Ministry Of Higher Education and Scientific Research

Salahaddin University - Erbil

College of Engineering

Aviation Engineering Department

Fluid mechanic

First year

Lecture: 3

Spring semester

salar.sherwani@su.edu.krd

salar.saber@mail.ru

Lecturer:

Dr. Salar Saber Kartas

Erbil 2024

1. Introduction

❖ Any characteristic of a system is called a **property**. Some familiar properties are pressure *P*, temperature *T*, volume *V*, and mass *m*. The list can be extended to include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.

❖ In this lecture, we discuss properties that are encountered in the analysis of fluid flow. This is followed by a discussion of energy and specific heat and incompressible substances, the coefficient of compressibility, and the speed of sound.

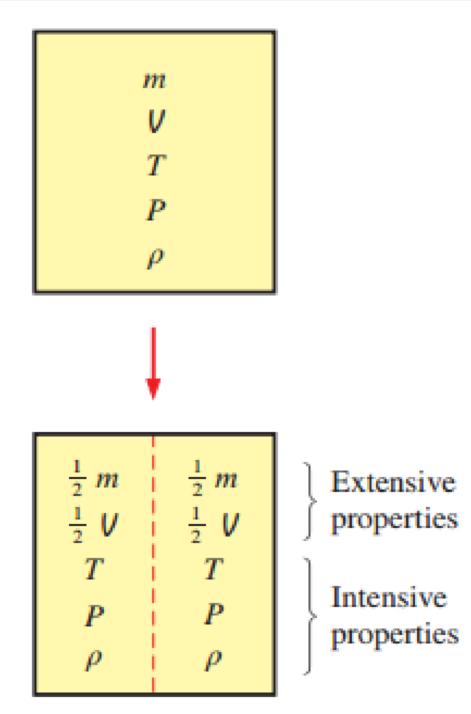


Fig –1 Criterion to differentiate intensive and extensive properties.

2. Energy and specific heat

❖ Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear (Fig. 2–9) and their sum constitutes the **total energy E** (or e on a unit mass basis) of a system. The forms of energy related to the molecular structure of a system and the degree of the molecular activity are referred to as the microscopic energy. The sum of all microscopic forms of energy is called the **internal energy** of a system, and is denoted by **U** (or u on a unit mass basis).

Fig –2 At least six different forms of energy are encountered in bringing power from a nuclear plant to your home, nuclear, thermal, mechanical, kinetic, magnetic, and electrical.

❖ **Kinetic energy -** the energy that a system possesses as a result of its motion is called **kinetic energy**. When all parts of a system move with the same velocity, the kinetic energy per unit mass is expressed as $k_e = v^2/2$ where v denotes the velocity of the system relative to some fixed reference frame.

❖ **Potential energy -** the energy that a system possesses as a result of its elevation in a gravitational field is called **potential energy** and is expressed on a per-unit mass basis as pe = gz where g - is the gravitational acceleration and z - is the elevation of the center of gravity of the system relative to some arbitrarily selected reference plane.

❖ In daily life, we frequently refer to the sensible and latent forms of internal energy as **heat**, and we talk about the heat content of bodies. In engineering, however, those forms of energy are usually referred to as **thermal energy** to prevent any confusion with heat transfer.

❖ The international unit of energy is the joule (J) or kilojoule (1 kJ = 1000 J). A joule is 1 N times 1 m. In the English system, the unit of energy is the British thermal unit (Btu), which is defined as the energy needed to raise the temperature of 1 lbm of water at 68°F by 1°F. The magnitudes of kJ and Btu are almost identical (1 Btu = 1.0551 kJ). Another well-known unit of energy is the calorie (1 cal = 4.1868 J), which is defined as the energy needed to raise the temperature of 1 g of water at 14.5°C by 1°C.

❖ **enthalpy *h* -** In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties u and Pv. For convenience, this combination is called **enthalpy *h***. That is,

$$h = u + Pv = u + \frac{P}{\rho}$$

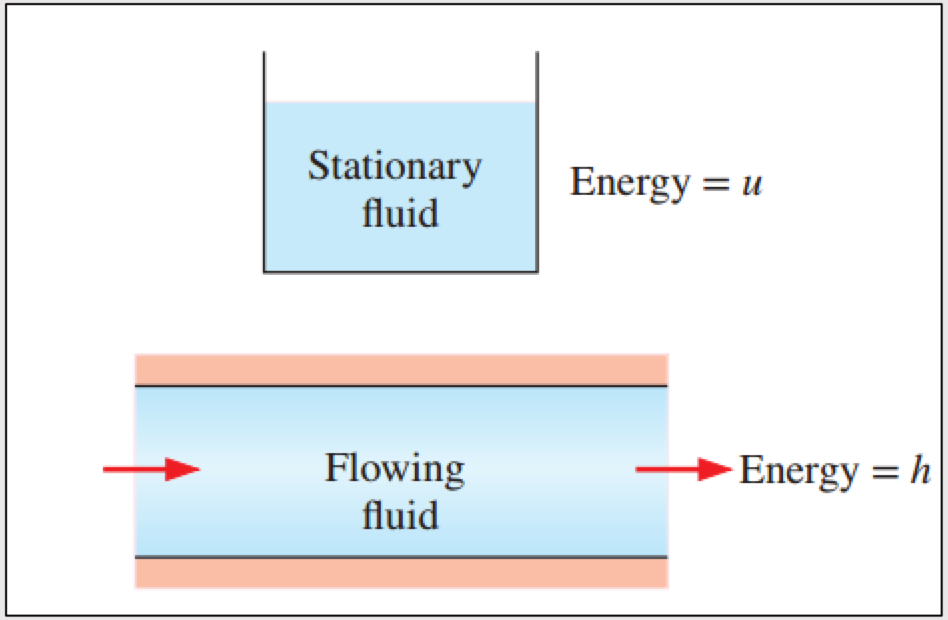


Fig –3 The internal energy u represents the microscopic energy of a non flowing fluid per unit mass, whereas enthalpy h represents the microscopic energy of a flowing fluid per unit mass.

❖ where P/ρ is the flow energy, also called the flow work, which is the energy per unit mass needed to move the fluid and maintain flow. In the energy analysis of flowing fluids, it is convenient to treat the flow energy as part of the energy of the fluid and to represent the microscopic energy of a fluid stream by enthalpy h (Fig.–3). Note that enthalpy is a quantity per unit mass, and thus it is a specific property.

3. Compressibility and speed of sound

3.1. Coefficient of Compressibility

❖ We know from experience that the volume (or density) of a fluid changes with a change in its temperature or pressure. Fluids usually expand as they are heated or depressurized and contract as they are cooled or pressurized. But the amount of volume change is different for different fluids, and we need to define properties that relate volume changes to the changes in pressure and temperature. Two such properties are the bulk modulus of elasticity κ and the coefficient of volume expansion β.

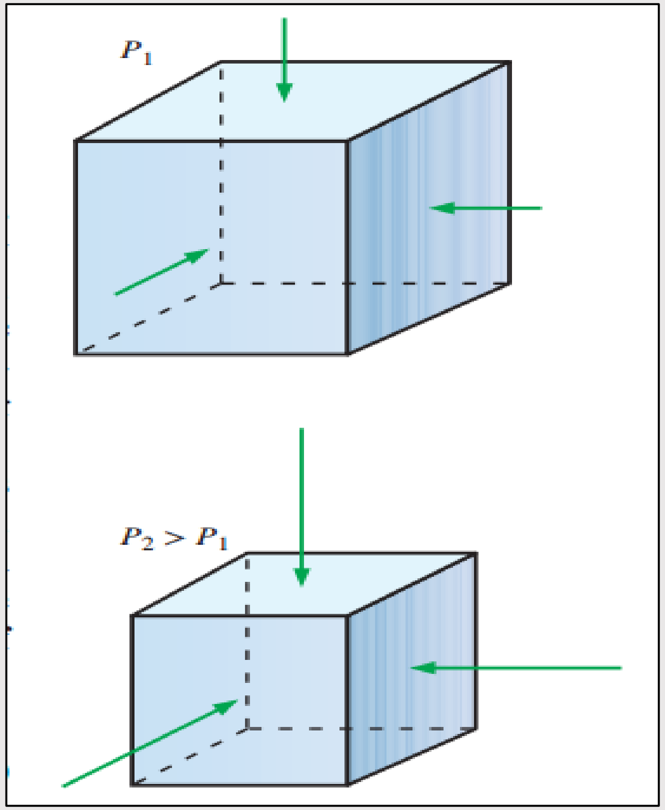


Fig –4 Fluids, like solids, compress when the applied pressure is increased from $P1$ to $P2$.

❖ It is a common observation that a fluid contracts when more pressure is applied on it and expands when the pressure acting on it is reduced (Fig.–4). That is, fluids act like elastic solids with respect to pressure. Therefore, in an analogous manner to Young's modulus of elasticity for solids, it is appropriate to define a **coefficient of compressibility** κ (also called the **bulk modulus of compressibility** or **bulk modulus of elasticity**) for fluids as:

$$\kappa = -\upsilon\left(\frac{\partial P}{\partial \upsilon}\right)_T = \rho\left(\frac{\partial P}{\partial \rho}\right)_T \qquad \text{(Pa)}$$

❖ The inverse of the coefficient of compressibility is called the **isothermal compressibility** α and is expressed as:

$$\alpha = \frac{1}{\kappa} = -\frac{1}{\upsilon}\left(\frac{\partial \upsilon}{\partial P}\right)_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T \qquad \text{(1/Pa)}$$

3.2. Coefficient of Volume Expansion

❖ The density of a fluid, in general, depends more strongly on temperature than it does on pressure, and the variation of density with temperature is responsible for numerous natural phenomena such as winds, currents in oceans, rise of plumes in chimneys, the operation of hot-air balloons, heat transfer by natural convection, and even the rise of hot air and thus the phrase “heat rises” (Fig.–5). To quantify these effects, we need a property that represents the variation of the density of a fluid with temperature at constant pressure. The property that provides that information is the **coefficient of volume expansion** (or volume expansivity) β, defined as (Fig.–6).

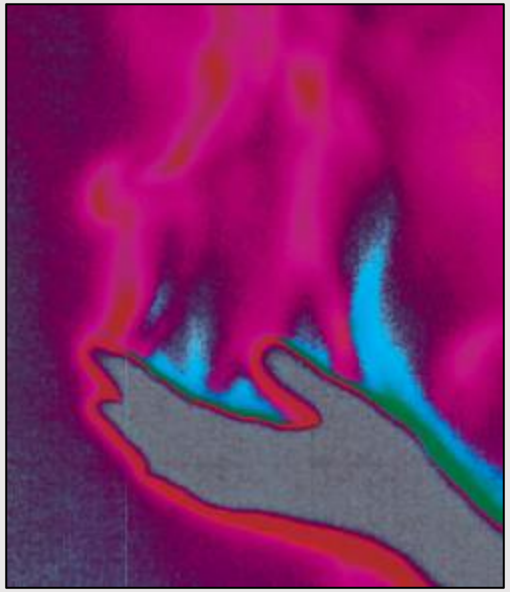


Fig – 5 Natural convection over a woman’s hand.

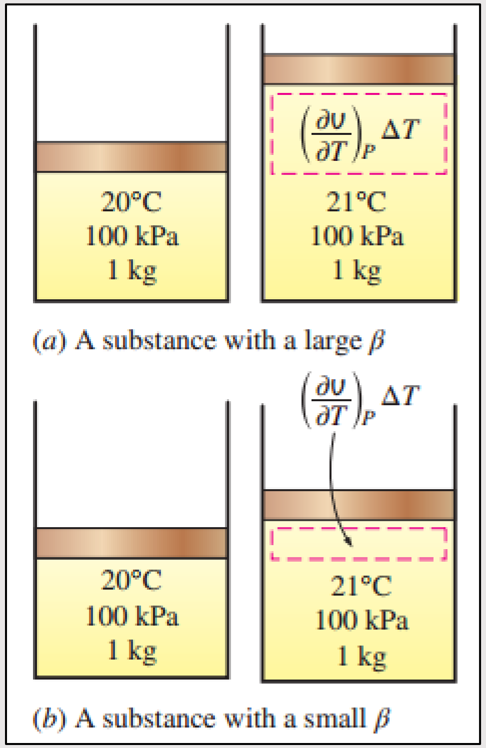


Fig – 6 The coefficient of volume expansion is a measure of the change in volume of a substance with temperature at constant pressure.

$$\beta = \frac{1}{\upsilon}\left(\frac{\partial \upsilon}{\partial T}\right)_P = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \qquad (1/\mathrm{K})$$

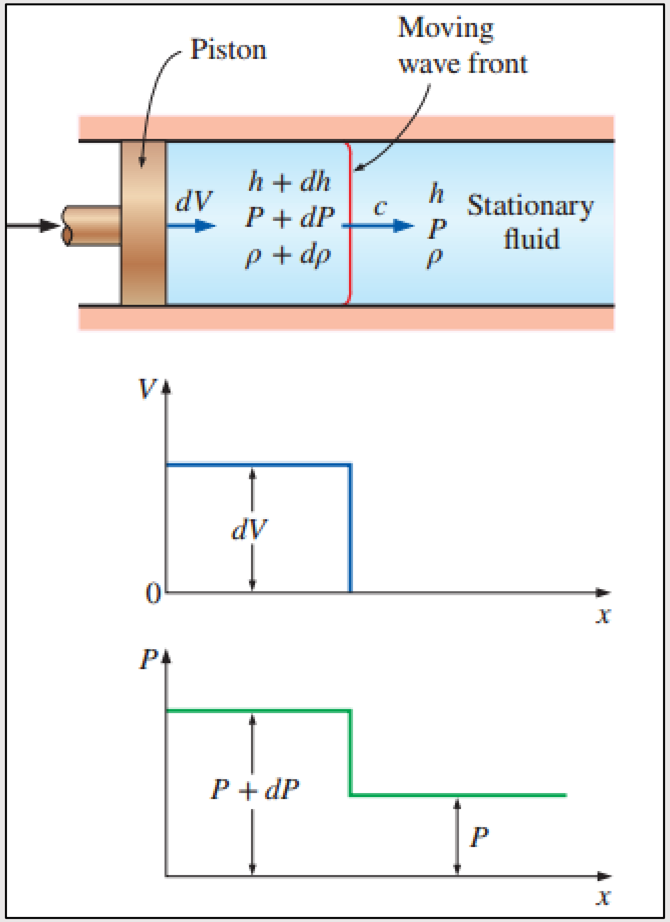
❖ Then the fractional change in volume (or density) due to changes in pressure and temperature can be expressed approximately as:

$$\frac{\Delta \upsilon}{\upsilon} = -\frac{\Delta \rho}{\rho} \cong \beta\,\Delta T - \alpha\,\Delta P$$

3.3. Speed of Sound and Mach Number

❖ An important parameter in the study of compressible flow is the **speed of sound** (or the **sonic speed**), defined as the speed at which an infinitesimally small pressure wave travels through a medium. The pressure wave may be caused by a small disturbance, which creates a slight change in local pressure.

❖ To obtain a relation for the speed of sound in a medium, consider a duct that is filled with a fluid at rest, as shown in Fig.–7. A piston fitted in the duct is now moved to the right with a constant incremental velocity dV, creating a sonic wave. The wave front moves to the right through the fluid at the speed of sound c and separates the moving fluid adjacent to the piston from the fluid still at rest. The fluid to the left of the wave front experiences an incremental change in its thermodynamic properties, while the fluid on the right of the wave front maintains its original thermodynamic properties, as shown in Fig.–7.



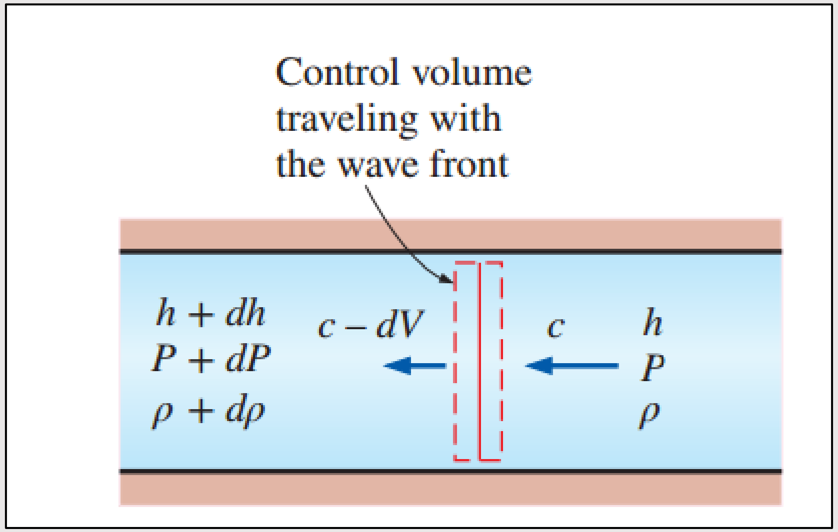
Fig–7 Propagation of a small pressure wave along a duct.

❖ To simplify the analysis, consider a control volume that encloses the wave front and moves with it, as shown in Fig.–8. To an observer traveling with the wave front, the fluid to the right appears to be moving toward the wave front with a speed of c and the fluid to the left to be moving away from the wave front with a speed of $c - dV$. Of course, the observer sees the control volume that encloses the wave front (and herself or himself) as stationary, and the observer is witnessing a steady-flow process. The mass balance for this single-stream, steady-flow process is expressed as:

$$\dot{m}_{\text{right}} = \dot{m}_{\text{left}}$$

Or

$$\rho A c = (\rho + d\rho) A (c - dV)$$



Fig–8 Control volume moving with the small pressure wave along a duct.

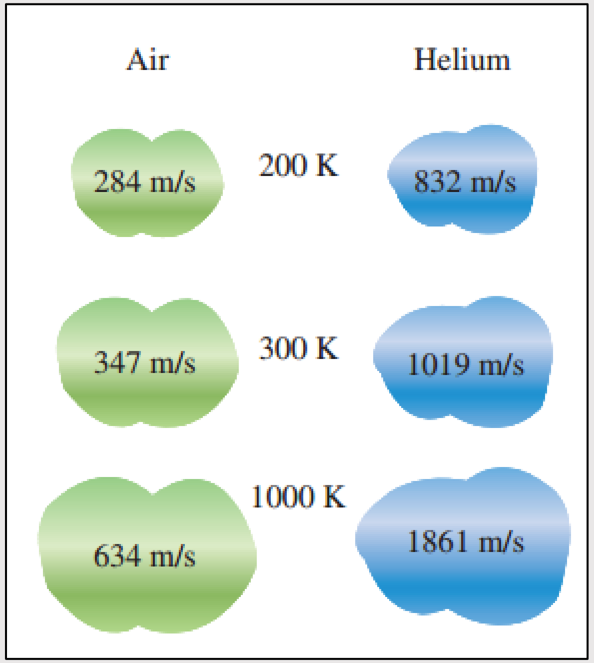
❖ When the fluid is an ideal gas ($P = \rho RT$), the differentiation ,can be performed to yield:

$$c^2 = k\left(\frac{\partial P}{\partial \rho}\right)_T = k\left[\frac{\partial(\rho RT)}{\partial \rho}\right]_T = kRT$$

Or

$$c = \sqrt{kRT}$$

❖ Noting that the gas constant R has a fixed value for a specified ideal gas and the specific heat ratio k of an ideal gas is, at most, a function of temperature, we see that the speed of sound in a specified ideal gas is a function of temperature alone (Fig.–9).



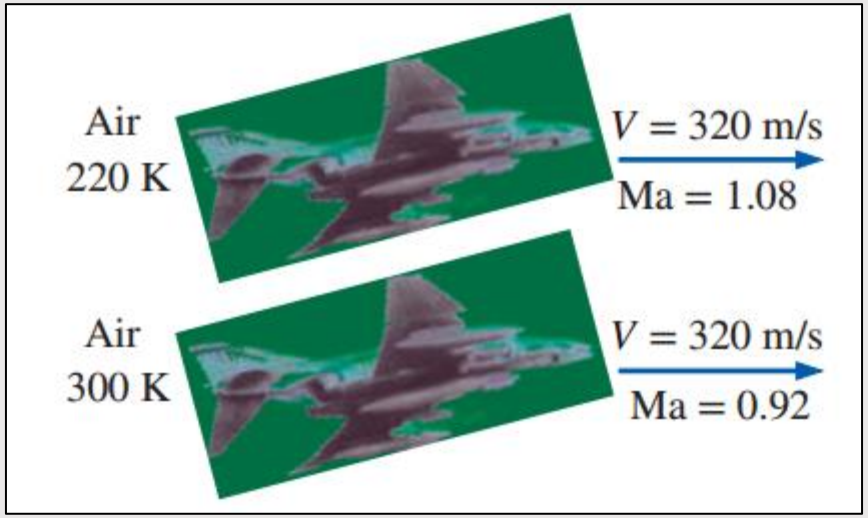
Fig–9 The speed of sound changes with temperature and varies with the fluid.

❖ A second important parameter in the analysis of compressible fluid flow is the **Mach number** Ma, named after the Austrian physicist Ernst Mach (1838–1916). It is the ratio of the actual speed of the fluid (or an object in still fluid) to the speed of sound in the same fluid at the same state:

$$\mathrm{Ma} = \frac{V}{c}$$

❖ Mach number can also be defined as the ratio of inertial forces to elastic forces. If Ma is less than about 1/3, the flow may be approximated as incompressible since the effects of compressibility become significant only when the Mach number exceeds this value.

❖ Note that the Mach number depends on the speed of sound, which depends on the state of the fluid. Therefore, the Mach number of an aircraft cruising at constant velocity in still air may be different at different locations (Fig.–10).



Fig–10 The Mach number can be different at different temperatures even if the flight speed is the same.

❖ Fluid flow regimes are often described in terms of the flow Mach number. The flow is called **sonic** when Ma = 1, **subsonic** when Ma < 1, **supersonic** when Ma > 1, **hypersonic** when Ma >> 1, and **transonic** when Ma ≅ 1.

Example

Air enters a diffuser shown in Fig. 2–22 with a speed of 200 m/s. Determine (*a*) the speed of sound and (*b*) the Mach number at the diffuser inlet when the air temperature is 30°C.

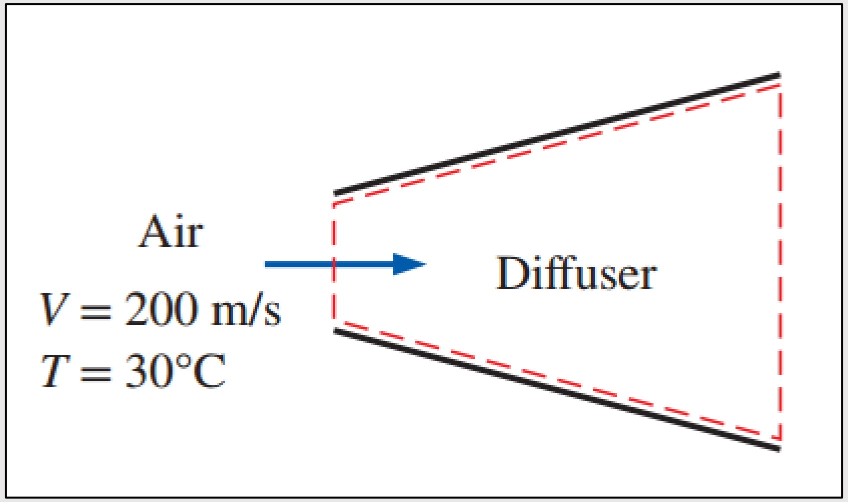


Fig 2–22

Solution

SOLUTION Air enters a diffuser at high speed. The speed of sound and the Mach number are to be determined at the diffuser inlet.

Assumption Air at the specified conditions behaves as an ideal gas.

Properties The gas constant of air is $R = 0.287$ kJ/kg·K, and its specific heat ratio at 30°C is 1.4.

Analysis We note that the speed of sound in a gas varies with temperature, which is given to be 30°C.

(*a*) The speed of sound in air at 30°C is determined from Eq. 2–26 to be

$$c = \sqrt{kRT} = \sqrt{(1.4)(0.287\ \text{kJ/kg·K})(303\ \text{K})\left(\frac{1000\ \text{m}^2/\text{s}^2}{1\ \text{kJ/kg}}\right)} = \mathbf{349\ m/s}$$

(*b*) Then the Mach number becomes

$$\text{Ma} = \frac{V}{c} = \frac{200\ \text{m/s}}{349\ \text{m/s}} = \mathbf{0.573}$$

Discussion The flow at the diffuser inlet is subsonic since Ma < 1.

Example

❖ An Aero plane travelling at a speed of 1800 km/hr in the air of pressure of 1 bar at 10-degree celsius. Find the Mach number. (k=1.4 and R=287 J/Kg K).

Solution

Temperature $t = 10°C$

$$T = 10 + 273 = 283\ k$$

Speed of 1800 km/hr= 500 m/s

$$c = \sqrt{KRT} = \sqrt{1.4 * 287 * 283} = 337.20 \text{ m/s}$$

$$M = \frac{V}{C} = \frac{500}{337.20} = 1,48$$