Technical Language for mechanical engineering
Fluid mechanics

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Fluid mechanics

Fluid mechanics is the study of fluids either in motion (fluid dynamics) or at rest (fluid statics). Both gases and liquids are classified as fluids, and the number of fluid engineering applications is enormous: breathing, blood flow, swimming, pumps, fans, turbines, airplanes, ships, rivers, windmills, pipes, missiles, icebergs, engines, filters, jets, and sprinklers.

From the point of view of fluid mechanics, all matter consists of only two states, fluid and solid. The technical distinction lies with the reaction of the two to an applied shear or tangential stress. A solid can resist a shear stress by a static deflection; a fluid cannot. Any shear stress applied to a fluid, no matter how small, will result in motion of that fluid. The fluid moves and deforms continuously as long as the shear stress is applied. As a corollary, we can say that a fluid at rest must be in a state of zero shear stress, a state often called the hydrostatic stress condition in structural analysis.

When the fluid element subjected to shear stress τ_{yx}, it experiences a rate of deformation (shear rate) given by du/dy. Fluids in which shear stress is directly proportional to rate of deformation are Newtonian fluids. The term non-Newtonian is used to classify all fluids in which shear stress is not directly proportional to shear rate. Most common fluids such as water, air, and gasoline are Newtonian under normal conditions. If the fluid is Newtonian, then:

$$\tau_{yx} \propto \frac{du}{dy}$$

The constant of proportionality is the absolute (or dynamic) viscosity, μ. Thus Newton’s law of viscosity is given for one-dimensional flow by:

$$\tau_{yx} = \mu \frac{du}{dy}$$

Note that, since the dimensions of τ are F/L2 and the dimensions of du/dy are 1/t, μ has dimensions Ft/L2. Since the dimensions of force, F, mass, M, length, L, and time, t, are related by Newton's second law of motion, the dimensions of μ can also be expressed as M/Lt. Note that for gases, viscosity increases with temperature, whereas for liquids, viscosity decreases with increasing temperature.

Fluids in which shear stress is not directly proportional to deformation rate are non-Newtonian. Strictly speaking, our definition of a fluid is valid only for materials that have zero yield stress. Non-Newtonian fluids commonly are classified as having time-independent or time-dependent behavior. Examples of time-independent behavior are shown in Fig. 1. Numerous empirical equations have been proposed to model the observed relations between τyx and du/dy for time-independent fluids. They may be adequately represented for many engineering applications by the power law model, which for one-dimensional flow becomes:

$$\tau_{yx} = k \left(\frac{du}{dy} \right)^n$$

where the exponent, n, is called the flow behavior index and the coefficient, k, the consistency index. This equation reduces to Newton's law of viscosity for n= 1 with k =μ.

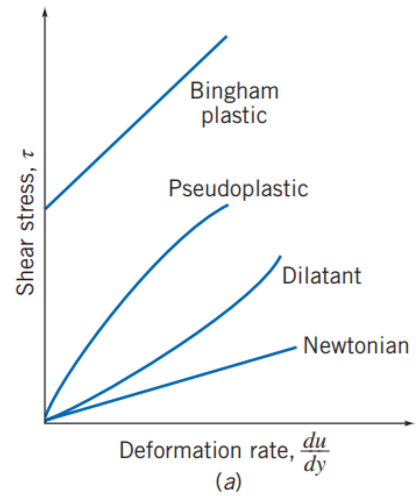

Fig. 1 (a) Shear stress, as a function of deformation rate for one-dimensional flow of various non-Newtonian fluids.

A fluid that behaves as a solid until a minimum yield stress, τ_y, is exceeded and subsequently exhibits a linear relation between stress and rate of deformation is referred to as an ideal or Bingham plastic. The corresponding shear stress model is:

$$\tau_{yx} = \tau_y + \mu_p \frac{du}{dy}$$

Most engineers subdivide fluid mechanics in terms of whether or not viscous effects and compressibility effects are present, as shown in Fig. 2. Also shown are classifications in terms of whether a flow is laminar or turbulent, and internal or external.

Laminar and Turbulent Flows

A laminar flow is one in which the fluid particles move in smooth layers. A turbulent flow is one in which the fluid particles rapidly mix as they move along due to random three-dimensional velocity fluctuations. The Reynolds number (Re) is a dimensionless quantity that helps predict fluid flow patterns in different situations by measuring the ratio between inertial and viscous forces. At low Reynolds numbers, flows tend to be dominated by laminar (sheet-like) flow, while at high Reynolds numbers, flows tend to be turbulent. The Reynolds number is defined as:

$$Re = \rho \frac{VL}{\mu}$$

where ρ and μ are the fluid density and viscosity, respectively, and V and L are the typical or "characteristic" velocity and size scale of the flow (in this example the ball velocity and diameter), respectively.

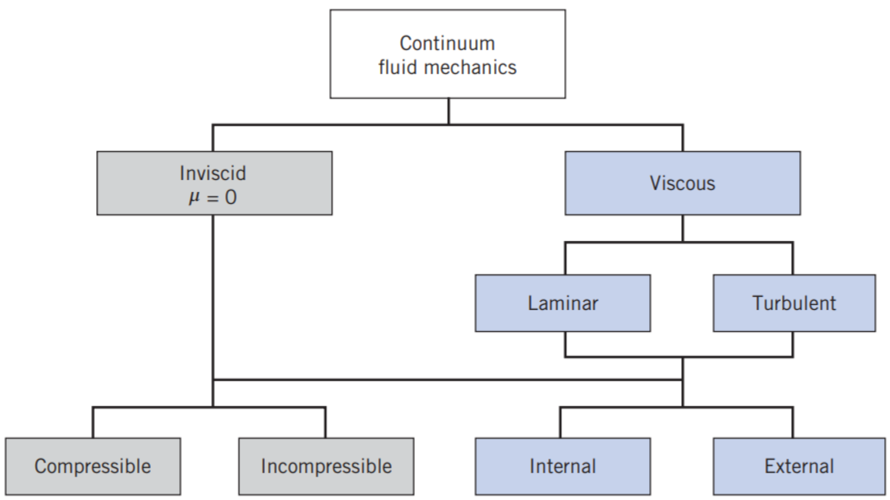

Fig. 2 Possible classification of continuum fluid mechanics.

Compressible and Incompressible Flows

Flows in which variations in density are negligible are termed incompressible; when density variations within a flow are not negligible, the flow is called compressible. The most common example of compressible flow concerns the flow of gases, while the flow of liquids may frequently be treated as incompressible. It turns out that gas flows with negligible heat transfer also may be considered incompressible provided that the flow speeds are small relative to the speed of sound; the ratio of the flow speed, V, to the local speed of sound, c, in the gas is defined as the Mach number,

$$M \equiv \frac{V}{c}$$

For M < 0.3, the maximum density variation is less than 5 percent. Thus, gas flows with M < 0.3 can be treated as incompressible. The speed of sound in an ideal gas is given by $c = \sqrt{kRT}$, where k is the ratio of specific heats, R is the gas constant, and T is the absolute temperature.

Internal and External Flows

Flows completely bounded by solid surfaces are called internal or duct flows. Flows over bodies immersed in an unbounded fluid are termed external flows. Both internal and external flows may be laminar or turbulent, compressible or incompressible.

References

Introduction to Fluid Mechanics, FOX AND MCDONALD