

Liquid Friction - The Tarantino Effect

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Take an orange, cut it in half, and rub the two halves together. What do you get? Pulp Friction. OK, maybe you had to see that 1994 Tarantino movie. So, what is Tarantino effect? If you have ever seen one of his movies you will remember that his plots and timelines are totally nonlinear just like the friction that arises when a fluid flows in a pipe. Now, our human brains love straight line relationships because they are easy to comprehend. But, when it comes to liquid friction, we are forced to deal with that Tarantino effect.

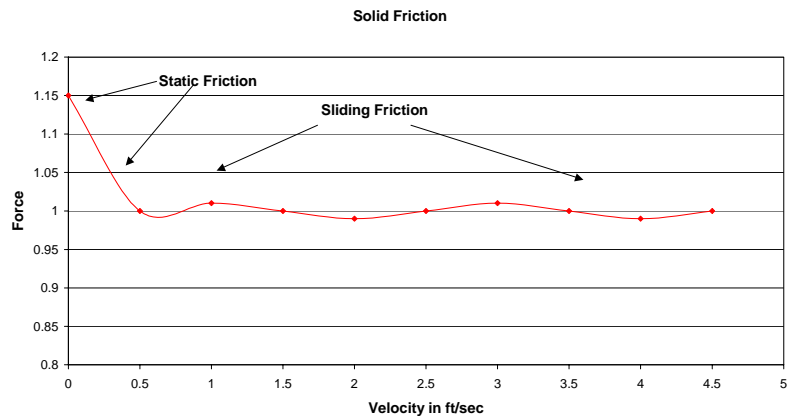
The friction that opposes motion between two solids or between a liquid and the wall of a pipe is considered to be a **real force**. Now, if it is a real force you would think that there would be some laws of Physics that could accurately predict its effect under various conditions. But, unlike most forces, friction is quite complicated and there are no definitive laws that explain its actions. We do have some theories and "approximate" laws but, most of the knowledge available today is empirical (from experimentation). And, that is why we still use those friction tables when we design a pumping system.

Solid Friction

Solid friction is the simpler of the two because, most of the time, it follows a few simple rules and, tends to be linear. It depends upon just two factors - - the composition of the interacting materials and the total force that is pressing them together. The composition and nature of the surfaces of the materials give rise to a value known as the coefficient of friction (μ). This value quantifies the resistance to movement between the two surfaces. The force (f_n) that is pressing the two together is proportional to the weight one surface exerts on the other one. Through experimentation we have found that the force of friction (f_f) that arises between two solids is $f_f = \mu f_n$ - - a simple linear relationship that says that friction is directly proportional to a change in either of the two values. Although this formula is not exact, it is a good empirical rule and applies much of the time.

Solid friction exists in two forms - - static and sliding. An example of static friction is a crate resting on a concrete floor or an automobile tire rolling down the highway. If you were to push the crate across the floor or if that car begins to skid, static friction changes into sliding friction. You have probably noticed that it takes more effort to get that crate sliding than it does to keep it sliding. This is due to the fact that static friction exerts a greater force than does sliding friction. And, this is the reason antilock braking systems can be more effective than manual ones. We have also found that the force produced by sliding friction is relatively independent of velocity. Figure 1

compares the forces of static and sliding friction. The static component is greatest the instant before an object begins to slide and then falls quickly as velocity increases. Once sliding the force remains nearly constant regardless of velocity.

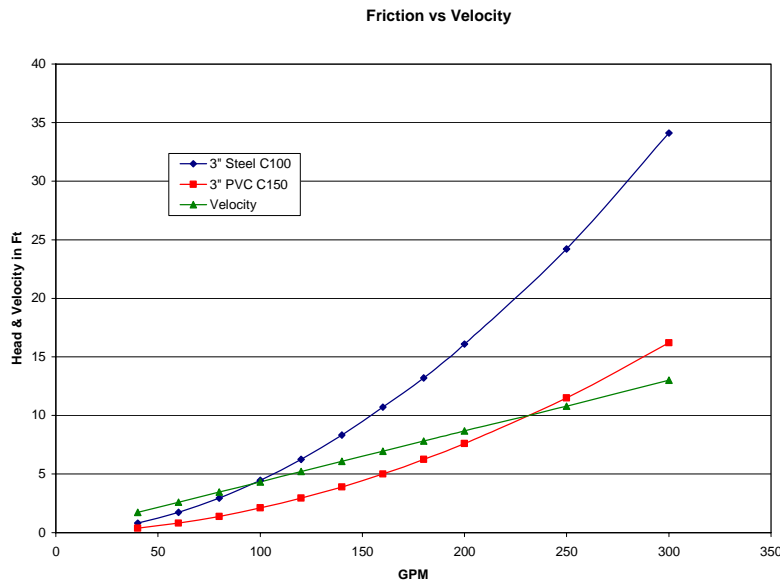


An unexpected characteristic of solid friction is that it tends to be independent of surface area. If you reduce the surface area by one half but keep the total force (weight) constant, the force per unit area doubles and friction remains the same. When viewed at the molecular level, a surface that appears perfectly flat to the naked eye would look like a bunch of mountains and canyons. Because of this "rough terrain", the actual surface contact between two solids is just a fraction of their total surface area. But, if you reduce the total area these peaks and valleys compress and the area in contact remains nearly the same. So those oversized tires used on dragsters may dissipate more heat but they do not produce more friction.

Another result of this microscopic roughness is that friction can be reduced if the surfaces of harder materials are polished. But, if they are over polished friction can be even greater than it was before polishing. And, this is the reason that mechanical seal faces can fail quickly if they lose their lubricating fluid.

Liquid Friction

It would be nice if liquid friction was this simple. But, unlike solid friction, velocity is a big factor. And, it does not stop there. The elemental make up of the conduit



(steel, copper, plastic, etc) and the condition of its inner surface can also be factors. And, we cannot neglect the molecular forces that, not only hold the liquid together but also exert an attractive force on the conduit itself.

Figure 2 shows the velocity and friction curves produced by water flowing in 3" steel and PVC pipe. As expected,

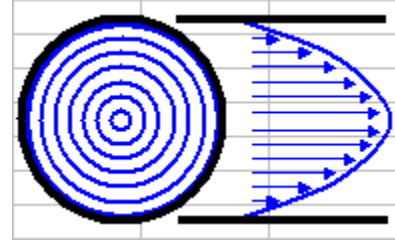
velocity is a nice straight line since it is directly proportional to the rate of flow as long as pipe size remains constant. But, what we may not have anticipated is that exponential increase in friction. We will revisit this chart a little later.

When we try to visualize liquid friction we tend to use the solid friction model as a starting point. By this I mean that we see liquid "rubbing" against the pipe wall and this rubbing creates friction in a way that is similar to two solids rubbing together. But, this simply does not occur when water is flowing at lower velocities. The friction that arises is actually caused by the liquid molecules rubbing together!

Those molecular forces I spoke of earlier are probably the most important contributors to friction during low velocity flow. Cohesion is the attractive force that occurs among liquid molecules and causes them to cling together. Adhesion is a similar force but occurs between the liquid and the material that contains it. In some liquids, cohesion may be stronger than adhesion but in others the roles can be reversed. For example, if you place a drop of mercury on a clean glass surface, it will remain nearly spherical except for a flat spot on its bottom due to its weight. Perform that same experiment with a drop of water and it will spread out and form a thin layer that is just a few molecules thick. Why? Because water's attraction to glass is much greater than its attraction to itself while mercury's stronger cohesive forces behave exactly opposite.

It is the actions of these two forces that influences the flow characteristics of a liquid at low velocity. Laminar flow is the term used to describe the normal flow of water and other low viscosity liquids at lower velocities.

If you could view water flowing in a steel pipe at the molecular level, you would see something similar to Figure 3. The drawing on the left is a cross sectional view while the one on the right shows the flow profile from the side (try to think three dimensional). The



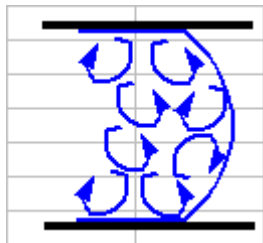
The water column moves as a series of concentric layers (lamina), some of which may be just a few molecules thick. The outer layer, which is in contact with the surface of the pipe, does not move at all while the one in the very center of the pipe moves at the highest velocity. Those in between become progressively slower as their diameters increase. From the side, flow appears as a "bullet" shaped cone and the length of the arrows (streamlines) is proportional to the velocity in that region of the pipe. Now, this cone is not the leading edge of the water column, rather it is the profile of flow throughout the pipe. But this profile is not the same everywhere in the pipe. As water enters the pipe its profile will be more "blunt" due to a smaller difference in velocity between its outer layers and those towards the center. But, as it continues its journey, more and more of the total flow is away from the wall's surface and the profile becomes that of Figure 3.

Now, don't let anyone tell you that this is a well understood process because it is not. There has been quite a bit of research but much more is needed. What we do know is that this flow pattern and the resulting friction is due to the rather complex interactions of the forces of adhesion and cohesion and the momentum of the moving water. Adhesion causes a layer of water molecules to bond tightly to the pipe's inner surface. Even though this layer is motionless, their cohesive forces still try to keep them in contact with the moving water. In doing so, they slow down the movement of the molecules that are flowing just a few thousands of an inch away. Likewise, these slower moving molecules have a similar effect upon those flowing next to them. This process continues, with a progressively smaller effect, all the way to the center of the pipe. The slower moving layers away from the center effectively reduce the pipe diameter that would normally be available to flow.

As long as flow is laminar, the roughness of the pipe wall has very little effect on friction because a relatively small percentage of the total flow occurs near the wall. But, if this is true why is friction lower in that smoother PVC pipe shown in Figure 3? Well, it could have something to do with the fact that the adhesive

forces between water and PVC are much smaller than those of water and steel. Laminar flow in the PVC pipe is similar to that in the steel pipe but the lower adhesive forces probably reduce the thickness of water layer that bonds to the wall of the pipe. This thinner boundary layer would exhibit a smaller slowing effect on the molecules nearby and effectively increases the diameter available to flow. This is probably a valid theory but, it has **absolutely no effect** on the flows shown in Figure 2. Why? Because, even at 40 GPM, the flow of water in a 3" pipe is not laminar regardless of its construction!

Once the flow in a pipe reaches a certain velocity its profile changes into



something we call turbulent flow and this profile is shown in Figure 4. Those nice horizontal streamlines seen in laminar flow change into a bunch of random eddies and vortexes that causes mixing of those concentric layers. Although a thin layer may still be motionless, more and more of the flowing water comes in contact with the wall due to these random movements.

Therefore, when flow is turbulent the roughness of the pipe wall does have an influence on the friction that arises.

The change from laminar to turbulent flow is not abrupt, but occurs over some range of velocity. The Reynolds equation ($Re = \rho V D / \mu$) and the dimensionless Reynolds number (Re) is used to predict the occurrence these two flow types. It takes into account the density (ρ), viscosity (μ), and velocity (V) of the fluid as well as the diameter (D) of the pipe. When Re is less than 2000 flow is considered laminar and when it is greater than 4000 it is turbulent. The range in between is known as transitional and flow can be either laminar or turbulent or a hybrid of the two.

Most of us have probably never computed a Reynolds number but, if we did, we might be surprised at what we see. We would find that almost ALL water pumping applications involve turbulent flow. In our 3" steel and PVC pipe examples shown in Figure 2, a flow rate of just 100 GPM (4.34 fps) produces a Reynolds number of about 100,000 - - quite a bit larger than the 4000 needed to indicate turbulent flow. In order to attain true laminar flow, velocity would have to drop below 0.1 fps or 2 - 3 GPM. Due to the often confusing references to laminar flow, many of us have been led to think that it is the "preferred flow". Even that popular rule of thumb - **keep flow velocity below 7 feet per second** - is often interpreted as a means of keeping flow laminar. But, as you have seen above, it doesn't even come close!

So, if almost all water pumping applications are turbulent and turbulent flow is not a bad thing, do we even care about the Reynolds number? Well, pipeline flow is just a small piece of Osborne Reynolds' (1883) greater work. It is also the basis for similitude analysis and the modeling of airfoils and hydrofoils. And, it is especially important in studying the behavior of biological fluids. But that number has also contributed to the development of methods of predicting the friction that will arise in various pipe materials over a broad range of velocities and viscosities. One of the most useful is the Moody Diagram (LF Moody 1944). It uses the Reynolds number in conjunction with the relative roughness of a pipe's interior to predict the friction factor. That quantity can then be used in the Darcy - Weisbach equation (1845) to predict head loss due to friction. Even today, this equation is still the most accurate and since the advent of the calculator, in the seventies, it has become the most popular. The Hazen-Williams equation (1905), on the other hand, is a less accurate empirical approach that was developed to reduce the amount of manual computation required (pre calculator).

I hope that you noticed the dates in the paragraph above. It is interesting to note that the methods we use today to calculate liquid friction were developed well over 100 years ago. Although there are many web based calculators that make it easier for us to use these equations, the logic remains the same. Richard Feynman (1918-1988), one of America's finest physicists, said that "a major failure of physics in the 20th century was a lack of focus on liquid friction even though its economic effects could be enormous". That was over thirty-five years ago and his comment is still valid today. So, even though that rule of thumb won't keep flow laminar, it will probably keep you out of trouble - - most of the time!

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