Universal Viscosity Curve Theory

Turbine Flow Meters and Flow Viscosity

Introduction

Like any transducer, a turbine flow meter is sensitive to physical parameters other than the one which is of interest. While designed to measure flow, a turbine meter responds to the viscosity of a fluid as well as its velocity. Following is a brief discussion of the viscosity sensitivity of a turbine flow meter.

The discussion begins with a review of the nature of viscosity and the means by which it is measured. The characteristics of viscous drag and its action within the turbine meter are also discussed. Following this, there is a description of Universal Viscosity Calibration techniques as a practical means of dealing with the viscosity sensitivity of turbine meters. Readers familiar with the viscous properties of fluids may wish to begin with the section on Universal Viscosity Calibration.

Nature of Absolute Viscosity

Absolute viscosity is the characteristic of a fluid which causes it to resist flow. The higher the numerical value of absolute viscosity assigned to a fluid, the greater the resistance that fluid offers to flow.

Water and gasoline are relatively low viscosity fluids which flow very easily. Such a low viscosity fluid is frequently referred to as an approximately inviscid fluid. Motor oil and maple syrup are examples of more viscous fluids which offer far greater resistance to flow. Castor oil and molasses are even more viscous. It is the viscosity of the molasses which prevents it from running out of the bottle when cold.

The viscosity of a fluid causes a loss in pressure as it flows, so that an increase in viscosity requires an increased amount of energy to pump fluid at the same rate. When it is necessary to cause fluids to flow through small openings, such as in low capacity flow meters, too high a viscosity can cause so much pressure loss that it becomes impossible to establish the desired flow rate. Expressed another way, flow from a constant pressure source will decrease as the viscosity of the flowing fluid increases.

The viscosity of a liquid is highly temperature dependent. An increase in temperature will cause a decrease in viscosity. For this reason, it is possible for a temperature change to affect the performance of a flow meter considerably.

Absolute Viscosity Defined

The absolute viscosity of a fluid is a measure of its resistance to shear stresses. Shear stresses occur whenever a fluid experiences an angular deformation as it flows. Consider a fluid flowing over a surface as illustrated in Figure 1. Due to viscosity, the film of fluid next to the surface will be sticking to it and will, therefore, have zero velocity. Fluid further away from the surface will be sticking to it and will, therefore, have zero velocity.

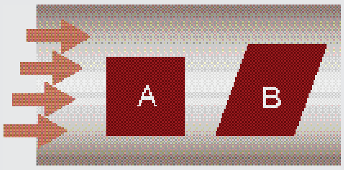

Figure 1

Fluid further away from the surface will slip over the fluid beneath it as it moves to the right. Since each successive layer of fluid will slip over the layer below it, the velocity of the fluid will increase with the distance from the surface over which the fluid is flowing.

Consider then a small cube of fluid as shown at point A in Figure 1. By the time this small cube of fluid gets to B it will have to have deformed as illustrated because the fluid further from the surface is moving faster. This is referred to as angular deformation.

Now consider the forces acting between such a cube and a similar cube directly above or below it. Since the two cubes are in effect sliding over each other, there is a force between them resisting this sliding or shearing. If H is the height of the cubes, and V is the difference in velocity between the center of the top cube and the center of the bottom cube, the force between them may be represented by:

$$\tau = \mu \frac{\Delta V}{h}$$

In differential form, this equality is usually expressed as:

$$\tau = \mu \frac{dv}{dy}$$

assuming that y designates vertical distance. Fluids are said to be Newtonian fluids if the proportionality factor, μ, is a constant. The constant of proportionality is defined as the absolute viscosity of the fluid. It is usually identified by the Greek letter mu.

Kinematic and Absolute Viscosity

The ratio between shear forces and the velocity gradient in a fluid (as defined in the previous section) is absolute viscosity, and is identified with the symbol μ (Greek letter mu). Because the ratio for absolute viscosity to density appears in so many engineering equations, a second symbol is assigned to that ratio. The symbol used is v (Greek letter nu). Thus:

$$\nu = \frac{\mu}{\rho}$$

It is the kinematic viscosity, v, which is of interest in turbine flow meter applications. Thus, both the absolute viscosity and the density must be known. Knowing the specific gravity is equivalent to knowing the density. In the metric system, μ is expressed in centipoise, v is expressed in centistokes, and v = μ/S, where S is the specific gravity.

Viscosity Measurement

Viscosity is most commonly measured with rotating cylinder viscometers or capillary tube devices. Rotating cylinder viscometers measure the shear forces associated with a fluid, and thus determine the absolute viscosity. The absolute viscosity is usually determined in metric units, which are centipoise. The density of the fluid must then be measured so that the kinematic viscosity may be obtained. Kinematic viscosity is expressed in centistokes in the metric system. When absolute viscosity is expressed in centipoise and density is expressed in gram/cc, the ratio will result in centistokes.

Capillary tube viscometers measure kinematic viscosity directly. This is done by observing the time required for a specific volume of fluid to flow through the capillary tube. Rather than converting the data to centistokes, the raw data itself has been used to establish some viscosity scales, and they then have units in seconds. The Saybolt Seconds Universal (SSU) is an example of such a viscosity scale.

Temperature & Pressure

The absolute viscosity of a fluid is strongly influenced by temperature. As temperature increases, the viscosity of a liquid decreases and the viscosity of a gas increases. It is customary to express these relationships as a plot of viscosity vs. temperature, and such plots can be found in many references for common engineering fluids. Many oils have a straight line characteristic if the viscosity temperature relationship is plotted as on an ASTM chart (ASTM D-341-43). An example of such a plot is shown in Figure 2 for MIL C-7024B, Type II solvent and MIL H-5606-B Hydraulic Fluid. Because of the temperature dependency of viscosity, it is important to specify the temperature as well as the service medium for turbine meter systems.

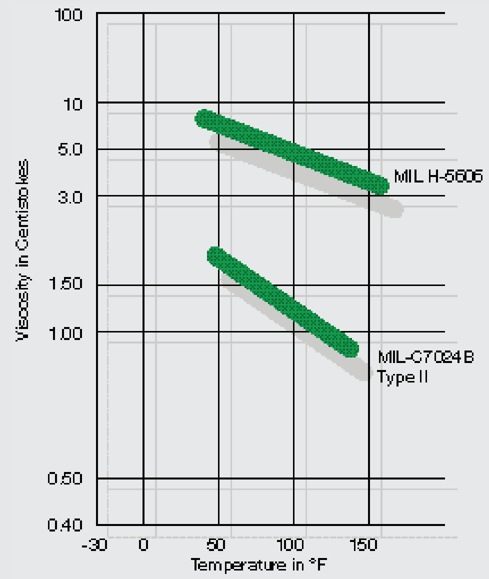

Figure 2

The influence of pressure on absolute viscosity is usually neglected, and this approximation is reasonable for low pressures. However, for pressures over about 1000 PSI, the absolute viscosity of a fluid may be a strong function of pressure. Generally, an increase in pressure will increase the viscosity of a liquid.

Kinematic viscosity is the ratio of absolute viscosity and density. Therefore, if density changes with temperature or pressure, the kinematic viscosity will also change. For gas applications, kinematic viscosity is a strong function of pressure. Remember kinematic viscosity is the key fluid parameter that influences the turbine meter performance.

Laminar & Turbulent Flow

Fluid flow is characterized as being either laminar or turbulent. In laminar flow the fluid moves in layers, with one sliding smoothly over the other. There is no mixing of fluid from layer to layer, since viscous shear forces damp out relative motions between layers. Since each layer of fluid is in effect flowing over the one adjacent to it, the fluid velocity increases with the distance from the pipe wall. The resulting velocity profile is approximately parabolic in shape. This is illustrated in Figure 3.

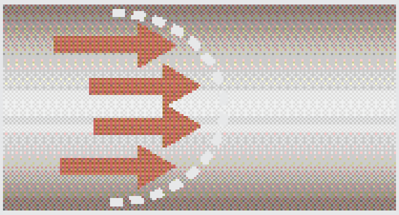

Figure 3 Laminar Flow Profile

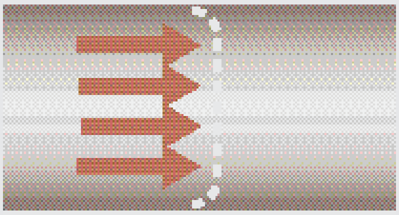

Figure 4 Turbulent Flow Profile

In turbulent flow, there are no discrete layers of flowing liquid. The momentum of the fluid overcomes the viscous shear forces, and there is extensive and continual mixing across the flow stream. This causes the velocity profile across a pipe to be nearly flat. This is illustrated in Figure 4.

A measure of the laminar or turbulent nature of flow is the Reynolds Number (Re). By definition:

$$Re = \frac{pVD}{\mu} \quad \text{where}$$

p = Fluid density
V = Fluid velocity
D = Diameter of pipe
μ = Absolute velocity

The numerator in the Reynolds Number is directly related to the momentum possessed by the fluid. The denominator is the absolute viscosity of the fluid, and is therefore, directly related to the shear forces existing in the fluid. The Reynolds Number is, therefore, a ratio of momentum to viscous forces.

Recalling that a predominance of momentum is associated with turbulent flow and a predominance of viscous forces are associated with laminar flow, it is then to be expected that a large Reynold Number will be associated with turbulent flow. This is because inertial forces associated with the momentum of the fluid will be large in comparison to any viscous shear forces which tend to damp out turbulent motions, and considerable mixing of the flowing fluid will result.

Conversely, a low Reynolds Number is associated with laminar flow. The transition from laminar to turbulent flow generally occurs at a Reynolds Number between 2000 and 4000. Another means of visualizing the effects of laminar and turbulent flow is by the nature of the boundary layer.

The boundary layer is that layer which is influenced by adherence of the fluid to the pipe wall. Flow essentially moves in layers in the boundary layer, and the flow is laminar. In completely laminar flow, the boundary layers meet in the center of the pipe. However, in very turbulent flow the boundary layers are very thin regions adjacent to the pipe wall. This is illustrated in Figure 5. The more viscous a fluid, the more the shear forces damp out mixing between layers. This allows the fricional drag from the pipe wall to influence boundaries closer to the center of the pipe.

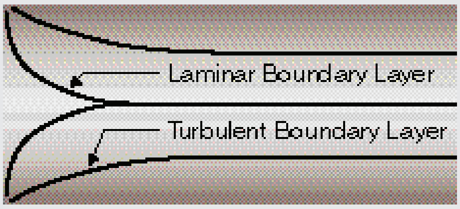

Figure 5 Boundary Layer

Viscous Drag

When a viscous fluid flows over a solid surface, a force is exerted on the surface in a tangential direction. In effect, the moving fluid is attempting to drag the solid surface along with it. The magnitude of this force is dependent upon the viscosity and velocity of the fluid.

Experimentally measured drag forces are generally plotted in terms of CD vs. Re on a log-log chart. CD is the drag coefficient and Re is the Reynolds Number. The drag coefficient is defined by:

$$C_D = \frac{F}{\frac{1}{2} V^2 A} \quad \text{where}$$

F = Drag Force
V = Fluid velocity
A = Wetted surface area

A plot of CD vs. Re usually looks something like Figure 6. The drag coefficient decreases rapidly with the Reynolds Number in laminar flow, rises abruptly in the transition region, then levels off and eventually decreases slowly in the turbulent region.

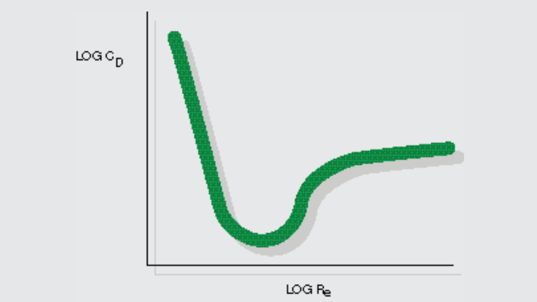

Figure 6

Viscous Drag In A Turbine Flowmeter

The viscous drag exerted by the metered fluid acts on all of the moving surfaces of a turbine flow meter. This drag acts within the bearing and in the space between the rotor blade tips and the housing. The viscous drag exerted on the surfaces of the rotor blades produces both a downstream thrust and a retarding torque on the rotor.

Because of the viscous retarding forces on the rotor, it does not spin as fast as it would in an inviscid fluid. The rotor actually slips in the stream of flowing fluid, so that the surface of the blades slightly deflect the fluid. The deflection of the fluid by the rotor blades causes a change in momentum in the fluid and a resulting force on the rotor blades. This force on the blades causes a driving torque which overcomes the retarding torque caused by viscous drag forces. The rotor then spins at a rate at which the slip causes the driving torques to exactly cancel the retarding torques. The amount of slip of the rotor will depend upon both the kinematic viscosity and the velocity of the fluid, just as do the viscous drag forces discussed in the previous section. Therefore, the performance of the meter is a function of the Reynolds Number associated with the flow.

The performance of the turbine meter does not actually change in exactly the same manner as the viscous drag forces change. This is because the changes in Reynolds Number changes the velocity profile of the flow and this also affects the speed of rotation of the rotor.

The viscous drag also contributes to the pressure drop across the turbine meter. Very high viscosities will limit the maximum possible flow rate because of this

Universal Viscosity Calibration

The calibration of a turbine flow meter consists of observing the output frequency of the meter for specific rates of flow as determined by the particular calibrator being used. The result is a linear curve as illustrated in Figure 7. However, this curve is valid only for fluids with a kinematic viscosity similar to that of the fluid used in calibration.

For operation in high viscosity fluids, the curve in Figure 7 will have less slope and a positive zero offset along the horizontal axis. This is illustrated in Figure 8. Since a different curve will result for every viscosity, this is not a usable form for the calibration data except for single and constant viscosity operation.

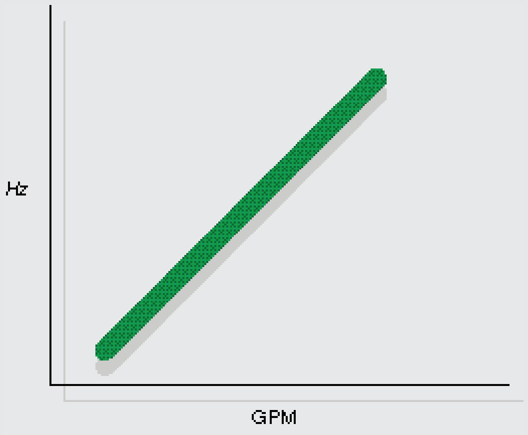

Figure 7

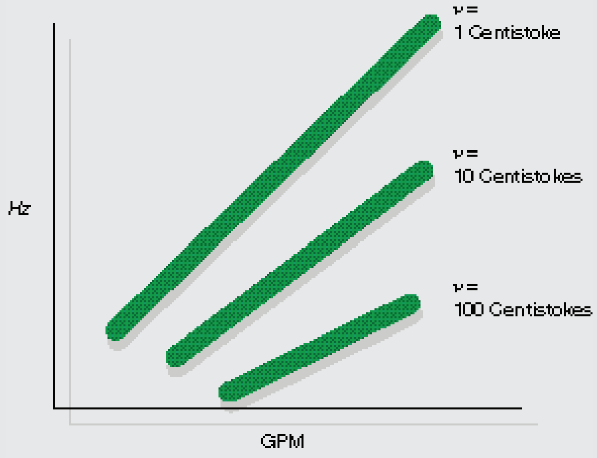

Figure 8

A more usable form for the calibration data is called a universal viscosity curve. This is a semi log plot of the sensitivity of the meter as a function of the ratio of the output frequency to the kinematic viscosity. An example is shown in Figure 9. The sensitivity of the meter is commonly known as the K factor, and it is the number of pulses the meter will produce for each gallon of fluid which flows through it. It is derived from the calibration data as follows: K = HZ x 60 / GPM

The rational for using the ratio HZ/v may be seen by observing that it is directly proportional to the Reynolds Number for the flow through the meter. Hence the Universal Viscosity Curve is essentially a plot of meter sensitivity vs. Reynolds Number. As such, it reflects the combined effects of velocity, density and absolute viscosity acting on the meter. The latter two are combined into a single parameter by using kinematic viscosity (v).

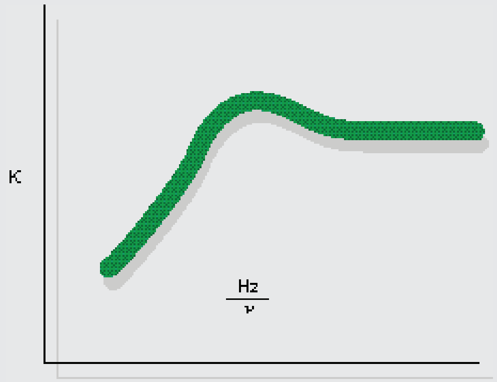

Figure 9

The Universal Viscosity Curve is formed by plotting K vs. HZ/v for every calibration data point. Typically, thirty points are used; ten each for three different fluids. The thirty points are plotted on a common graph to form a smooth curve. Once this is done, the K factor may be determined for any flow rate in fluid of any viscosity as long as the ratio HZ/v is within the range of values covered by the graph.

To determine the flow rate from measured output frequencies and viscosities simply follow the steps shown in Figure 10.

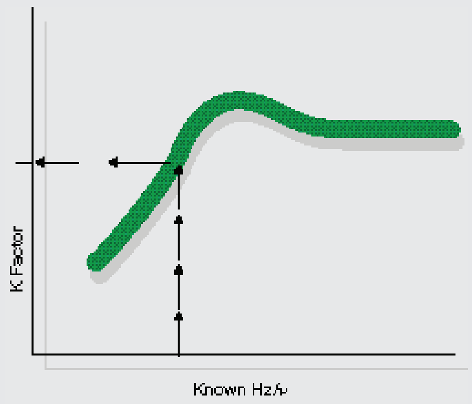

Figure 10

1. Determine output frequency Hz
2. Measure kinematic viscosity v or measure temperature and use temperature to determine v
3. Calculate Hz/v
4. Read up from known Hz/v to curve
5. Read over from curve to find K factor
6. Calculate GPM: GPM = Hz x 60/K

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