Introduction to Fluid Mechanics: A Review

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ABSTACT

The aim of the present paper is to give the introduction about the fundamentals of fluid mechanics. History of Fluid mechanics is given in this paper. Characteristics of fluid and Classification of flows are detailed. A literature review on hydromagnetic flow problems is also present.

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1. INTRODUCTION TO FLUID

Mechanics is the oldest physical science that deals with both stationery and moving boundaries under the influence of forces. The branch of the mechanics that deals with bodies at rest is called statics while the branch that deals with bodies in motion is called dynamics. Fluid Mechanics is the science that deals with behavior of fluids at rest (fluid statics) or in motion (fluid dynamics) and the interaction of fluids with solids or other fluids at the boundaries. A substance in liquid / gas phase is referred as 'fluid'. Distinction between a solid & a fluid is made on the basis of substance's ability to resist an applied shear (tangential) stress that tends to change its shape. A solid can resist an applied shear by deforming its shape whereas a fluid deforms continuously under the influence of shear stress, no matter how small is its shape. In solids, stress is proportional to strain, but in fluids, stress is proportional to 'strain rate.'

2. HISTORY OF FLUID MECHANICS

The study of fluid mechanics goes back at least to the days of ancient Greece, when Archimedes investigated fluid statics and buoyancy and formulated his famous law known now as the Archimedes' principle, which was published in his work *On Floating Bodies* – generally considered to be the first major work on fluid mechanics. Rapid advancement in fluid mechanics began with Leonardo da Vinci , Evangelista Torricelli (invented the barometer), Isaac Newton (investigated viscosity) and Blaise Pascal (researched hydrostatics, formulated Pascal's law), and was continued by Daniel Bernoulli with the introduction of mathematical fluid dynamics in *Hydrodynamica* (1739).

Inviscid flow was further analyzed by various mathematicians (Leonhard Euler, Jean le Rond d'Alembert, Joseph Louis Lagrange, Pierre-Simon Laplace, Siméon Denis Poisson) and viscous flow was explored by a multitude of engineers including Jean Léonard Marie Poiseuille and Gotthilf Hagen. Further mathematical justification was provided by Claude-Louis Navier and George Gabriel Stokes in the Navier–Stokes equations, and boundary layers were investigated (Ludwig Prandtl, Theodore von Kármán), while various scientists such as Osborne Reynolds, Andrey Kolmogorov, and Geoffrey Ingram Taylor advanced the understanding of fluid viscosity and turbulence.

3. CHARACTERISTICS OF A FLUID

Some most common properties of Fluid are:

I. Pressure p: It is the normal force exerted by a fluid per unit area. In SI system the unit and dimension of pressure can be written as, Nm^2 and $ML^{-1}T^{-2}$ respectively.

II. Density, Specific Gravity and Specific Volume: The mass per unit volume of material is called the density, which is generally expressed by the symbol ρ. The density of a gas changes according to the pressure, but that of a liquid may be considered unchangeable in general. The units of density are Kg/m^3 (SI). The density of water at 4°C and 1 atm (101 325 Pa, standard atmospheric pressure) is 1000Kg/m^3 . The ratio of the density of a material ρ to the density of water ρ_w, is called the specific gravity, which is expressed by the symbol s. $s = \frac{\rho}{\rho_w}$.

The reciprocal of density, i.e. the volume per unit mass, is called the specific volume, which is generally expressed by the symbol v. $v = \frac{1}{\rho}$ (m^3/Kg).

III. Temperature T : It is the measure of hotness and coldness of a system. In thermodynamic sense, it is the measure of internal energy of a system. Many a times, the temperature is expressed in centigrade scale (°C) where the freezing and boiling point of water is taken as 0°C and 100°C, respectively. In SI system, the temperature is expressed in terms of absolute value in Kelvin scale (K = °C+ 273).

IV. Viscosity μ: When two solid bodies in contact, move relative to each other, a friction force develops at the contact surface in the direction opposite to motion. The situation is similar when a fluid moves relative to a solid or when two fluids move relative to each other. The property that represents the internal resistance of a fluid to motion (i.e. fluidity) is called as viscosity. The fluids for which the rate of deformation is proportional to the shear stress are called Newtonian fluids and for the linear relationship of a one-dimensional system, the shear stress τ is then expressed as, $= \mu \frac{du}{dy}$, where, du, dy is the shear strain rate and μ is the dynamic (or absolute) viscosity of the fluid. The dynamic viscosity has the dimension $ML^{-1}T^{-1}$ and the unit of $Kg/m.s$ (or, $N.s/m^2$ or $Pa.s$). A common unit of dynamic viscosity is poise which is equivalent to 0.1 $Pa.s$. Many a times, the ratio of dynamic viscosity to density appears frequently and this ratio is given by the name kinematic viscosity $\left(\nu = \frac{\mu}{\rho}\right)$. It has got the dimension of L^2T^{-1} and unit of stoke (1 stoke = 0.0001 m^2/s). Typical values of kinematic viscosity of air and water at atmospheric temperature are $1.46 \times 10^{-5} m^2/s$ and $1.14 \times 10^{-6} m^2/s$, respectively. In general, the viscosity of a fluid mainly depends on temperature. For liquids, the viscosity decreases with temperature and for gases, it increases with temperature. Sutherland's correlation is used to determine viscosity of gases as a function of temperature.

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^{3/2} \left(\frac{T_0+S}{T+S}\right) ,$$

For air, the reference value of viscosity $\mu_0 = 1.789 \times 10^{-5} Kg/m.s$ at $T_0 = 288K$ and $S = 110K$. In the case of liquids, the viscosity is approximated as below;

$$ln\left(\frac{\mu}{\mu_0}\right) = a + b\left(\frac{T_0}{T}\right) + c\left(\frac{T_0}{T}\right)^2.$$

For water at $T_0 = 273K$, $\mu_0 = 0.001792 Kg/m.s$, $a = -1.94, b = -4.8, c = 6.74.$

V. Thermal Conductivity k: It relates the rate of heat flow per unit area $\dot{q}$ to the temperature gradient $\frac{dT}{dx}$ and is governed by Fourier Law of heat conduction i.e. $\dot{q} = -k\frac{dT}{dx}$. In SI system the unit and dimension of pressure can be written as, W/m.K and $T^{-3}\theta^{-1}$, respectively. Thermal conductivity varies with temperature for liquids as well as gases in the same manner as that of viscosity. The reference value of thermal conductivity (k_0) for water and air at reference temperature is taken as, 0.6 W/m.K and 0.025 W/m.K, respectively.

VI. Coefficient of compressibility/Bulk modulus (E_v): It is the property of that fluid that represents the variation of density with pressure at constant temperature. Mathematically, it is represented as, $E_v = \rho\left(\frac{\partial p}{\partial T}\right)_T$. In terms of finite changes, it is approximated as, $E_v = -\frac{(\Delta\rho/\rho)}{\Delta T}$. It can be shown easily that E_v for an ideal gas at a temperature p is equal to its absolute pressure (N/m^{-2}).

VII. Specific heats: It is the amount of energy required for a unit mass of a fluid for unit rise in temperature. Since the pressure, temperature and density of a gas are interrelated, the amount of heat required to raise the temperature from T_1 to T_2 depends on whether the gas is allowed to expand during the process so that the energy supplied is used in doing the work instead of raising the temperature. For a given gas, two specific heats are defined corresponding to the two extreme conditions of constant volume and constant pressure. (i) Specific heat at constant volume (c_v), (ii) Specific heat at constant pressure (c_p). The following relation holds good for the specific heat at constant volume and constant pressure. For air ; c_p = 1.005 KJ/kg.K , c_v= 0.718 KJ/kg. K .$c_p - c_v = R;\ c_p = \frac{\gamma R}{\gamma-1}, c_v = \frac{R}{\gamma-1}$.

VIII. Speed of sound (c) : An important consequence of compressibility of thec fluid is that the disturbances introduced at some point in the fluid propagate at finite velocity. The velocity at which these disturbances propagate is known as "acoustic velocity/speed of sound". Mathematically, it is represented as below;$c = \sqrt{\frac{dp}{d\rho}} = \sqrt{\frac{E_v}{\rho}}$.

In an isothermal process $E_v = p \Rightarrow c = \sqrt{\frac{p}{\rho}}, c = \sqrt{RT}$ (for an ideal gas medium).

In isentropic process, $E_v = \gamma p \Rightarrow c = \sqrt{\frac{\gamma p}{\rho}}, c = \sqrt{\gamma RT}$ (for an ideal gas medium).

IX. Vapour pressure(p_v) : It is defined as the pressure exerted by its vapour in phase equilibrium with its liquid at a given temperature. For a pure substance, it is same as the saturation pressure. In a fluid motion, if the pressure at some location is lower than the vapour pressure, bubbles start forming. This phenomenon is called as cavitation because they form cavities in the liquid.

X. Surface Tension (σ) : When a liquid and gas or two immiscible liquids are in contact, an unbalanced force is developed at the interface stretched over the entire fluid mass. The intensity of molecular attraction per unit length along any line in the surface is called as surface tension. For example, in a spherical liquid droplet of radius (r) , the pressure difference (Δp) between the inside and outside surface of the droplet is given by, $\Delta p = \frac{2\sigma}{r}$. In SI system the unit and dimension of pressure can be written as, N/m and MT^{-2} respectively.

State Relations for Gases and Liquids: All gases at high temperatures and low pressures are in good agreements with 'perfect gas law' given by, $p = \rho RT = \rho\left(\frac{\bar{R}}{M}\right)T$ .where, R is the characteristic gas constant, $\bar{R}$ is the universal gas constant and is the M molecular weight. Liquids are nearly incompressible and have a single reasonable constant specific heat. Density of a liquid decreases slightly with temperature and increases moderately with pressure. Neglecting the temperature effect, an empirical pressure- density relation is expressed as, $\frac{p}{p_a} = (B+1)\left(\frac{p}{p_a}\right)^n - B$

Here, B and$n$ are the non-dimensional parameters that depend on the fluid type and vary slightly with the temperature. For water at 1 atm, the density is 1000 kg/m^3 and the constants are taken as, B = 3000 and n =7 .[41]

4. CLASSIFICATIONS OF FLUID FLOWS

Some of the general categories of fluid flow problems are as follows;

I. Viscous and inviscid flow: The fluid flow in which frictional effects become signification, are treated as viscous flow. When two fluid layers move relatively to each other, frictional force develops between them which is quantified by the fluid property 'viscosity'. Boundary layer flows are the example viscous flow. Neglecting the viscous terms in the governing equation, the flow can be treated as inviscid flow.

II. Internal and External flow: The flow of an unbounded fluid over a surface is treated as 'external flow' and if the fluid is completely bounded by the surface, then it is called as 'internal flow'. For example, flow over a flat plate is considered as external flow and flow through a pipe/duct is internal flow. However, in special cases, if the duct is partially filled and there is free surface, then it is called as open channel flow. Internal flows are dominated by viscosity whereas the viscous effects are limited to boundary layers in the solid surface for external flows.

III. Compressible and Incompressible flow: The flow is said to be 'incompressible' if the density remains nearly constant throughout. When the density variation during a flow is more than 5% then it is treated as 'compressible'. This corresponds to a flow Mach number of 0.3 at room temperature.

IV. Laminar and Turbulent flow: The highly ordered fluid motion characterized by smooth layers of fluid is called 'Laminar Flow', e.g. flow of highly viscous fluids at low velocities. The fluid motion that typically occurs at high velocities is characterized by velocity fluctuations are called as 'turbulent.' The flow that alternates between being laminar & turbulent is called 'transitional'. The dimensionless number i.e. Reynolds number is the key parameter that determines whether the flow is laminar or turbulent.

V. Steady and Unsteady flow: When there is no change in fluid property at point with time, then it implies as steady flow. However, the fluid property at a point can also vary with time which means the flow is unsteady /transient. The term 'periodic' refers to the kind of unsteady flows in which the flow oscillates about a steady mean.

VI. Natural and Forced flow: In a forced flow, the fluid is forced to flow over a surface by external means such as a pump or a fan. In other case (natural flow), density difference is the driving factor of the fluid flow. Here, the buoyancy plays an important role. For example, a warmer fluid rises in a container due to density difference.

VII. One/Two/Three dimensional flow: A flow field is best characterized by the velocity distribution, and thus can be treated as one/two/three dimensional flow if velocity varies in the respective directions.[41]

5. LITERATURE REVIEW OF WORK IN HYDROMAGNETIC FLOW PROBLEMS

Several researches have appeared in literature and below we have listed only a few of them, which are relevant to Hydromagnetic flow problems. Hartmann[4] has studied the theory of the laminar flow of an electrically conducting liquid in a homogenous magnetic field. Ostrach[7] has studied the variable convection in vertical channel with heating from below including effect of heat source and frictional heating. Alpher[8]has investigated the heat transfer in magnetohydrodynamic flow between parallel plates. Nigam and Singh [9] was analyzed the heat transfer by laminar flow between parallel plates under the action of transverse magnetic field. Walter [10] was analyzed the non-Newtonian effects in some elasticoviscous liquids whose behavior at small rate of shear is characterized by a general linear equation of state. Vidyanidhu and Nigam[11] was discussed the secondary flow in a rotating channel. Pop [12] and Mazumder etal [13] has analyzed the effect of Hall currents on hydromagnetic flow near an accelerated plate. Raptis [14] has analyzed the unsteady free convection flow through a porous medium. Jha and Singh [15] has analyzed the Soret effects on free convection and Mass transfer flow in the Stokes problem for an infinite vertical plate. Mazumder [16] was discussed the exact solution of oscillatory Couette flow in a rotating system. Singh and Rana [17] was discussed the three dimensional flow and heat transfer through a porous medium. Attia and Kotb [18] has analyzed the MHD flow between two parallel plate with heat transfer. Raptis[19] has analyzed the radiation and free convection flow through a porous medium. Hall etal [20] was discussed the natural convection cooling of vertical rectangular channels in air considering radiation and wall conduction. Hakiem [21] was discussed MHD oscillating flow on free convection radiation through a porous medium with constant suction velocity. Bakier [22] was discussed the thermal radiations effects on mixed convections from vertical surfaces in saturated porous media. Muthucumaraswamy and Ganesan [23] has analyzed the first order chemical reaction on flow past an impulsively started vertical plate with uniform heat and mass flux. Singh [24] has analyzed the MHD free convection and mass transfer flow with heat sources and thermal diffusion. Attia [25] has studied the influences of temperature dependent viscosity on MHD couette flow of dusty fluid with heat transfer. Sanyal and Adhikari [26] has studied the effect of radiation on MHD vertical channel flow. Hakiem and Rashad [27] has analyzed the effect of radiation on non –Darcy free `convection from a vertical cylinder embedded in a fluid saturated porous medium with a temperature dependent viscosity. Linga Raju [28]was discussed the Magnetohydrodynamic slipflow regime in a rotating channel. Muthucumraswamy and Kulandaive [29] has analyzed the radiation effect on moving vertical plate with variable temperature and uniform mass diffusion. Singh and Mathew [30] has analyzed the injection/suction effects on an oscillatory hydromagnetic flow in a rotating horizontal porous channel. Al-Azab [31] was discussed the unsteady mixed convection heat and mass transfer past an infinite porous plate with thermophoresis effect. Rashad [32] was analyzed the perturbation analysis of radiative effect on free convection flows in porous medium in pressure work and viscous dissipation. Dash [33] has studied the effect of chemical reaction on free convection flow through a porous media bounded by vertical surfaces. Singh and Pathak[34] was analyzed the oscillatory free and forced convection flow through a porous medium filled in a rotating vertical channel with slip flow conditions and radiation heat. Srinivas and Muthuraj[35] was analyzed the MHD flow with slip effects and temperaturedependent heat sources in a vertical wavy porous space. Anand Rao and Shivaish[36] has analyzed the chemical reaction effects on an unsteady MHD free convective flow past a vertical porous plate in the presences of a vertical oscillating plate with variable temperature. Chand and Kumar [37] has discussed the Soret and hall current effects on heat and mass transfer in MHD flow of viscoelastic fluid past a porous plate in a rotating porous medium in slip flow regime. Hayat etal [38] has analyzed the radiation effects on MHD flow of Maxwell fluid in a channel with porous medium. Murthya et. Al [39] was discussed the effect of chemical reaction on convective heat and mass transfer through a porous medium in a rotating channel. Singh etal [40] was analyzed the effects of thermophoresis on hydromagnetic mixed convection and mass transfer flow past a vertical permeable plate with variable suction and thermal radiation.

6. CONCLUSION

The paper provides the basic knowledge for fluid mechanics and a review of work done in hydromagnetic flow problems.

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