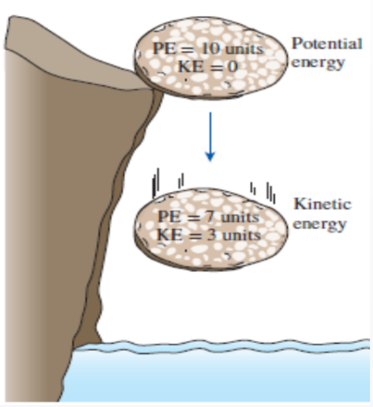
Basic Mechanical Engineering

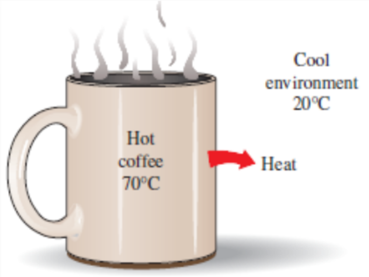
THERMODYNAMICS AND ENERGY

- Thermodynamics can be defined as the science of *energy*.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power), which is most descriptive of the early efforts to convert heat into power.
- One of the most fundamental laws of nature is the **conservation of energy principle**.
- The first law of thermodynamics is simply an expression of the conservation of energy principle, and it asserts that energy is a thermodynamic property.



THERMODYNAMICS AND ENERGY

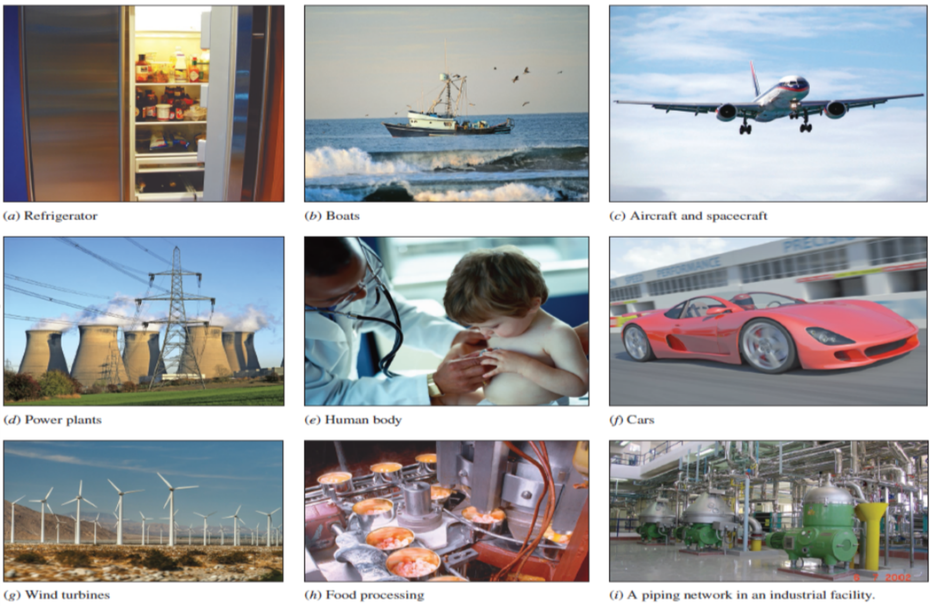
- The **second law of thermodynamics** asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.
- "Thermodynamics is a fundamental subject that describes the basic laws governing the occurrence of physical processes associated with transfer of energy or transformation of energy and it also establishes the relationship between different physical properties which have been affected by these processes."
- How to adopt these interactions to our benefit?



classical thermodynamics Vs statistical thermodynamics

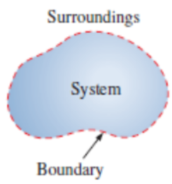
- It is well known that a substance consists of a large number of particles called molecules. The properties of the substance naturally depend on the behaviour of these particles.
- In macroscopic approach, the average molecular behaviour is taken into account and the individual molecular behaviour is disregarded.
- In microscopic approach, individual molecule behaviour is studied.

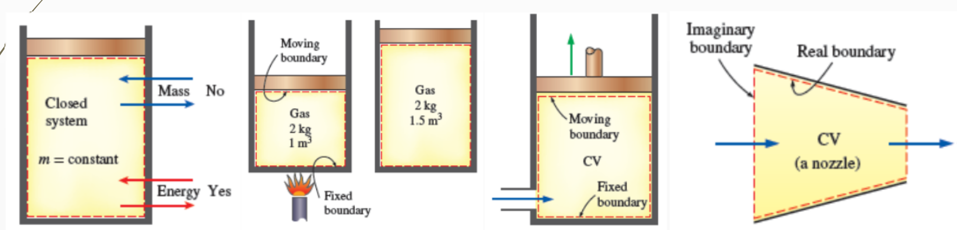
Application Areas of Thermodynamics



SYSTEMS AND CONTROL VOLUMES

- A system is defined as a *quantity of matter or a region in space chosen for study.* The mass or region outside the system is called the **surroundings**.
- The real or imaginary surface that separates the system from its surroundings is called the **boundary.**





Closed or Control Mass System Open or Control Volume System

SYSTEMS AND CONTROL VOLUMES

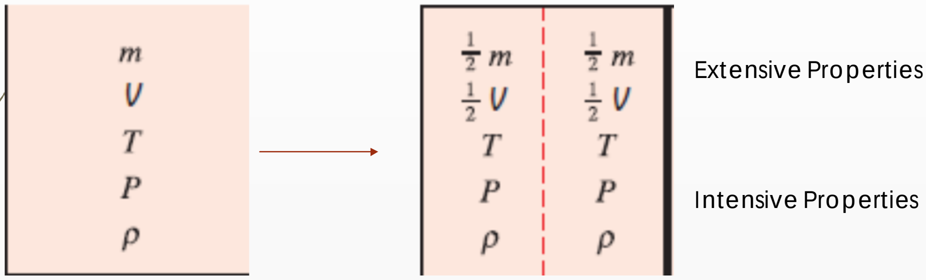
Types of System	Mass Transfer	Energy Transfer	Example
Closed	X	✓	Piston Cylinder Arrangement with Valve Closed.
Open	✓	✓	Piston Cylinder Arrangement with Valve Open.
Isolated	X	X	Insulated Flask, Universe

PROPERTIES OF A SYSTEM

- These are the characteristic features by which a system can be specified.
- These are macroscopic in nature.
- We must choose the most appropriate set of properties.
- Properties are considered to be either *intensive* or *extensive*.
- **Intensive properties** are those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties** are those whose values depend on the size—or extent—of the system. Total mass, total volume, and total momentum are some examples of extensive properties.
- Note: All specific properties are intensive properties.

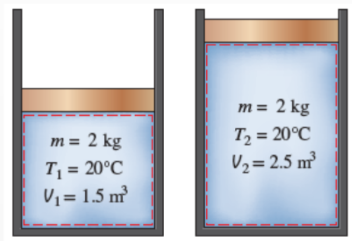
Characteristics of Properties

- Properties are state or point function
- They are independent of path.
- Properties are exact differentials.



STATE AND EQUILIBRIUM

- State: It is the condition of the system as defined by the value of all its properties. It gives complete description of the system.
- Thermodynamics deals with *equilibrium* states. The word **equilibrium** implies a state of balance.
- There are many types of equilibrium, and a system is not in thermodynamic equilibrium unless the conditions of all the relevant types of equilibrium are satisfied.



(a) State 1 (b) State 2

The State Postulate

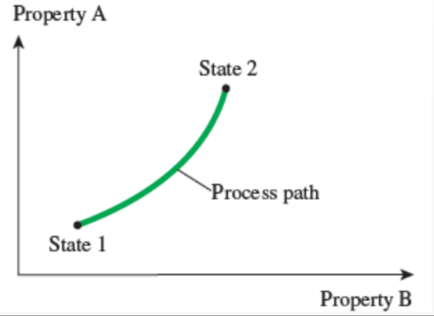
- The number of properties required to fix the state of a system is given by the **state postulate**.

- $F = C - \phi + 2$

Where, F = number of properties required to specify / fix the state.

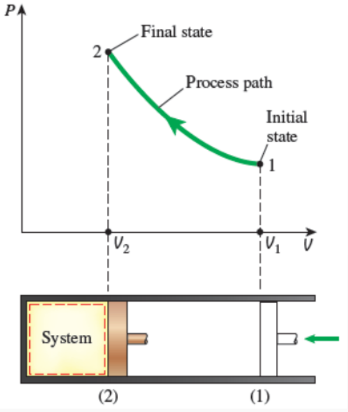
C = number of component

ϕ = number of phase



PROCESSES AND CYCLES

- Any change that a system undergoes from one equilibrium state to another is called a **process**, and the series of states through which a system passes during a process is called the **path** of the process.
- To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings.
- Processes are of two types: Reversible & Irreversible

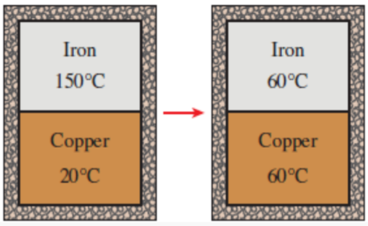


Quasi-static / Quasi-equilibrium process

- When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called a **quasi-static**, or **quasi-equilibrium**, **process**.
- A quasi-equilibrium process can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.
- Engineers are interested in quasi-equilibrium processes for two reasons. First, they are easy to analyze; second, work-producing devices deliver the most work when they operate on quasi-equilibrium processes.
- Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared.

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

- Although we are familiar with temperature as a measure of "hotness" or "coldness," it is not easy to give an exact definition for it.
- Fortunately, several properties of materials change with temperature in a *repeatable* and *predictable* way, and this forms the basis for accurate temperature measurement.
- The **zeroth law of thermodynamics** states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.*



Temperature Scales

All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water, which are also called the *ice point* and the *steam point*, respectively.

- The temperature scales used in the SI and in the English system today are the **Celsius scale** and the **Fahrenheit scale** On the Celsius scale, the ice and steam points were originally assigned the values of 0 and 100°C, respectively. The corresponding values on the Fahrenheit scale are 32 and 212°F.
- In thermodynamics, it is very desirable to have a temperature scale that is independent of the properties of any substance or substances. Such a temperature scale is called a **thermodynamic temperature scale**, which is developed later in conjunction with the second law of thermodynamics.
- The absolute scale related to Celsius scale is the Kelvin scale and is designated as K.
  - K = °C + 273.15
- 1K is defined as the 1/273.16 of the temperature at the triple point of water.

Problem-1 on Temperature Scale

- The resistance of a platinum wire is found to be 11.000 ohms at Ice Point, 15.247 ohms at Steam Point, and 28.887 ohms at 445°C. Find the constants A and B in the equation: $R = R_0(1 + At + Bt^2)$, where R is resistant, t is temperature and is constant and also the resistance of platinum wire at 300°C.

[ANS: A = 3.919 x 10 -3, B = -5.97 x 10 -7 , R = 23.345 ohms]

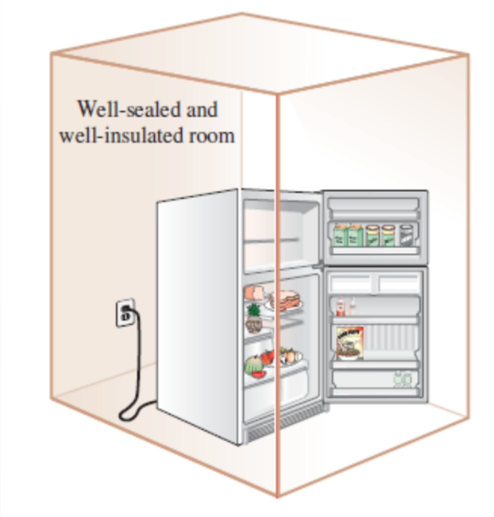
Problem-2 on Temperature Scale

- A temperature scale of a certain thermometer is given by the relation: $T = a.\ln(P) + b$, Where 'a' and 'b' are constants and P is the thermometric property of fluid in thermometer. If at the ice point and steam point, the thermometric property is found to be 1.83 and 6.78 respectively, what will be the temperature corresponding to the thermometric property of 2.42 on Celsius scale.

Problem-3 on Temperature Scale

- The readings t_A and t_B of two thermometer of A and B at ice point and steam point and related by equation $t_A = m\, t_B + n\, t_B^2 + L$ between these points, where L, m and n are constant. When both are immersed in oil A reads 51°C and B reads 50°C. Determine the reading on A, When B reads 25°C. Discuss the question which thermometer is correct.
- **Ans: m=1.04,n= -4 x 10^4 and t_A=25.75°C**

ENERGY

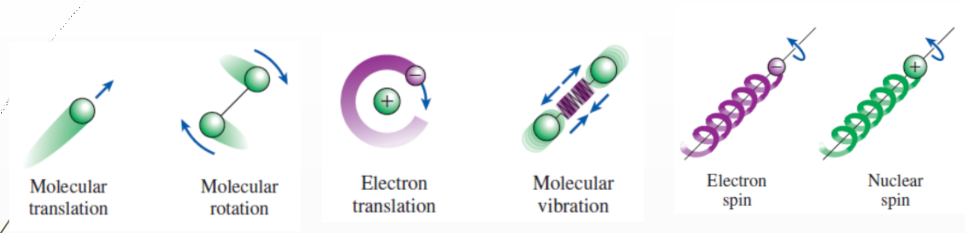


ENERGY

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy** *E* of a system.
- Thermodynamics provides no information about the absolute value of the total energy. It deals only with the *change* of the total energy.
- In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups: *macroscopic* and *microscopic*.
- The **macroscopic** forms of energy are those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies. The **microscopic** forms of energy are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames.
- The sum of all the microscopic forms of energy is called the **internal energy** of a system and is denoted by *U*

Some Physical Insight to Internal Energy

- The portion of the internal energy of a system associated with the kinetic energies of the molecules is called the **sensible energy.**

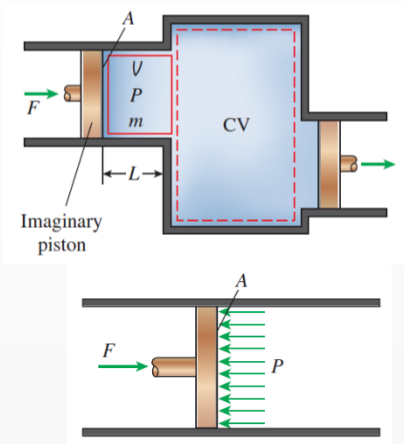


- The internal energy associated with the phase of a system is called the **latent energy**.

FLOW WORK

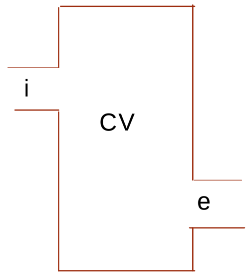
- Unlike closed systems, control volumes involve mass flow across their boundaries, and some work is required to push the mass into or out of the control volume. This work is known as the **flow work**, or **flow energy**, and is necessary for maintaining a continuous flow through a control volume.
- If the fluid pressure is P and the cross-sectional area of the fluid element is A, the force applied on the fluid element by the imaginary piston is
- F = PA
- To push the entire fluid element into the control volume, this force must act through a distance L. Thus, the work done in pushing the fluid element across the boundary (i.e., the flow work) is

$$W_{flow} = FL = PAL = PV$$



Conservation of Mass

- Let I and e be the state at the inlet and exit of the control volume.
- $m_i - m_e = m_{cv}$
- $\frac{dm_i}{dt} - \frac{dm_e}{dt} = \frac{dm_{cv}}{dt}$
- $\dot{m}_i - \dot{m}_e = \dot{m}_{cv}$
- As there is no mass accumulation, $\dot{m}_{cv} = 0$
- $\dot{m}_i = \dot{m}_e$
- Mass flow rate $\dot{m} = \rho \times A \times C = \frac{A \times C}{v}$



Steady Flow Energy Equation

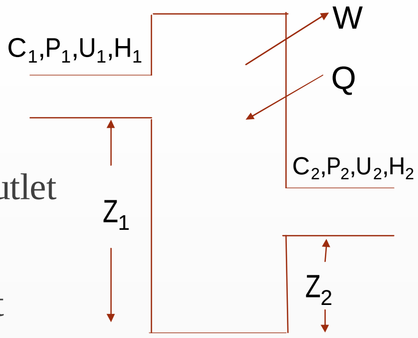
The term steady implies no change with time. Steady flow process is defined as a process during which the fluid properties can change from point to point with in the control volume, but at any fixed point, they remain the same during the entire process.

- **Assumptions:**
- The mass flow through the system remain constant.
- Fluid is uniform in composition.
- The only interaction between system and surrounding are work and heat.
- The state of fluid at any point remain constant with time.
- In the analysis, only potential, kinetic and flow energies are considered.

Steady Flow Energy Equation

- Let:
- C1, C2 = Velocities of the fluid at inlet and outlet
- P1, P2 = Pressure of the fluid at inlet and outlet
- U1, U2 = Internal energy of the fluid at inlet and outlet
- H1, H2 = Enthalpy of the fluid at inlet and outlet
- Z1, Z2 = Height above the datum at inlet and outlet
- We know that $\partial Q = dE + \partial W$ ----------- (1)
- Now the total energy E = K.E. + P.E. + I.E.

dE = d(K.E.) + d(P.E.) + d(I.E.)



Steady Flow Energy Equation

- $dE = \frac{1}{2}m(C_2^2 - C_1^2) + mg(Z_2 - Z_1) + (U_2 - U_1)$
- Also W = Entry Displacement Work + Control Volume Work + Exit Displacement Work
- $W = -P_1V_1 + W_{cv} + P_2V_2$
- Put the value of dE and W in eq 1
- $Q = \frac{1}{2}m(C_2^2 - C_1^2) + mg(Z_2 - Z_1) + (U_2 - U_1) - P_1V_1 + W_{cv} + P_2V_2$
- Rearranging the above equation

Steady Flow Energy Equation

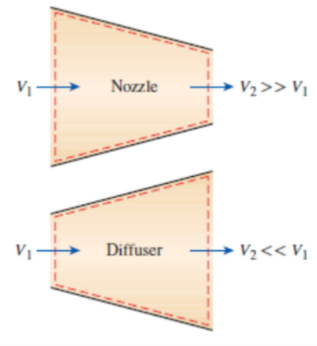
- $U_1 + P_1V_1 + \frac{1}{2}mC_1^2 + mgZ_1 + Q = U_2 + P_2V_2 + \frac{1}{2}mC_2^2 + mgZ_2 + W_{cv}$
- $H_1 + \frac{1}{2}mC_1^2 + mgZ_1 + Q = H_2 + \frac{1}{2}mC_2^2 + mgZ_2 + W_{cv}$
- $h_1 + \frac{1}{2}C_1^2 + gZ_1 + q = h_2 + \frac{1}{2}C_2^2 + gZ_2 + w_{cv}$
- $h_1 + \frac{1}{2000}C_1^2 + \frac{1}{1000}gZ_1 + q = h_2 + \frac{1}{2000}C_2^2 + \frac{1}{1000}gZ_2 + w_{cv}$
- $\dot{m}\left[h_1 + \frac{1}{2000}C_1^2 + \frac{1}{1000}gZ_1\right] + \dot{q} = \dot{m}\left[h_2 + \frac{1}{2000}C_2^2 + \frac{1}{1000}gZ_2\right] + \dot{w}_{cv}$

SOME STEADY-FLOW ENGINEERING DEVICES

Nozzles and Diffusers

The SFEE can be written as:

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + W_{cv}$$



As per discussion $gZ_1 = gZ_2$, q = 0,
For Nozzle: $C_1 <<< C_2$ While for Diffuser: $C_2 <<< C_1$
Also there is no involvement of flow work so $W_{cv} = 0$

Hence the SFEE can be written as

For Nozzle: $h_1 = h_2 + \frac{C_2^2}{2}$,

For Diffuser: $h_1 + \frac{C_1^2}{2} = h_2$

Turbines and Compressors

- The SFEE can be written as:
- $h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + W_{cv}$
- For Turbine & Compressor : $gZ_1 = gZ_2$, q = 0, $(\frac{C_1^2}{2} - \frac{C_2^2}{2}) <<< (h_1 - h_2)$
- Hence the SFEE can be written as
- For Turbine: $h_1 = h_2 + W_T$ or $W_T = h_1 - h_2$
- For Compressor: $h_1 = h_2 - W_C$ or $W_C = h_2 - h_1$

Heat Exchangers & Boilers

- The SFEE can be written as:
- $h_1 + \frac{c_1^2}{2} + gZ_1 + q = h_2 + \frac{c_2^2}{2} + gZ_2 + W_{cv}$
- For Heat Exchanger & Boilers : $gZ_1 = gZ_2$, q = 0, $\frac{c_1^2}{2} = \frac{c_2^2}{2}$, W_{cv} = 0
- Hence the SFEE can be written as
- $h_1 + q = h_2$
- $q = h_2 - h_1$

Problems on SFEE

- A steam turbine operates under steady flow conditions. It receives 7200 kg/h of steam from the boiler. The steam enters the turbine at enthalpy of 2800 kJ/kg, velocity of 4000 m/min and at an elevation of 4m. The steam leaves the turbine at an enthalpy of 2000 kJ/kg, velocity of 8000 m/min and at an elevation of 1m. Due to radiation heat losses from the turbine to the surrounding amount to 1580 kJ/h. Calculate the power output of the turbine.

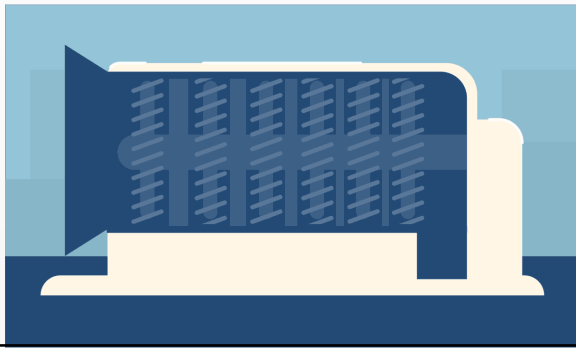
Solution

- $h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + W_{cv}$
- $\dot{m}\left[h_1 + \frac{C_1^2}{2000} + \frac{gZ_1}{1000}\right] + \dot{q} = \dot{m}\left[h_2 + \frac{C_2^2}{2000} + \frac{gZ_2}{1000}\right] + \dot{W}_{cv}$
- Given: $\dot{m}$ = 7200 kg/h = $\frac{7200}{3600}$ kg/sec = 2 kg/sec
- h_1= 2800 kJ/kg, C_1 = 4000 m/min = 66.66 m/sec, Z_1 = 4m
- h_2= 2000 kJ/kg, C_2 = 8000 m/min = 133.33 m/sec, Z_2 = 1m
- $\dot{q}$ = -1580 kJ/h = 0.438 kW
- Put these value in SFEE

- 2 x $\left[2800 + \frac{66.66}{2000} + \frac{9.81 \times 4}{1000}\right] - 0.438 = 2 \times \left[2000 + \frac{133.33}{2000} + \frac{9.81 \times 1}{1000}\right] + \dot{W}_{cv}$
- $\dot{W}_{cv}$ = 1586.287 kW Ans

Problem - 2

- An axial flow compressor of a gas turbine plant receives air from atmosphere at a pressure 1 bar, temperature 300 K and velocity 300 m/sec. At the discharge of compressor, the pressure is 5 bar and the velocity is 100 m/sec. The mass flow rate through the compressor is 20 kg/sec. Assuming adiabatic compression, calculate the power required to drive the compressor. Also calculate the inlet and outlet pipe diameter.



- $h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + W_{cv}$
- $\dot{m}\left[h_1 + \frac{C_1^2}{2000} + \frac{gZ_1}{1000}\right] + \dot{q} = \dot{m}\left[h_2 + \frac{C_2^2}{2000} + \frac{gZ_2}{1000}\right] + \dot{W}_{cv}$
- As we know $h \propto T$ or $h = c_pT$, we can write
- $\dot{m}\left[c_pT_1 + \frac{C_1^2}{2000} + \frac{gZ_1}{1000}\right] + \dot{q} = \dot{m}\left[c_pT_2 + \frac{C_2^2}{2000} + \frac{gZ_2}{1000}\right] + \dot{W}_{cv}$
- Given: P_1 = 1 bar = 100 kPa, T_1 = 300 K, C_1 = 60 m/sec
- P_2 = 5 bar = 500 kPa, T_2 = ?, C_2 = 100 m/sec, $\dot{m}$ = 20 kg/sec
- As the compression is adiabatic, $\dot{q}$ = 0 and $Z_1 = Z_2$

- For adiabatic compression process: $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$
- $T_2 = 300 \times \left(\frac{500}{100}\right)^{\frac{1.4-1}{1.4}} = 475.145\ K$
- $20 \text{ x } \left[1.005 \times 300 + \frac{60^2}{2000}\right] = 20 \times \left[1.005 \times 475.145 + \frac{100^2}{2000}\right] + \dot{W}_{cv}$
- $\dot{W}_{cv} = -3584.41\ kW$ Ans
- Mass flow rate $\dot{m} = \rho \times A \times C, where\ \rho\ is\ the\ density$
- $\rho = \frac{m}{v}, Also\ pv = mRT\ or\ \frac{m}{v} = \frac{p}{RT}\ so\ we\ can\ write\ \rho = \frac{p}{RT}$

- So $\dot{m} = \frac{\rho_1 A_1 C_1}{RT_1}$
- $20 = \frac{1 \times 10^5 \times A_1 \times 60}{287 \times 300}$
- $A_1 = 0.287\ m^2$
- $\frac{\pi}{4} d_1^2 = 0.287$
- $d_1 = 0.604\ m. Ans$

Which of the following variables controls the physical properties of a perfect gas
•(a) pressure
•(b) temperature
•(c) volume
•(d) all of the above
•(e) atomic mass.

The unit of temperature in S.I. units is
•(a) Centigrade
•(b) Celsius
•(c) Fahrenheit
•(d) Kelvin
•(e) Rankine.

Which of the following laws is applicable for the behavior of a perfect gas
•(a) Boyle's law
•(b) Charles'law
•(c) Gay-Lussac law
•(d) all of the above
•(e) Joule's law.

General gas equation is
•(a) PV=nRT
•(b) PV=mRT
•(d) PV = C
•(c) PV=KiRT
•(e) Cp-Cv = Wj

The unit of pressure in S.I. units is
•(a) kg/cm2
•(b) mm of water column
•(c) pascal
•(d) dynes per square cm
•(e) bars

Temperature of a gas is produced due to
•(a) its heating value
•(b) kinetic energy of molecules
•(c) repulsion of molecules
•(d) attraction of molecules
•(e) surface tension of molecules

A closed system is one in which
•(a) mass does not cross boundaries of the system, though energy may do so
•(b) mass crosses the boundary but not the energy
•(c) neither mass nor energy crosses the boundaries of the system
•(d) both energy and mass cross the boundaries of the system
•(e) thermodynamic reactions take place.

According to kinetic theory of gases, the absolute zero temperature is attained when
•(a) volume of the gas is zero
•(b) pressure of the gas is zero
•(c) kinetic energy of the molecules is zero
•(d) specific heat of gas is zero
•(e) mass is zero

Kinetic theory of gases assumes that the collisions between the molecules are
•(a) perfectly elastic
•(b) perfectly inelastic
•(c) partly elastic
•(d) partly inelastic
•(e) partly elastic and partly inelastic

Absolute zero pressure will occur
•(a) at sea level
•(b) at the center of the earth
•(c) when molecular momentum of the system becomes zero
•(d) under vacuum conditions
•(e) at a temperature of – 273 °K

The unit of power in S.I. units is
•(a) newton
•(b) pascal
•(c) erg
•(d) watt
•(e) joule

The condition of perfect vacuum, i.e., absolute zero pressure can be attained at
•(a) a temperature of – 273.16°C
•(b) a temperature of 0°C
•(c) a temperature of 273 °K
•(d) a negative pressure and 0°C temperature
•(e) can't be attained.

Intensive property of a system is one whose value
•(a) depends on the mass of the system, like volume
•(b) does not depend on the mass of the system, like temperature, pressure, etc.
•(c) is not dependent on the path followed but on the state
•(d) is dependent on the path followed and not on the state
•(e) remains constant

Characteristic gas constant of a gas is equal to
•(a) C/Cv
•(b) Cv/Cp
•(c) Cp – Cv
•(d) Cp + Cv
•(e) Cp x Cv

Work done in a free expansion process is
•(a) + ve
•(b) -ve
•(c) zero
•(d) maximum
•(e) minimum.

An open system is one in which
•(a) mass does not cross boundaries of the system, though energy may do so
•(b) neither mass nor energy crosses the boundaries of the system
•(c) both energy and mass cross the boundaries of the system
•(d) mass crosses the boundary but not the energy
•(e) thermodynamic reactions do not occur.

Extensive property of a system is one whose value
•(a) depends on the mass of the system like volume
•(b) does not depend on the mass of the system, like temperature, pressure, etc.
•(c) is not dependent on the path followed but on the state
•(d) is dependent on the path followed and not on the state
•(e) is always constant.

Properties of substances like pressure, temperature and density, in thermodynamic coordinates are
•(a) path functions
•(b) point functions
•(c) cyclic functions
•(d) real functions
•(e) thermodynamic functions.

An isolated system is one in which
•(a) mass does not cross boundaries of the system, though energy may do so
•(b) neither mass nor energy crosses the boundaries of the system
•(c) both energy and mass cross the boundaries of the system
•(d) mass crosses the boundary but not the energy
•(e) thermodynamic reactions do not occur.

Which of the following quantities is not the property of the system
•(a) pressure
•(b) temperature
•(c) specific volume
•(d) heat
•(e) density.

Which of the following is the property of a system
•(a) pressure and temperature
•(b) internal energy
•(c) volume and density
•(d) enthalpy and entropy
•(e) all of the above.

Which of the following is not the intensive property
•(a) pressure
•(b) temperature
•(c) density
•(d) heat
•(e) specific volume.

Which of the following items is not a path function
- (a) heat
- (b) work
- (c) kinetic energy
- (d) vdp
- (e) thermal conductivity.

In an isothermal process, the internal energy of gas molecules
- (a) increases
- (b) decreases
- (c) remains constant
- (d) may increase/decrease depending on the properties of gas
- (e) shows unpredictable behaviour.

The value of n = 1 in the polytropic process indicates it to be
- (a) reversible process
- (b) isothermal process
- (c) adiabatic process
- (d) irreversible process
- (e) free expansion process.

Zeroth law of thermodynamics
- (a) deals with conversion of mass and energy
- (b) deals with reversibility and irreversibility of process
- (c) states that if two systems are both in equilibrium with a third system, they are in thermal equilibrium with each other
- (d) deals with heat engines
- (e) does not exist.

Heat and work are
- (a) point functions
- (b) system properties
- (c) path functions
- (d) intensive properties
- (e) extensive properties.

Work done is zero for the following process
- (a) constant volume
- (b) free expansion
- (c) throttling
- (d) all Of the above
- (e) none of the above.