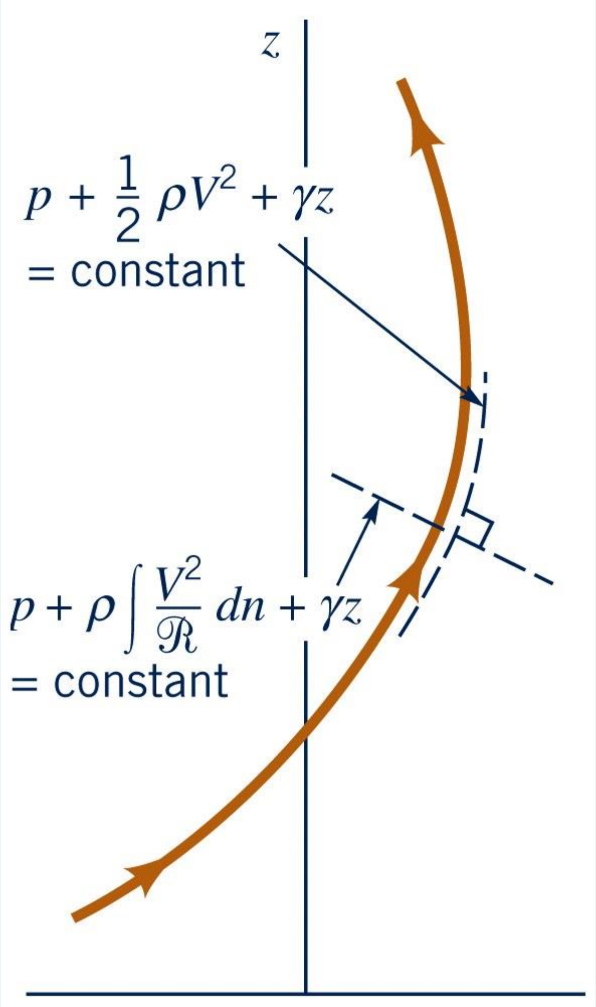


Figure (B)

To use it correctly we must constantly remember the basic assumptions used in its derivation:

1- Viscous effects are assumed negligible.
2- The flow is assumed to be steady.
3- The flow is assumed to be incompressible.
4- The equation is applicable along a streamline.

The basic equations governing fluid motion under a fairly stringent set of restrictions.

Applies to all points on the streamline and thus provides a useful relationship between pressure ***P***, the magnitude ***V*** of the velocity, and the height ***z*** above datum. The Bernoulli constant ***H*** is also termed the ***total head***.

$$\frac{p}{\gamma} + \frac{V^2}{2g} + z = \text{constant on a streamline} \quad ...(6)$$

The elevation term, ***z***, is related to the **potential energy** of the particle and is called the ***elevation head***.

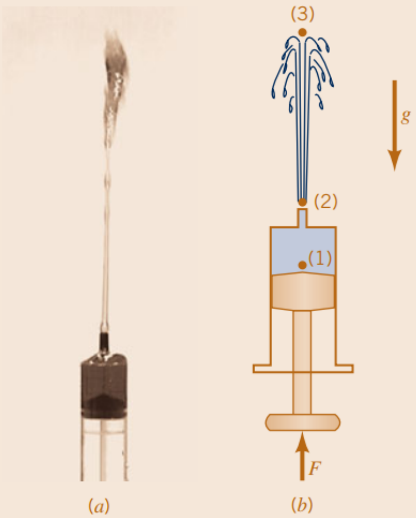
The pressure term, ***P/γ***, is called the ***pressure head*** and represents the height of a column of the fluid that is needed to produce the pressure ***p***.

The velocity term ***$v^2/2g$***, is the ***velocity head*** and represents the vertical distance needed for the fluid to fall freely (neglecting friction) if it is to reach velocity V from rest.

The Bernoulli equation states that the sum of the pressure head, the velocity head, and the elevation head is constant along a streamline.

Example 3.4 Kinetic, Potential, and Pressure Energy

GIVEN Consider the flow of water from the syringe shown in Fig. E3.4*a*. As indicated in Fig. E3.4*b*, a force, *F*, applied to the plunger will produce a pressure greater than atmospheric at point (1) within the syringe. The water flows from the needle, point (2), with relatively high velocity and coasts up to point (3) at the top of its trajectory.



■ Figure E3.4

FIND Discuss the energy of the fluid at points (1), (2), and (3) by using the Bernoulli equation.

Point	Energy Type: Kinetic $\rho V^2/2$	Potential γz	Pressure p
1	Small	Zero	Large
2	Large	Small	Zero
3	Zero	Large	Zero

Solution

If the assumptions (steady, inviscid, incompressible flow) of the Bernoulli equation are approximately valid, it then follows that the flow can be explained in terms of the partition of the total energy of the water. According to Eq. 4, the sum of the three types of energy (kinetic, potential, and pressure) or heads (velocity, elevation, and pressure) must remain constant. The table above indicates the relative magnitude of each of these energies at the three points shown in the figure.

The motion results in (or is due to) a change in the magnitude of each type of energy as the fluid flows from one location to another. An alternate way to consider this flow is as follows. The pressure gradient between (1) and (2) produces an acceleration to eject the water from the needle. Gravity acting on the particle between (2) and (3) produces a deceleration to cause the water to come to a momentary stop at the top of its flight.

Static, Stagnation, Dynamic, and Total Pressure

A useful concept associated with the Bernoulli equation deals with the ***stagnation*** and ***dynamic pressures***.
These pressures arise from the conversion of kinetic energy in a flowing fluid into a "pressure rise" as the fluid is brought to rest.

Each term of the Bernoulli equation, Eq. 4, has the dimensions of ***force per unit area***—psi, ***lb/ft²***, ***N/m²***. The first term, p, is the actual thermodynamic pressure of the fluid
as it flows.

$$p + \frac{1}{2}\rho V^2 + \gamma z = \text{constant along the streamline}$$

The ***first term***, ***P***, is the actual thermodynamic pressure of the fluid as it flows. To measure its value, one could move along with the fluid, thus being "static" relative to the moving fluid. Hence, it is normally termed the ***Static Pressure***.

Another way to measure the static pressure would be to drill a hole in a flat surface and fasten a piezometer tube as indicated by the location of point (3) in Fig. C.

The pressure in the flowing fluid at (1) is $\boldsymbol{P_1 = \gamma\, h_{3-1} + P_3}$, the same as if the fluid were static. The $P_3 = \gamma\, h_{4-3}$. And $h_{3-1} + h_{4-3} = h$

Then $\boldsymbol{P_1 = \gamma\, h}$.

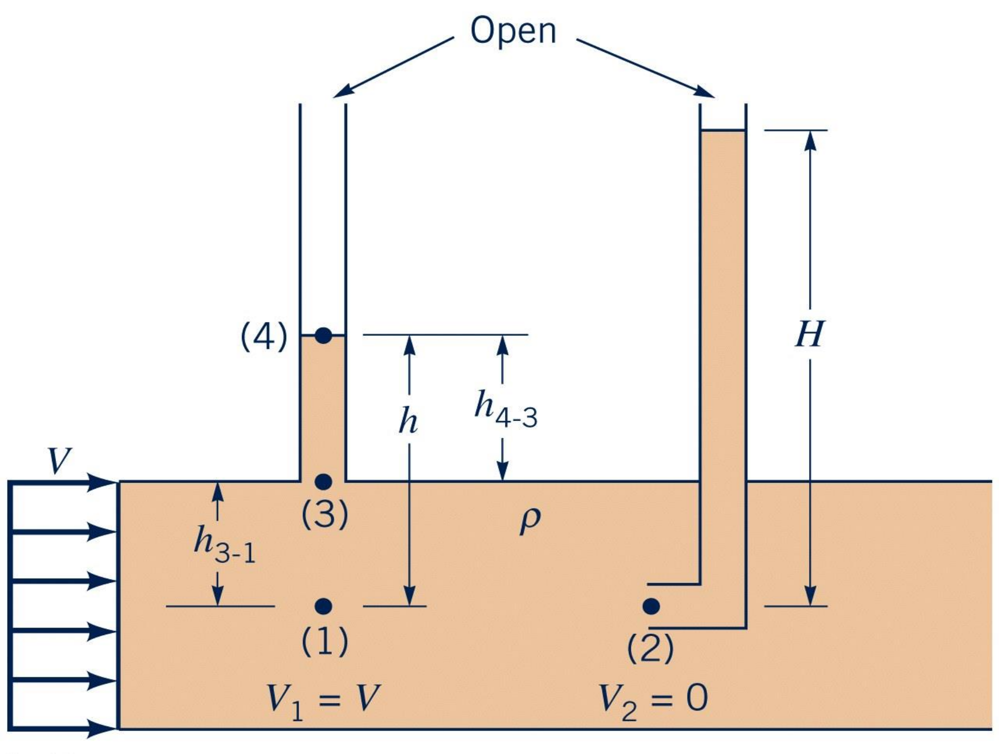


Figure (C)

The ***third term*** γz is termed the ***Hydrostatic Pressure.*** It is not actually a pressure but does represent the change in pressure possible due to potential energy variations of the fluid as a result of elevation changes.

The ***second term*** in the Bernoulli equation, $\rho V^2/2$ is termed the ***Dynamic Pressure***.

After the initial transient motion has died out, the liquid will fill the tube to a height of ***H*** as shown. The fluid in the tube, including that at its tip, (2), will be stationary. That is, $V_2=0$ or point (2) is a ***stagnation point.***

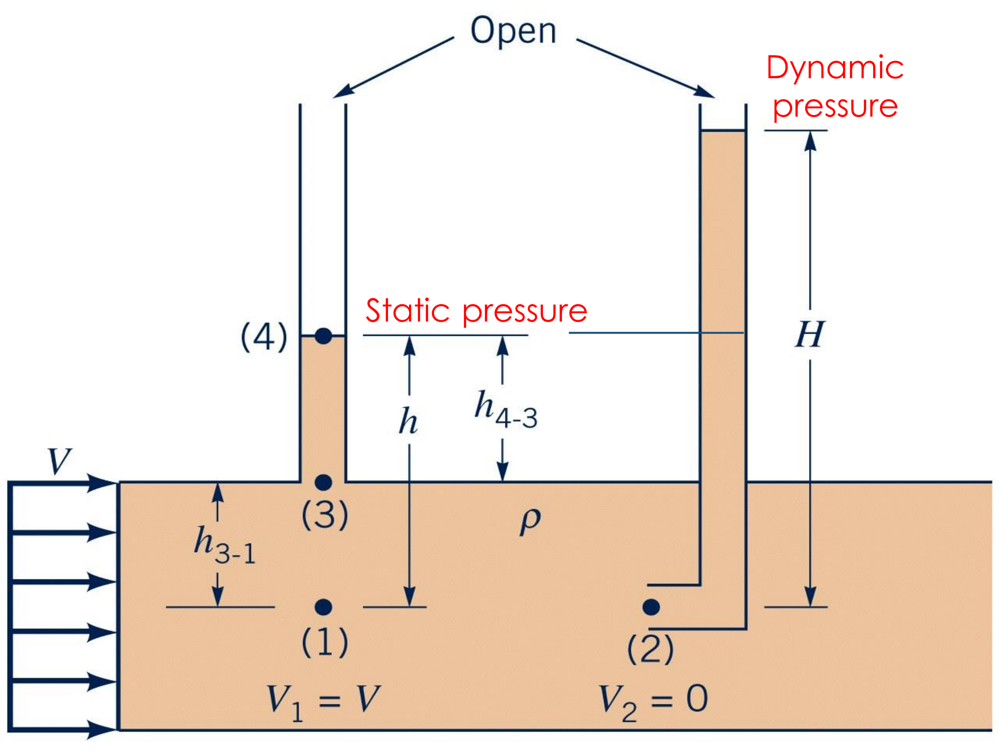


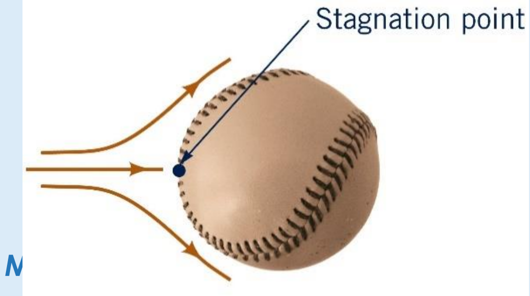
Figure (C)

If we apply the Bernoulli equation between points (1) and (2), using $V_2 = 0$ and assuming that $z_1 = z_2$ we find that

$$p_2 = p_1 + \frac{1}{2}\rho V_1^2$$

the pressure at the stagnation point is greater than the static pressure P_1, by an amount $\frac{1}{2}\rho V_1^2$ the ***dynamic pressure***.

It can be shown that there is a stagnation point on any stationary body that is placed into a flowing fluid.



If elevation effects are neglected, the ***stagnation pressure***, $p + \frac{1}{2}\rho V^2$, is the largest pressure obtainable along a given streamline.

It represents the conversion of all of the kinetic energy into a pressure rise.

The sum of the ***static pressure, hydrostatic pressure,*** and ***dynamic pressure*** is termed the ***total pressure***, The Bernoulli equation is a statement that the total pressure remains constant along a streamline. That is

$$p + \frac{1}{2}\rho V^2 + \gamma z = P_T = \text{constant along a streamline}$$

Water flows through the pipe contraction shown in Fig. P3.51. For the given 0.2-m difference in manometer level, determine the flowrate as a function of the diameter of the small pipe, *D*.

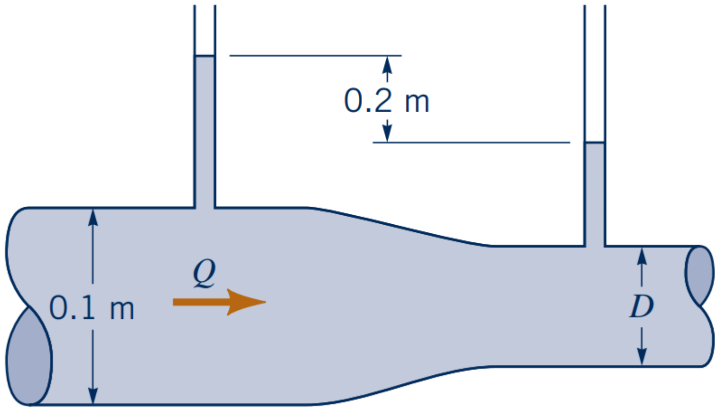


Figure P3.51

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \quad \text{with} \quad A_1 V_1 = A_2 V_2$$

Thus, with $z_1 = z_2$ or $V_2 = \frac{\left(\frac{\pi}{4} D_1^2\right)}{\left(\frac{\pi}{4} D_2^2\right)} V_1 = \left(\frac{0.1}{D}\right)^2 V_1$

$$\frac{p_1 - p_2}{\gamma} = \frac{V_2^2 - V_1^2}{2g} = \frac{\left[\left(\frac{0.1}{D}\right)^4 - 1\right] V_1^2}{2g}$$

but

$p_1 = \gamma h_1$ and $p_2 = \gamma h_2$ so that $p_1 - p_2 = \gamma (h_1 - h_2) = 0.2\gamma$

Thus,

$$\frac{0.2\gamma}{\gamma} = \frac{\left[\left(\frac{0.1}{D}\right)^4 - 1\right] V_1^2}{2g} \quad \text{or} \quad V_1 = \sqrt{\frac{0.2\,(2g)}{\left[\left(\frac{0.1}{D}\right)^4 - 1\right]}}$$

and

$$Q = A_1 V_1 = \frac{\pi}{4}(0.1)^2 \sqrt{\frac{0.2\,(2\,(9.81))}{\left[\left(\frac{0.1}{D}\right)^4 - 1\right]}}$$

or

$$Q = \frac{0.0156\, D^2}{\sqrt{(0.1)^4 - D^4}} \ \frac{m^3}{s} \quad \text{when } D \sim m$$

Water flows through the pipe contraction shown in Fig. P3.52. For the given 0.2-m difference in the manometer level, determine the flowrate as a function of the diameter of the small pipe, D.

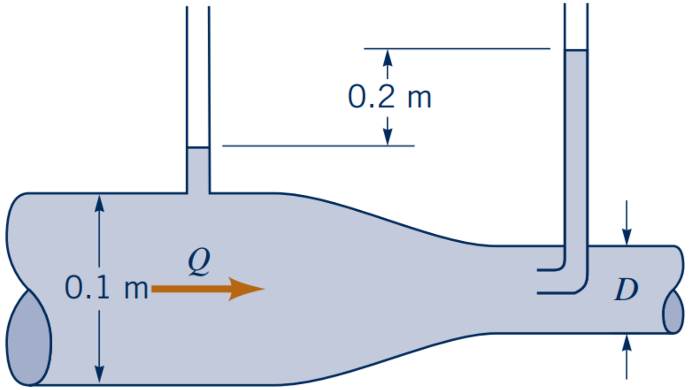


Figure P3.52

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2$$

where $z_1 = z_2$ and $V_2 = 0$.

Thus,

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} = \frac{p_2}{\gamma}$$

But

$\frac{p_1}{\gamma} = x$ and $\frac{p_2}{\gamma} = 0.2\,m + x$ so that

$$x + \frac{V_1^2}{2g} = 0.2\,m + x \quad \text{or}$$

$$V_1 = \sqrt{2g(0.2m)} = \left(2\left(9.81\frac{m}{s^2}\right)(0.2m)\right)^{1/2} = 1.98\frac{m}{s}$$

Thus,

$$Q = A_1 V_1 = \frac{\pi}{4}(0.1m)^2\left(1.98\frac{m}{s}\right) = 0.0156\frac{m^3}{s} \text{ for any } D$$