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Abstract

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Keywords

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A SIMPLE MODEL TO EXTEND 1-D HYDRAULICS TO 3-D HYDRAULICS

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ABSTRACT: the core of fluid mechanics is the study of friction on a solid/liquid interface, the friction force can be divided into skin friction and form drag. Nikuradse's experiments reveal that the friction factor depends on the Reynolds number (Re) and relative roughness (r), this observation implies the co-existence of skin friction and form drag, but the definitions of Re and r given by Nikuradse cannot be linked with the skin friction and form drag, this leads to the invalidity of existing theory to predict the friction factor in a complex flow, like a channel flow with vegetation. To establish a universal relationship, the hydraulic radius, Reynolds numbers and relative roughness are redefined, and the connection of these parameters with the skin friction and form drag is established. For the flowing fluid, the separation region is generated after passing the fluid, and these eddies form a "dead zone", this study reveals that the drag force is proportional to the volume of dead zone. By analyzing the measured data available in the literature, an equation has been established to express the drag force and the volume of dead zone, thus it provides an alternative way to interpret Nikuradse's work and extends the existing outcomes to complex flows.

KEY WORDS: Hydraulic Radius, skin friction, form drag, separation zone, dead fluid volume.

1 INTRODUCTION

Probably, the origin of fluid mechanics can be traced back to Archimedes, the first one who realized the relationship between the force and fluid volume. The Archimedes principle states that the buoyant force of a submerged object is equal to the weight of the fluid volume that the object is displaced. Now it becomes very clear that the buoyant force is a result of pressure force that normal to the interface of liquid/solid of the object. The great contribution made by Euler and Bernoulli is that they developed the governing equations to express the pressure force for ideal fluid that is also called as potential fluid or inviscid fluid. In their equations, there is no force tangent to the interface of solid/liquid, or friction force, i.e., no energy loss incurs, obviously this is impossible. But in practice, the theorem of Euler and Bernoulli can solve some problems in a certain extent. The inclusion of shear stress was made by Navier and Stockes who added the viscous term into Euler's equations (the last term in Eq. 2), and Reynolds added the turbulent shear stress with the following form:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = X_i + \frac{\partial p}{\rho \partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

$$\tau_{ij} = \mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) - \rho\overline{u_i^{'}u_j^{'}} \tag{3}$$

where u = velocity, t = time, x = directions, X = body force; p = pressure, ρ = fluid density; μ = dynamical viscosity, τ = shear stress.

The breakthrough of the above unsolvable equations was made by Prandlt who proposed the concept of boundary layer theory, which divides the whole flow region into two parts, one closes to the object where the simplified Reynolds equations can be applied, the other is called as outer region where the Euler's equations can be used. Unfortunately, the idea of flow region division proposed by Prandtl is only limited to streamlined objects or a flat plate, and the form drag by bluff objects have not been described by any theoretical works.

Generally speaking, flows could be internal and external in terms of its relative position between the fluid and solid boundary. It is interesting to note that all measured curves of friction factor versus Reynolds number are similar. For example, the measured friction factor by Nikuradse reveals and f = f(Re, r), but the mechanism of similarity is not well understood, this leads to that the existing theory cannot be extended to complex flows.

The objective of this paper is to interpret Nikuradse' observations on flow resistance using the concept of skin friction and drag forces, which is be proportional area (e.g., boundary shear stress) and volume (e.g., buoyancy), respectively. This study aims to develop a universal relationship to express the resistance on the interface of solid and fluid, thus the complex flows in porous media and on vegetated bed can be predict.

2 REYNOLDS NUMBER, HYDRAULIC RADIUS AND SKIN FRICTION

The flow resistance is always compromised by skin friction and the form drag, their basic characteristics can be classified by the follow direction near the solid boundary: if the flow is opposite to the incoming flow, the boundary bears the form drag, otherwise the skin friction that depends on the velocity gradient or u_*, viscosity, etc.. For the form drag, the velocity gradient and viscosity are no longer important, and the force depends on the separation zone (or dead zone). The coexistence of form drag and skin friction can be widely observed, and their difference can be defined as shown in Fig. 1:

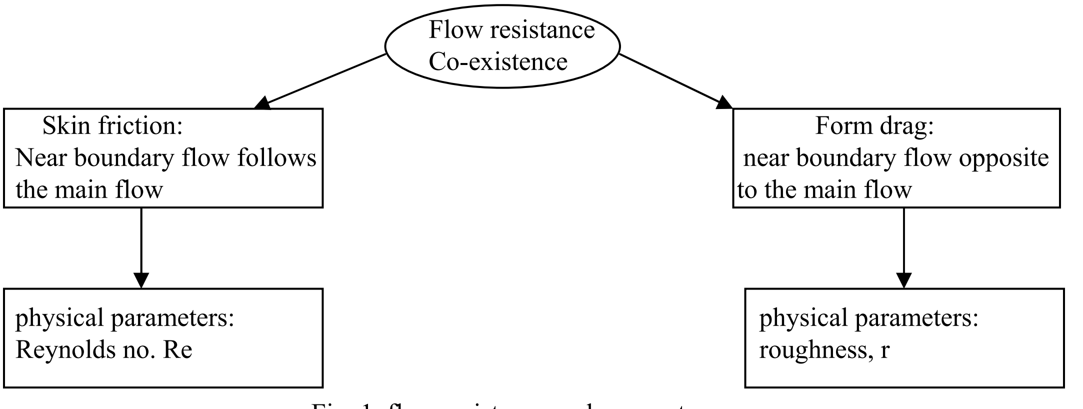


Fig. 1, flow resistance and parameters

The famous experiment by Reynolds in 1883 demonstrated the existence of turbulent and laminar status, which depends on the Reynolds number:

$$\mathrm{Re} = \frac{\rho U R}{\mu} \tag{4}$$

In 3-D hydraulics, it is very hard to definite the Reynolds number as the velocity U has not specified by Reynolds, it could be the mean velocity, shear velocity, etc., also the viscosity that could be a variable dependent on the strain (e.g., viscoelastic fluid). The definition of hydraulic radius R is also very ambiguous with this form of

$$R = \frac{A}{P} \tag{5}$$

where A = cross section area, P = wetted perimeter. The cross area could be very ambiguous in 3-D hydraulics if there is a dead zone in the cross section like a dead zone generated by an abatement in a river, or if there are dense trees or vegetation in the floodplain. Similarly the definition of P is very difficult to determine if the roughness distribution along the wetted perimeter is uneven.
For 3-D hydraulics, we define the hydraulic radius with the following form and the reason will be explained in the following sections,

$$R_y = \frac{V}{A_w} \tag{6}$$

where V = Volume of fluid between any two cross sections, and A_w = the wetted area that fluid may contact the solid surface. Obviously for a pipe/channel flow V = AL and A_w= PL where L is the length of the two cross section, then Eq. 6 gives $R = A/P$ and it has the same result as the 1-D hydraulics gives.
As shown above, the Reynolds number is the index to express the shin friction on the interface of solid/fluid, thus all parameters used in the definition of Reynolds number must be the parameters on the interface, therefore the new definition of Reynolds number in 3-D hydraulics should have the following form:

$$\mathrm{Re}_y = \frac{\rho_y u_* R_y}{\mu_y} \tag{7}$$

where Re_y is the Reynolds number to express the skin friction, the subscript "y" denotes the parameters at the solid/liquid interface (y = 0), and ρ_y = fluid density at the interface, μ_y = fluid viscosity at the interface. Therefore, the Reynolds number in Eq. 7 has very specific definition for every parameter, it has very clear physical interpretation that this Reynolds number is used to express the skin friction on the boundary, and it can be used in 3-D hydraulics if the hydraulic radius is expressed by Eq. 6, which avoids the confusion in the definition of general Reynolds number.

3 SEPARATION ZONE, DEAD FLUID VOLUME AND FORM DRAG

As mention before, the skin friction is proportional to the contact area, this is why the total contact area of solid/fluid interface should be included in Eq. 6. But the dependence of flow resistance on the contact area disappears if the boundary is fully covered by the dead zone where the flow may be opposites to the direction in the main stream. In 3-D hydraulics, the separation zone or dead zone could be very big, and isolated like the bridge piers or abatements. The magnitude of flow resistance could be measured and expressed by the relative roughness with the following form:

$$r_y = \frac{V}{V_{mdz}} \tag{8}$$

where V_{mdz} = maximum volume of dead zone after the solid object, and r_y is the relative roughness in 3-D hydraulics. In 1-D Hydraulics and fluid mechanics, the relative roughness is express as

$$r = \frac{h}{\Delta} \tag{9}$$

where Δ = roughness height and h = water depth or pipe radius.
For a water column, if its base area is unit, then the water volume V = h*1, the V_{mdz} = Δ*1, and therefore Eqs. 8 and 9 may yield the similar result. But the definition in Eq. 9 has no any physical interpretation, and also it includes the volume of solid particles, it is incorrect as the this volume never dissipates any energy. However, Eq. 8 links the parameter to the dead zone volume, it has broader applications in practice, and more importantly, it gives the very clear definition for the parameters with the flow phenomenon.

In Eq. 8, we argued that the relative roughness defined by Nikuradse is actually an index to express the form drag, thus it implies that the form drag can be expressed by water volume. Herein, we explain the relationship shown in Fig. 2 where the volume of dead zone is V_{dz}:

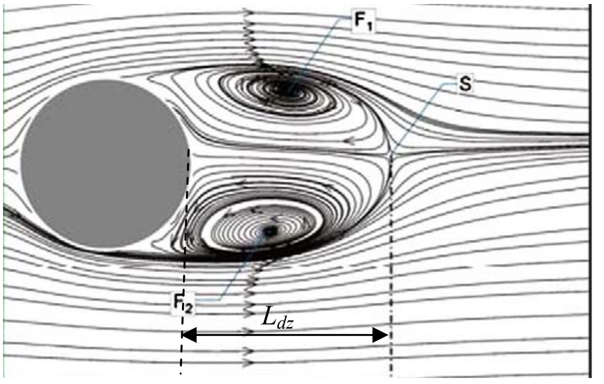


Fig. 2, Dead zone after a sphere as a typical example after Ozgoren et al. (2011).

In Fig. 2, the volume of the dead zone can be estimated as

$$V_{dz} = k_0 A_p L_{dz} \tag{10}$$

where k_0 is a coefficient, A_p is projection area of the object in the flow direction, and L_{dz} is the length of dead zone from an obstacle to the reattachment point with the following expression:

$$L_{dz} = k_1 \frac{U^2}{2g} \tag{11}$$

where U is the approaching velocity just before the obstacle, and k_1 is a coefficient. It is well known that the form drag can be expressed as

$$F_D = C_d \rho A_p \frac{U^2}{2} \tag{12}$$

where is the drag coefficient. Inserting Eqs. 10 and 11 into Eq. 12, one has

$$F_D = k\rho g V_{dz} \tag{13}$$

where $k = C_D/(k_1k_2)$.

Eq. 13 reveals that similar to the buoyant force, the form drag is also proportional to fluid volume, also it extends the concept of boundary layer theory that tells an object has influence only to the boundary region, or the majority of energy to overcome the form drag is dissipated in the dead zone, the larger the zone is, the higher the drag force will be. If the dead zone is occupied by a solid instead of fluid, then the drag force becomes very small and only the skin friction bears the flow resistance, in such case the object becomes streamlined. Eq. 13 provides us a very simple law to explains our daily observations, for example an opening at bridge pier can significantly reduce the form drag, Eq. 13 shows that the reduction of form drag is caused by the reduction of dead zone volume. In a windy day, the trees tend to bend its branches and trucks in order to reduce the dead zones, and then the form drag.

Although the buoyant force is caused by the pressure distribution in static state, Archimedes principle avoids the complex measurement of pressure distribution around an object submerged in fluid, this makes

the calculation of buoyance become very easy and simple. Similarly, the form drag is also caused by the uneven distribution of pressure in a flowing environment, it is almost impossible to measure the local pressure everywhere abound a submerged object, Eq. 13 greatly simplified the troublesome work as Archimedes principle achieves.

The novel idea of Prandtl's boundary layer theory is not his mathematical treatment for Reynolds equations, but the flow region division, which suggests that for an external flow, an solid object only has its influence to a small region adjacent to it. Out of this small region, the fluid can be treated as undisturbed. Similar to this, this study also divides the flow field as shown in Fig. 2 into the undisturbed region and the dead zone region by assuming that the energy dissipated in the undisturbed region is only small part (≈1%) of the energy dissipated in the dead zone, thus the former is negligible in practice. Thus the very difficult form drag determination has been converted to the prediction of dead zone, a relatively simpler work.

4 COEXISTENCE OF SKIN FRICTION AND FORM DRAG IN INTERNAL FLOWS (PIPE FLOW, VEGETATED CHANNEL FLOWS)

As discussed that the friction force could be either skin friction or form drag, the former is proportional to the contact area, thus the contact area should be included in the definition of hydraulic radius or Reynolds number; the latter should be the volume force and proportional to the volume of dead zone. Thus, Eqs. 7, 8 and 13 have interpreted the physical meaning of the conventional terminology used in fluid mechanics and hydraulics. It predicts that when a fluid flows over an object, the skin friction is incurred when the flow does not change its direction significantly, and the skin friction depends on the Reynolds number defined in Eq. 7 where the fluid contact area is included.

However, when the flow's direction near a solid surface is significantly different from its incoming direction, the object bears the form drag that is proportional to the dead zone volume as specified by Eq. 13. For an internal flow, the dead zones are also discernible, and the additional energy loss depends on r_y shown in Eq. 8.

For the internal flows, the friction factor was measured by Nikuradse in 1933 after the painstaking experiments. His measured data indicate that the friction factor depends on both the Reynolds number and relative roughness, this implies the coexistence of skin friction and form drag. Almost all text books in hydraulics and fluid mechanics comment that "at very large Reynolds number, the measured friction factors are independent of the Reynolds number because the thickness of the viscous sublayer decreases with increasing Reynolds number, and it becomes so thin that it is negligibly small compared to the surface roughness height" (Cengel and Cimbala, 2006, p. 342). Obviously, this explanation is misleading as the variation of thickness in vertical neglects the inflation of dead zone behind every roughness element in the horizontal direction. According to the theorem proposed in the paper, the independence of Reynolds number means the disappear of skin friction, and solid boundary is fully covered by dead zones as shown on Fig. 3, in the other words, the variation of dead zone length in horizontal direction causes the transitional and fully rough flow regions, rather than the variation of viscous sublayer thickness.

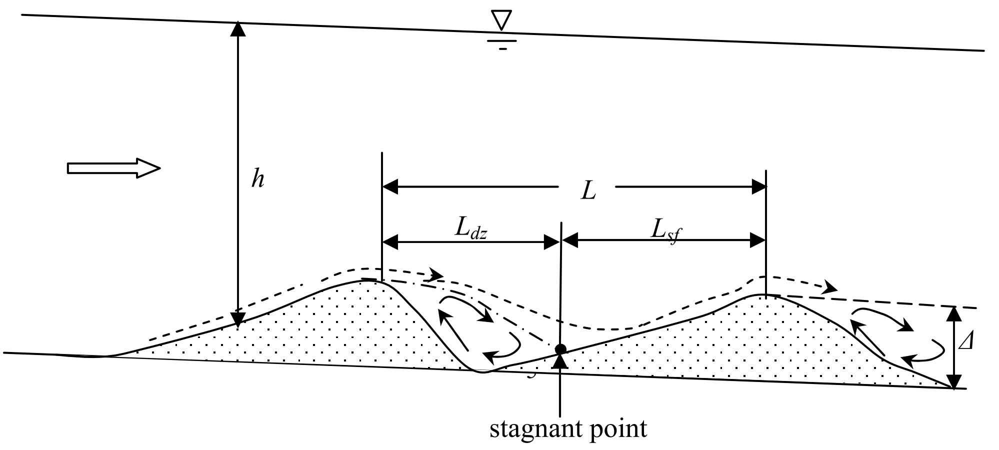


Fig. 3, the dead zones where flow direction is opposite to incoming flow, and the length of skin friction (L_{sf}) where the flow follows the incoming flow, the horizontal variation of L_{dz} yields the fully smooth (= 0), transitional ($0< L_{dz}/L <1$) and fully rough (=1) regions in internal flows, not the vertical variation.

As Nikuradse and Prandtl used incorrect concepts and parameters to interpret their measured data, it is needed to rectify their data in terms of the concept of skin friction and form drag. In Nikuradse's experiments, the diameter of the pipe was calculated from the volume of water required to fill the pipe and the length of the pipe, this is consistent with our new definition. Even so the hydraulic radius is still different from the value that Nikuradse obtained, as the water volume = $\pi r^2 L$ (L = pipe length, r = pipe radius), but the surface can be assumed as hemi-sphere as Japanese lacquer was used to glue sand that diameter is Δ, the total contact surface area for Δ^2 on the pipe's inner surface is $\Delta^2(4+\pi)/4$ (i.e., semi-sphere's surface plus the pipe surface area excluding the part occupied by roughness element), the pipe surface area $=2\pi rL$, the particle number = $2\pi rL/\Delta^2$. So one can find the total water contact area, from Eq. 6, one can determine the hydraulic radius as follows:

$$R_y = \frac{V}{A_w} = \frac{\pi r^2 L}{\frac{2\pi r L}{\Delta^2}\frac{\Delta^2}{4}(4+\pi)} = \frac{2r}{4+\pi} \approx 0.28r \qquad (14)$$

The conventional definition of hydraulic radius is $0.5r$, and it is valid only for a smooth pipe. For any roughened pipe covered with hemi-spherical elements the coefficient drops down to 0.28r because the water contact area becomes bigger by the roughness.

The form drag or the relative roughness should be expressed as:

$$r_y = \frac{V}{V_{dz}} = \frac{\pi r^2 L}{2\pi r \Delta L - 2\pi(\Delta/2)^3/3\left(2\pi r L/\Delta^2\right)} = \left(\frac{12-\pi}{6}\right)\frac{r}{\Delta} \approx 1.477\frac{r}{\Delta} \qquad (15)$$

It should be stressed that

1) Eqs. 14 and 15 are obtained by assuming that the surface is covered by hemi-spherical particles;
2) Nikuradse gave the relative roughness = r/Δ, this was extended to open channel flows. But the new definition gives different results.
3) In Eq. 15, it is assumed that the dead zone can exist below the roughness height, no more dead zone exists above it, and the volume occupied by solid roughness should be deducted in the calculation of V_{dz}.

Nikuradse' experimental data shows that for the factor of skin friction can be expressed by

$$\lambda' = \frac{8}{\left(\frac{U}{u_{*y}}\right)^2} = \frac{8}{(2.5\ln \mathrm{Re}_y - 30\,\mathrm{Re}_y^{-0.72} + 12)^2} \qquad (16)$$

and the factor of friction by dead zones could be expressed by

$$\lambda'' = \frac{1}{\left(2.68\log(10 r_y)\right)^2} \qquad (17)$$

Let

$$\beta = \frac{V_{dz}}{V_{void}} \qquad (18)$$

where V_{void} is the volume that the dead zone could locate as shown in Fig. 3, i.e., the fluid volume below

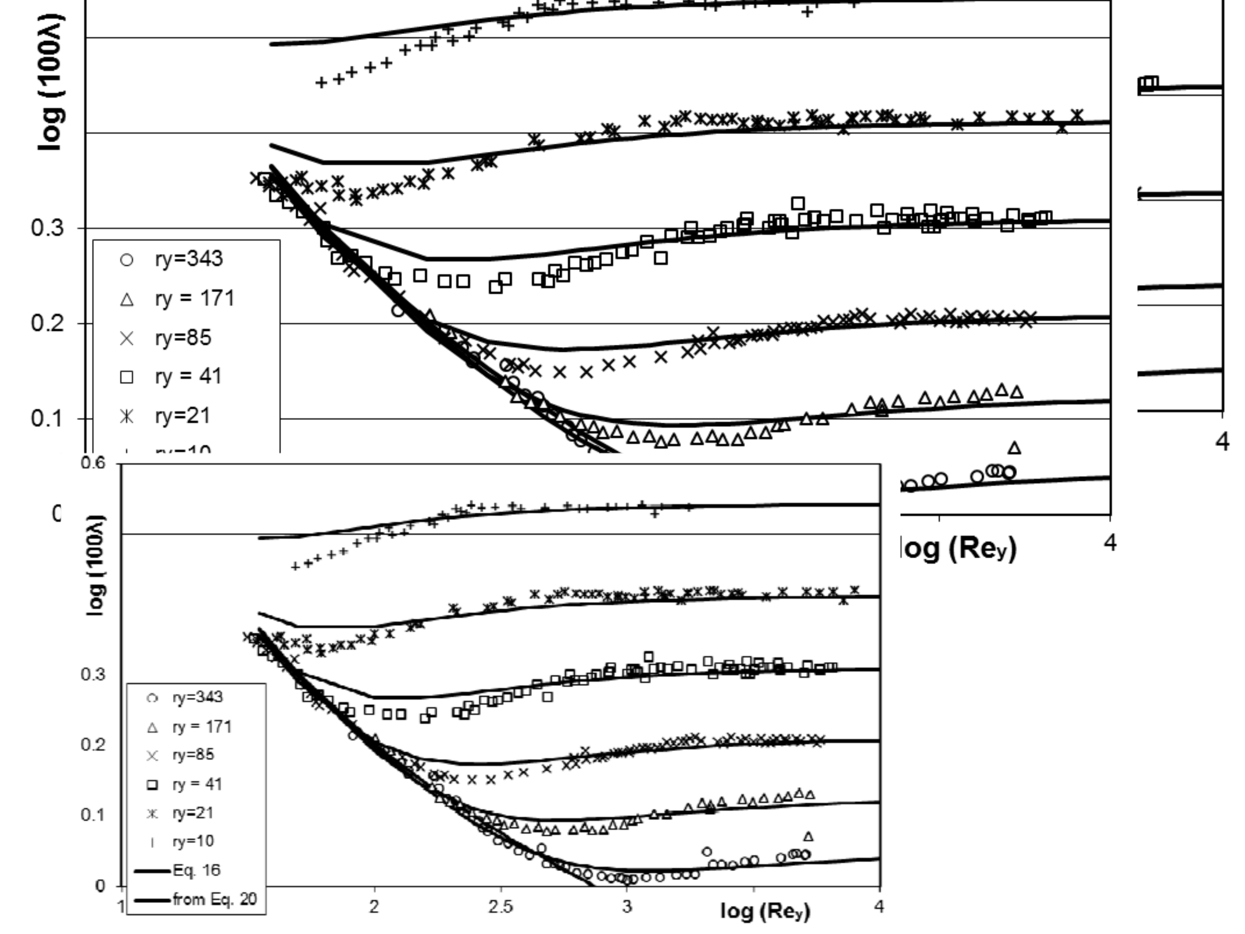


Fig. 4, comparison of Nikuradse' experimental data with Eqs. 16 and 20

The advantages of the new definitions of Reynolds number (hydraulic radius) and relative roughness can be seen from its application to 3-D hydraulics, for example flow in discontinuous rocks, river flows with rigid vegetation etc.

Recently the influence of vegetation on water, sediments, nutrients and pollutants transport both in streams and on floodplains has attracted attention (Tsujimoto 1999, Jordanova and James 2003). Vegetation also plays an essential role in ecological functions of river systems (Järvelä 2005). The new definitions of hydraulic radius in terms of skin friction and form drag are ideally suitable for such flows. In such case, the mean flow can be defined as follows:

$$U_y = \frac{QL}{V} \tag{21}$$

where Q = discharge, L is length between two cross sections, V = water volume. Eq. 21 gives the real or actual flow for groundwater, which is different from the nominal velocity u_0 (= Q/A_0),

$$U_y = \frac{Q}{A_0}\frac{A_0 L}{V} = \frac{u_0}{1-\varepsilon} \tag{22}$$

where ε is the porosity of soil in ground water.

Similarly, for a channel flow with vegetation that are often modeled by rigid steel bars (diameter = d and submerged height t), and it is uniformly distributed in space with density ε, the channel flow has water depth (= h), channel width (= b). The force balance for the water body between two cross sections apart away L can be written in the following way:

$$\rho V g S = \tau'(A_w - A_{dz}) + F_D \tag{23}$$

where A_{dz} is the area covered by dead zone eddies, F_D is the total form drag, from Eq. 23, one has

$$\rho g S \frac{V}{A_w} = \tau' \frac{A_w - A_{dz}}{A_w} + \frac{F_D}{A_w} \tag{24}$$

The number of steel bars can be calculated as

$$n = \frac{bhL\varepsilon}{\pi d^2 t/4} = 4\frac{bhL\varepsilon}{\pi d^2 t} \tag{25}$$

The total surface area of submerged bars can be determined by:

$$A_w = (2h+b)L + \pi dtn \tag{26}$$

If the steel bars are emerged then the contact area for skin friction will be

$$A_w = (2h+b)L + \pi dhn - n\pi d^2/4 \tag{27}$$

For submerged plants, the hydraulic radius is

$$R_y = \frac{V}{A_w} = \frac{bhL(1-\varepsilon)}{(2h+b)L + \pi dtn} = \frac{dbh(1-\varepsilon)}{(2h+b)d + 4bh\varepsilon} \tag{28}$$

For a very wide channel, the sidewall effect is negligible, Eq. 28 can be simplified as

$$R_y = \frac{dh(1-\varepsilon)}{d + 4h\varepsilon} \tag{29}$$

Eq. 28 and its simplified form Eq. 29 come from a very solid physical base of Eq. 24, thus it gets rid of the assumptions used, for example, Cheng and Nguyen (2011) assumed that the energy is dissipated only on the frontal area of the stem, which is the area of the stem projected on a plane normal to the streamwise direction, i.e., *dt*, obviously this argument cannot explain why sediment can move on the river bed with plants, which indicates that the channel bed also dissipates the turbulent energy. This assumption is not supported by Cheng and Castro's (2002) experiments. Cheng and Nguyen (2011) give

$$R = \frac{\pi}{4}\frac{1-\varepsilon}{\varepsilon} d \tag{30}$$

It reads that the hydraulic radius becomes higher and higher if the porosity decreases, if $\varepsilon = 0$ (no vegetation), R becomes infinity and it is unacceptable.
If we assume the volume of dead zone for each steel bar is v, and the area of dead zone A_{dz1} and be proportional to v/t, then from Eq. 13, one has

$$F_D = k\rho g n v \tag{31}$$

The area bears with the form drag can be written in the following way:

$$A_{dz} = n(A_{dz1} + A_{dz2}) = n(v/t + \pi dt/2) \tag{32}$$

where A_{dz1} is the bed area covered by the dead zone and shaded by slashed lines in Fig. 5, A_{dz2} is the area shaded by vertical lines in Fig. 5. Eq. 32 shows that the wetted area without skin friction includes the bed area, i.e., A_{dz1} and the back area of stems, i.e., A_{dz2}.

$$\frac{F_D}{A_w} = \frac{A_{dz1}}{A_w}\frac{F_D}{A_{dz1}} = 4\beta_1 k\rho g t \tag{33}$$

where $\beta_1 = A_{dz1}/A_w$, similarly we can define $\beta_2 = A_{dz2}/A_w$ and $\beta = A_{dz}/A_w$, $\beta = \beta_1 + \beta_2$.

Eq. 24 becomes

$$\frac{gSR_y}{U_y^2} = \frac{u_*^{'2}(1-\beta_1-\beta_2)}{U_y^2} + \frac{4\beta_1 kgt}{U_y^2} \tag{34}$$

where β_2 = constant if separation flow occurs, and

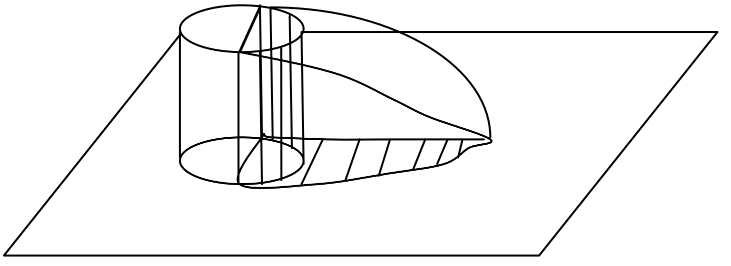


Fig. 5, a dead zone behind a submerged structure, *Adz1* is the bed area covered by the dead zone and shaded by slashed lines on the bed, A_{dz2} is the area shaded by vertical lines on the structure's surface.

$$\beta_2 = \frac{A_{dz2}}{A_w} = \frac{n\pi dt/2}{(2h+b)L+\pi dtn} \tag{35}$$

Eq. 35 can be rewritten as

$$\lambda = \lambda'(1-\beta_1-\beta_2) + \frac{4\beta_1 kgt}{U_y^2} \tag{36}$$

If λ' shown in Eq. 16 can be used for the submerged vegetation, and *k, t* and β_1 need to be calibrated, then the total friction factor can be calculated.

Now we only discuss the rationale of Eq. 36, it shows that if the porosity or *n* is very small (equivalent to isolated roughness elements, then $\beta_1 \approx \beta_2 \approx 0$, thus Eq. 36 gives $\lambda = \lambda'$, the channel friction factor is determined by the skin friction. If the steel bars are very dense or n is very large, $\beta_1 \approx 0$ as the dead zone is very small or $v/t \approx 0$ and Eq. 36 gives $\lambda = \lambda'(1-\beta_2)$, thus the friction factor is also very similar to the smooth channel. Between these two extremes, λ should have a peak value with the parameters of *n* and *v* are reasonably high.

5 COEXISTENCE OF SKIN FRICTION AND FORM DRAG IN EXTERNAL FLOWS (SPHERE, EXPERIMENTAL DATA, STREAMLINED OBJECTS)

The similarity of friction factor measured in an external flow and internal flow reveals that both skin friction and form drag co-exists in the both types flows. In the section, we will mainly explain why a streamlined object can significantly reduce its friction force by analyzing the drag coefficient from a series of objects from a circular plate, to a sphere and a streamlined object.

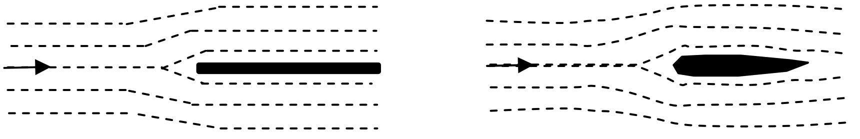
In 1905, Prandtl fully recognized the role of small viscosity. It appears that a body placed in a potential flow does not experience a force if the flow is almost irrotational. This is still correct until comparatively close to the body, so that the variation of velocity from the value corresponding to irrotational motion to the zero or negative velocity near or at the wall takes place within a thin layer adjacent to the wall. Thus, the effects of viscosity are significant only within a thin transition layer, which is called the boundary layer. Outside this layer, the flow is essentially free of viscosity and is described by an irrotational motion to a high degree of accuracy.

Drag refers to forces that oppose the relative motion of an object through a fluid (a liquid or gas). Drag forces act in a direction opposite to the oncoming flow velocity. For a solid object submerged in a fluid, the drag is the component of the net aerodynamic or hydrodynamic force acting opposite to the direction of the movement. A large body of work has been devoted to the determination of drag force in a submerged object such as spheres, disks or bullet-shaped bodies.

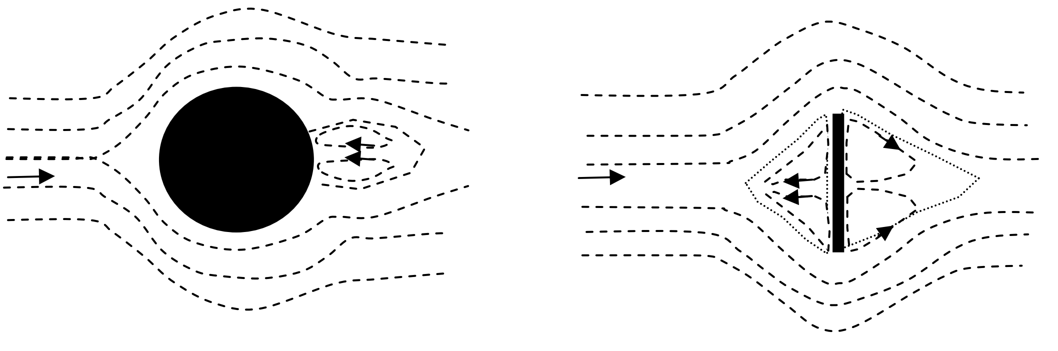
For a given-shaped object, the characteristics of the flow depend very strongly on various

parameters such as size, orientation, speed, and fluid properties. In general, the total drag of a blunt body is partly due to viscous resistance and partly due to pressure variation. The pressure drag is largely a function of the form or shape of the body; hence it is called form drag. The viscous drag is often called skin-friction drag. The total drag force on any immersed object is always the sum of friction and pressure drag, but the contribution of each drag is different for different objects at different Reynolds number.

The skin friction drag is due to the shear stress on the object and proportional to the contact area between the fluid and solid surface, for a smooth surface it is a function of Reynolds number; for a rough surface it is caused by small eddies behind the roughness and the friction depends on both Reynolds number and relative roughness height (Yang and Tan, 2008). The friction drag is dominate in an area where no large eddies occur, or there is no reverse flow over the solid surface (see Fig. 6a).



(a) (b)



(c) (d)

Fig. 6, friction drag and form drag, in (a) and (b) the form drag is negligible as there is no flow separation and reverse flow, the total drag is a function of Reynolds number and contact area. In (d) the object is fully surrounded by large eddies, thus the friction drag is negligible, and the form drag is dominate; In (c) there is no separation in the front part (friction dominate) and the rear part is under separation flow, thus both friction drag and form drag contribute to the total drag.

For a sphere in the fluid, the total form drag can be similarly written in the following way:

$$F_{total} = F_{skin} + F_{form} = 3\pi\rho\nu D u_\infty \cos^3\theta_* + 0.45\frac{\rho u^2}{2}\frac{\pi D^2}{4}\sin^3\theta_* \tag{37}$$

$$C_D = \frac{24}{\mathrm{Re}}\cos^3\theta_* + 0.45\sin^3\theta_*$$

The comparison of measured and Eq. 37 is shown in Fig. 6, and good agreement has been achieved. The above argument is very simple to explain the drag reduction of streamline objects. As shown in Fig. 6d where the dead zone is highest, thus the drag coefficient is the highest, and Fig. 6c has less dead zone volume, so the drag coefficient becomes less. Fig. 6b has the streamline shape, such it just bears the skin friction and has lest drag coefficient. Therefore we can conclude that the drag force is indeed depends on the contact surface area and dead zone volume.

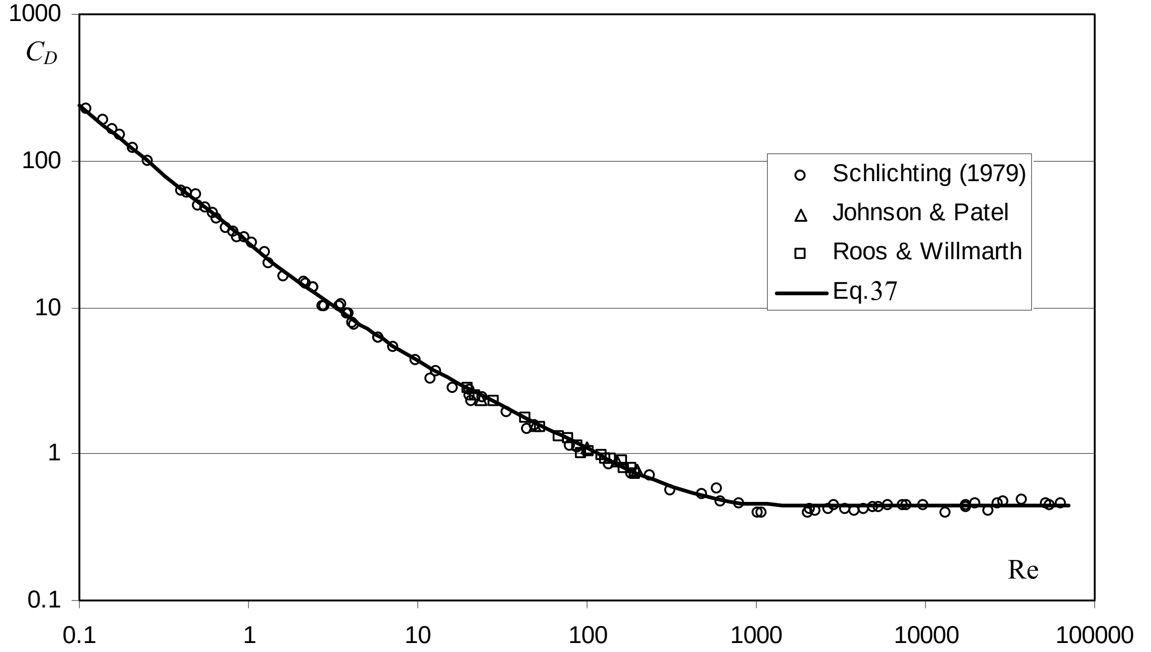


Fig. 7, Comparison of calculated and measured drag coefficients C_D

4 CONCLUSIONS

This paper investigates the mechanism of flow resistance on an interface of solid and fluid. It clarifies that the flow resistance can be divided to skin friction and form drag, and they are proportional the contact area and dead zone volume, respectively. It shows the idea of boundary layer theory developed by Prandtl can be extended to a bluff object placed in a flow, and the mechanism of flow resistance is the same for both internal and external flows. From this investigation, one can draw the following conclusions:

1) hydraulic radius is the ratio of water volume to the contact area, it interprets that the potential energy carried by volume V is dissipated on the surface of contact area A, or the physical meaning of hydraulic radius is that the energy from the water volume R is dissipated on a unit contact area.

2) Reynolds number is the measurement of skin friction. It contains the viscosity, velocity and these parameters must be those on the boundary, e.g., shear velocity, or the hydraulic radius. The paper redefines the Reynolds number in which all parameters comes from the boundary, thus it can be used to express the skin friction.

3) the relative roughness defined by Nikuradse lacks very clear physical interpretation. This paper redefines the parameter as the ratio of ratio of potential energy carried by volume V to the dead zone volume, i.e., the energy from the main flow is dissipated by the eddies in a dead zone.

4) using the above definitions and discovery, flow resistance in 3-D hydraulics becomes predictable. For the internal flows, the flow with vegetation is discussed and reasonable explanation is obtained.

5) After flow separates and the dead zone forms, the wake length is proportional to velocity square and the co-existence of skin friction and form drag can be expressed by the weighting factor that is the ratio of the area of skin friction to the total wetted area, and this ratio depends on the new defined Reynolds number.

6) The total force can be obtained by the superposition of viscous shin friction and form drag, this is valid for both external and internal flows. The obtained drag coefficient agrees well with experimental data and it demonstrates good predictability when compared with existing empirical equations available in the literature.

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