CHMLTECH 501 Computational Fluid Dynamics

Classification of Fluid Flows

The vast and potential confusing number of fluid flows can be classified into various types for more rational study. For example, if we wish to study the air flow around the Concord's wing as it flies through the sound barrier, we must know that we would be studying an *unsteady three-dimensional compressible irrotational inviscid* flow of a gas past a tick wing. This section will set forth the principles for classifying the types of fluids and fluid flows treated in CFD.

Gases versus Liquids

A fluid can be classified as either a liquid or a gas, or even a mixture of both. A gas, for example, is far more compressible than a liquid; a gas does not possess a free-surface that divides it from its environment; a gas expands and occupies the entire space of its container; most gases have no wetting characteristics, while most liquids are wet.

In gases, the average spacing between simple molecules at normal pressures and temperatures is of the order $10d_0$, whereas for liquids it is of the order d_0. the molecules are thus far apart for gases so that only weak cohesive forces act between molecules. In liquids, each molecule is within a strong force field and the molecules are packed as close together as the repulsive forces allow. The primary property of the liquid and solid phases of matter is that they are condensed phases when the molecules are within strong cohesive forces. The primary properties of the liquid and gaseous phases are the fluidity and the ability to change shape freely.

a fluid may first exist as a gas for some pressure and temperature, then as a liquid at a different pressure or temperature; this, of course, reflects changes in the intermolecular force and molecular spacing. We can understand this shift from gas to liquid by considering a gas that is being compressed isothermally. The kinetic energy of the molecule remains invariant as the distance between neighboring molecules decreases. When the specific volume of the gas becomes so small that the spacing between molecules is only a few times their distance, attractive forces become significant.

Continuum versus Discrete Fluids

A continuum is said to exist if in any given fluid volume $\forall$ (where the volume contains a sufficiently large number of molecules), the individual variational effects of molecules on the properties of density, temperature, and pressure of the fluid within the volume are negligible. From the continuum point of view, we consider properties at a pint in space. By taking smaller and smaller sized volume about the point, we approach a limit defined as the *property at the point.* The specific energy e is defined at a point,

$$e = \lim_{\forall \to \forall_\epsilon} \frac{E}{\forall} \tag{1}$$

If the volume becomes too small ($\forall < \forall_\epsilon$), the ratio will deviate from the norm, since we must then consider the specific energy of each individual molecule. Thus, the properties of the fluid are based on averaged results in a continuum, and change smoothly with both time and space.

The concept of the continuum is quite arbitrary as it allows one to study the macroscopic behavior of the fluid rather than its microscopic behavior. Use of the continuum concept results in an analysis vastly less complicated a discrete analysis. In the latter, a discrete or a particular molecule is identified. For each molecule the pressure and temperature must be determined because they are dependent on the probable state of the molecule. Hence, each molecule exhibits in the entire flow field has to be treated separately, since each molecule exhibits a behavior different from other such as free molecule flow, or in the ionization and dissociation of gases, the latter two of which are popular subjects in re-entry and high-energy space physics.

Perfect versus Real Fluids

A perfect fluid, according to L. Euler, who in 1768 wrote on the motion of “fluida perfecta”, does not sustain shear or the effects of compressive forces. To envision a fluid that does not sustain a shear σ_{yx}, we must posit one of two conditions, according to

$$\sigma_{yx} = 2\mu\dot{\epsilon}_{yx} = \mu\frac{du}{dy} \tag{2}$$

either the viscosity μ is zero or the rate of angular deformation $\dot{\epsilon}_{yx}$ is zero. For μ to be zero the fluid must be ideal. But in nature there is no such thing as an ideal fluid, though many (such sa air) approach the ideal.

The second conditions, i.e., $\dot{\epsilon}_{yx} = 0$ is a more plausible condition for the stress to be zero. What this latter condition means is that two adjacent horizontal layers of a perfect fluid can move at different velocities without one layer affecting the other layer through internal resistive stresses. We call such flows ***slip flow***. Thus, a perfect fluid can slip by a solid wall, the wall acting only to redirect the flow moving past it. For perfect fluids, each layer of a moving fluid can be hypothetically removed from the flow and replaced by a solid boundary of the identical geometric shape as the removed layer, and this layer can be fixed or moving (it does not matter since it will in no way alter the resultant flow pattern).

A real fluid, on the other hand, is not allowed to slip past a fixed solid wall. the presence of the wall communicates dynamic information from one fluid layer to the next via the shear stress σ_{yx}. The “stickiness” of fluid layers is controlled by the magnitude of the viscosity μ and is therefore responsible for creating whatever spatial variation of the velocity may exist in the flow field. Thus, at a stationary solid wall, the fluid lamina directly in contact with the wall has the velocity of the wall, provided that the mean free path of the molecule far from the wall is much *less* than the magnitude of a characteristic reference length.

If, however, the path of the molecule approaches the magnitude of the reference length—if, for example, the length of the mean free path of the molecule is much *greater* than the reference length—then the effect of the shear stress is totally negligible because of the ineffectiveness of the viscosity μ. Such a fluid cna be considered perfect. Free-molecule flow is where the path of the molecules is extremely large. It occurs at hypersonic speeds. In the problem we will be studying, the mean freepath of the molecule is many orders of magnitude smaller than any reference length so tha the fluid lamina next to the fixed wall cannot slip past the wall. This is a ***no slip flow***.

Real fluid effects are apparent in a region called the ***boundary layer***, a region very close to a body submerged in a fluid flow. The influence of viscosity spreads around the "wetted" surface of the body in a manner similar to the way heat would spread in that region.

Newtonian versus Non-Newtonian Fluids
A Newtonian fluid is one i which the viscosity μ is a constant for a fixed temperature and pressure. A non-Newtonian fluid such as jello, ink, milk, therefore, would be a fluid in which the viscosity varies.

Compressible versus Incompressible Fluids
Compressible fluids are fluids whose specific volume $\bar{v}$ is a function of pressure. Compressibility is not related to a fluid's ability to change shape, as is sometimes erroneously assumed. COnversely, an incompressible fluid is a fluid whose density if not changed by external forces acting on the fluid.

Hydrodynamic is the study of the behavior of incompressible fluids, whereas gas dynamics is the study of compressible fluids. The familiar Mach number M indicates the importance of the compressibility of gases in the dynamics of a fluid flow. The Mach number is defined as the ratio of the velocity of the fluid to the velocity of sound. Compressible fluids are subdivided into subsonic, transonic, supersonic and hypersonic compressible flows, meaning speeds less than, equal to, or greater than the speed of sound.

Steady versus Unsteady Fluid Flows
A steady fluid flow has properties and variables that are independent of real time. Mathematically, this can be stated as

$$\frac{\partial}{\partial t}(\quad) = 0 \tag{3}$$

Equation (3) states that none of the dependent variables change with time at any point in the flow. In unsteady flow, however, the fluid exhibits variations at a fixed point in space with respect to time. Thus, we shall have to consider whether the flow through a nozzle is steady or unsteady or if the flow past a wing is steady or unsteady.

Consider steady and unsteady flows for two different real fluids. Let one fluid be laminar (well-behaved), and the other turbulent (random). A turbulent flow can be viewed as steady provided that its time average velocity is constant at a specific point in the flow. We are primarily concerned with steady fluid flow, although unsteady motion are also treated.

One, Two, and Three-Dimensional Flows
A one-dimensional flow has spatial variations in one direction only. such a flow is also said to be uniform at every cross section normal to the main direction of flow. Only one independent space variable is needed to describe the variation. WE usually designate x to be that variable. Thus $f = f(x)$ is one-dimensional. Example: steady ideal fluid flow through a graduated tunnel.

Similarly, a two-dimensional flow is one in which spatial variations exist in two-directions, or variations exist along some planar surface. Two Cartesian independent space variables are needed to describe the variation. Thus $f = f(x, y)$ is two-dimensional. Example: steady flow through a pipe.

A three dimensional flow has spatial variations everywhere in the flow field. All turbulent fluid flows are three-dimensional. Thus $f = f(x, y, z)$ would be three-dimensional. Example: steady flow rotating in a fixed wall.

Rotational versus Irrotational Flow

A flow is irrotational if it exhibits no rate of angular deformation of any fluid particle. The converse holds for rotational flows. Irrotational flow means that the fluid masses may deform but cannot rotate. To recognize rotation we need to consider finite (though small) fluid masses called fluid parcels. Fluid particles, which are point masses, have no detectable rotation. To detect rotation, a coordinate system is attached to the fluid parcel, and if, the coordinate system rotates as the parcel moves along a path, then we say the flow is rotational. We shall define a fluid flow that is irrotational as a *potential flow.*