**Unit 3: FIRST LAW OF THERMODYNAMICS**

First Law of Thermodynamics: Joule’s Experiments, Equivalence of heat work. Statement of the 1st law of thermodynamics, extension of the 1st law to non cyclic processes, energy, energy as a property, modes of energy, pure substance; Definition, two property rule, specific heat at constant volume, enthalpy, specific heat at constant pressure. Extension of the 1st law to control volume; Steady state-steady flow energy equation, important applications, analysis of unsteady processes such as filling and evacuation of vessels with and without heat transfer.

The first law of thermodynamics is often called as the law of the conservation of energy, with particular reference to heat energy and mechanical energy i.e., work.

**First law of thermodynamics for a closed system undergoing a cyclic process**

The transfer of heat and the performance of work may both cause the same effect in a system. Energy which enters a system as heat may leave the system as work, or energy which enters the system as work may leave as heat. Hence, by the law of conservation of energy, the net work done by the system is equal to the net heat supplied to the system. The first law of thermodynamics can therefore be stated as follows:

“When a system undergoes a thermodynamic cyclic process, then the net heat supplied to the system from the surroundings is equal to the net work done by the system on its surrounding”.

i.e., δQ = δW where represents the sum for a complete cycle.

The first law of thermodynamics cannot be proved analytically, but experimental evidence has repeatedly confirms its validity and since no phenomenon has been shown to contradict it, therefore the first law is accepted as a ‘law of nature’.

**Joule’s Experiment:**

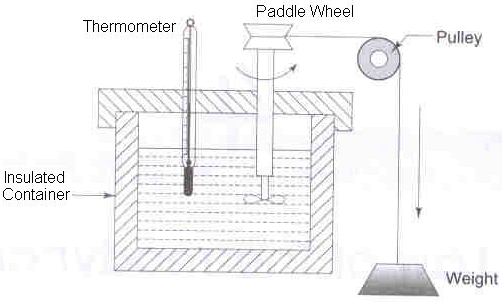
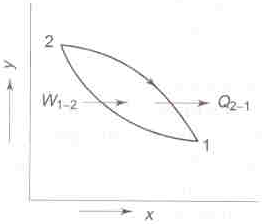
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Figure: Joule’s Experiment Figure: Cycle completed by a system

with two energy interactions i.e., work transfer followed by heat transfer

Figure shows the experiment for checking the first law of thermodynamics. The work input to the paddle wheel is measured by the fall of weight, while the corresponding temperature rise of liquid in the insulated container is measured by the thermometer.

The process 1-2 undergone by the system is shown in figure i.e., W1-2. Let the insulation be removed. The system and the surrounding interact by heat transfer till the system returns to its original temperature, attaining the condition of thermal equilibrium with the atmosphere. The amount of heat transfer Q2-1 from the system during this process 2-1 is shown in figure. The system thus executes a cycle, which consists of a definite amount of work input W1-2 to the system followed by the transfer of an amount of heat Q2-1 from the system.

Joule carried out many such experiments with different type of work interactions in a variety of systems, he found that the net work input the fluid system was always proportional to the net heat transferred from the system regardless of work interaction. Based on this experimental evidence Joule stated that,

“When a system (closed system) is undergoing a cyclic process, the net heat transfer to the system is directly proportional to the net work done by the system”. This statement is referred to as the first law for a closed system undergoing a cyclic process.

i.e., δQ α δW

If both heat transfer and work transfer are expressed in same units as in the S.I. units then the constant of proportionality in the above equation will be unity and hence the mathematical form of first law for a system undergoing a cyclic process can be written as

i.e., δQ = δW

If the cycle involves many more heat and work quantities as shown in figure, the same result will be found.

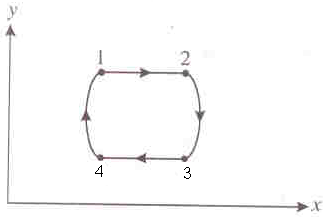
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Figure: Cyclic Process on a Property Diagram

For this cyclic process the statement of first law can be written as



The cyclic integral in the above equation can be split into a series of non cyclic integral as



or 1Q2 + 2Q3 + 3Q4 + 4Q1 = 1W2 + 2W3 + 3W4 + 4W1

i.e., δQ = δW

or (∑Q)cycle = (∑W)cycle

This is the first law for a closed system undergoing a cyclic process. i.e., it is stated as

“When a closed system is undergoing a cyclic process the algebraic sum of heat transfers is equal to the algebraic sum of the work transfers”.

**First law for a closed system undergoing a non-cyclic process (i.e., for a change of state):**

If a system undergoes a change of state during which both heat transfer and work transfer are involved, the net energy transfer will be stored or accumulated within the system.

If Q is the amount of heat transferred to the system and W is the amount of work transferred from the system during the process as shown in figure,

**System**

**W**

**Q**

The net energy transfer (Q-W) will be stored in the system. Energy in storage is either heat or work and is given the name internal energy or simply, the energy of the system.

∴Q-W = ∆E where ∆E is the increase in the energy of the system

or Q = ∆E + W

If there are more energy transfer quantities involved in the process as shown in figure.

**System**

**Q1**

**W1**

**W2**

**W3**

**W4**

**Q2**

**Q3**

First law gives

(Q2 + Q3 – Q1) = ∆E + (W­2 + W3 – W1 – W4)

i.e., energy is thus conserved in the operation. Therefore the first law is a particular formulation of the principle of the conservation of energy. It can be shown that the energy has a definite value at every state of a system and is therefore, a property of a system.

**Energy – A property of the system**:

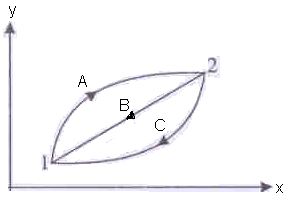
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Figure: First law to a non cyclic process

Consider a system that undergoes a cycle, changing from state 1 to state 2 by process A and returning from state 2 to state 1 by process B.

We have from 1st law of thermodynamics, 

For the process, 1-A-2-B-1, 

Considering the two separate processes, we have

 --- (1)

Now consider another cycle, the system changing from state 1 to state 2 by process A, as before and returning to state 1 by process C. For this cycle we can write

 --- (2)

Subtracting (2) from (1), we get



Or, by rearranging, 

Since B and C represent arbitrary processes between state 1 to state 2, we conclude that the quantity (δQ - δW) is the same for all processes between state 1 and state 2. ∴ (δQ - δW) depends only on the initial and final states and not on the path followed between the two states. ∴This is a point function and differential is a property of the system. This property is called the energy of the system, E. Therefore, we can write

δQ - δW = dE

Or δQ = dE + δW

If it is integrated between initial and final states, 1 and 2, we get

Q1-2 = E2 – E1 + W1-2

i.e., Q1-2 - W1-2 = E2 – E1

The above equation is the statement of first law for a closed system undergoing a non cyclic process, where Q1-2 represents the net heat transfer between the system and the surroundings during the process, W1-2 represents net work transfer between the system and the surroundings during the process and (E2 – E1) represents the change in the energy of the system during the process.

**Classification of Energy of the System**:

The energy E is an extensive property and the specific energy e = E/m (J/kg) is an intensive property. Energy E represents the total energy of the system.

i.e., E = kinetic energy (KE) + Potential Energy (PE) + remaining forms of energy.

Since K.E and P.E are macroscopic quantities and can be measured very easily and so they are considered separately in thermodynamics. The remaining energies (associated with the motion and position of the molecules, energy associated with the structure of the atom, chemical energy etc), which cannot be measured directly and is the summation of all microscopic energies is called internal energy of the system.

**Internal energy**:

It is the energy associated with internal structure of matter. This energy cannot be determined in its absolute values. But it is possible to determine the change in internal energy of the system undergoing a process by first law of thermodynamics.

∴ Total energy E = KE + PE + IE

Since the terms comprising E are point functions, we can write

dE = d(KE) + d (PE) + dU

The first law of thermodynamics for a change of state of a system may therefore be written as

δQ = dU + d (KE) + d (PE) + δW

In words this equation states that as a system undergoes a change of state, energy may cross the boundary as either heat or work, and each may be positive or negative. The net change in the energy of the system will be exactly equal to the net energy that crosses the boundary of the system. The energy of the system may change in any of three ways, namely, by a change in IE, KE or P.E

Sub. For KE and PE in the above equation

δQ = dU + + d (mgZ) + δW

In the integral form this equation is, assuming ‘g’ is a constant

Q1-2 = U2 – U1 +  + mg (Z2 – Z1) + W1-2

In most of the situations the changes in KE and PE are very small, when compared with the changes in internal energies. Thus KE and PE changes can be neglected.

∴δQ = dU + δW

or Q1-2 = U2 – U1 + W1-2

**Law of conservation of energy (2nd corollary of first law of thermodynamics)**

From first law of thermodynamics Q1-2 = E2 – E1 + W1-2

This equation in effect, a statement of the conservation of energy. The net change of the energy of the system is always equal to the net transfer of energy across the system boundary as heat and work. For an isolated system, Q = 0, W = 0 ∴E2 – E1 = 0

∴For an isolated system, the energy of the system remains constant.

Therefore, the first law of thermodynamics. may also be stated as follows, “Heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant”.

**Perpetual Machine of first kind (3rd Corollary)**:

Any system which violates the first law of thermodynamics is called the Perpetual Motion machine of first kind. i.e., “It is impossible to construct a perpetual motion machine of first kind”. A perpetual machine is one which can do continuous work without receiving energy from other systems or surroundings. It will create energy on its own and thus violates first law. But from our experience we also know that it is impossible to construct such a machine, as frictional resistance would not allow it to run for an indefinite period.

**The Pure Substance**

The system encountered in thermodynamics is often quite less complex and consists of fluids that don not change chemically, or exhibit significant electrical, magnetic or capillary effects. These relatively simple systems are given the generic name the Pure Substance.

**Definition**

A system is set to be a pure substance if it is (i) homogeneous in chemical composition, (ii) homogeneous in chemical aggregation and (iii) invariable in chemical aggregation.

Homogeneous in chemical composition means that the composition of each part of the system is same as the composition of any other part. Homogeneous in chemical aggregation implies that the chemical elements must be chemically combined in the same way in all parts of the system. Invariable in chemical aggregation means that the chemical aggregation should not vary with respect to time.

**H2 + O2 (Gas)**

**Water**

**Water**

**Steam**

**Water**

**Water**

**H2 + ½ O2 (Gas)**

**Water**

**Water**

(i) (ii) (iii)

1. (ii) (iii)

Satisfies condition (i) Satisfies condition (i) Does not satisfies condition (i)

Satisfies condition (ii) Does not satisfies condition (ii) Satisfies condition (iii)

Figure Illustration of the definition of pure substance

In figure three systems are shown. The system (i) shown in the figure is a mixture of steam and water. It is homogeneous in chemical composition because in every part of the system we have, for every atom of oxygen we have two atoms of hydrogen, whether the sample is taken from steam or water. The same is through for system (ii) consisting of water and uncombined mixture of hydrogen and oxygen. System (iii) however is not homogeneous in chemical composition because in the upper part of the system hydrogen and oxygen are present in the ratio 1:1 where as in the bottom portion they are present in the ratio 2:1.

System (i) also satisfies condition (ii), because both hydrogen and oxygen have combined chemically in every part of the system. System (ii) on the other hand does not satisfies condition (ii) because the bottom part of the system has two elements namely hydrogen and oxygen have chemically combined where as in the upper part of the system the (ii) elements appear as a mixture of two individual gases.

Invariable in chemical aggregation means that the state of chemical combination of the system should not change with time. Thus the mixture of hydrogen and oxygen, if it is changing into steam during the time the system was under consideration, then the systems chemical aggregation is varying with time and hence this system is not a pure substance. Thus the system (i) is a pure substance where as the systems (ii) and (iii) are not pure substances.

**The Two Property Rule for a Pure Substance**

*The thermodynamics state of a pure substance of a given mass can be fixed by specifying two independent properties provided (i) the substance is in equilibrium and (ii) the effects of gravity, motion, capillarity, electricity and magnetism are negligible*.

The above rule indicates that if the values of two properties of a pure substance are fixed then the values for all other properties are fixed. This means that there is a definite relation between the two independent properties and each of the other properties. Each of these relations is called “Equation of state” for a pure substance. The equation of state for a pure substance can be in any one of the following forms: (i) Algebraic equation (example: perfect gas equation), (ii) Tables (example: steam tables) and (iii) Charts (example: Mollier chart for steam).

**Specific heat, C**

When interaction of heat takes place between a closed system and its surroundings, the internal energy of the system changes. If δQ is the amount of heat transferred to raise the temperature of 1 kg of substance by dT, then, specific heat C = δQ/dT

As we know, the specific heat of gas depends not only on the temperature but also upon the type of the heating process. i.e., specific heat of a gas depends on whether the gas is heated under constant volume or under constant pressure process.

∴ We have dQ = m CV. dT for a rev. non-flow process at constant volume

and dQ = m Cp. dT for a rev. non-flow process at constant pressure

For a perfect gas, Cp & CV are constant for any one gas at all pressure and temperatures. Hence, integrating above equations.

Flow of heat in a rev. constant pressure process = m Cp (T2 – T1)

Flow of heat in a rev. constant volume process = m CV (T2 – T1)

The internal energy of a perfect gas is a function of temperature only. i.e, u = f (T), to evaluate this function, let 1 kg of gas be heated at constant volume

From non-flow energy equation, δQ = dU + δW

δW = 0 since volume remains constant

∴δQ = dU = CV. dT

Int. U = CVT + k where k is a constant

For mass m, Int. energy = m CVT

Any process between state 1 to state 2,

Change in int. energy = m CV (T2 – T1)

(U2 – U1) = m CV (T2 – T1)

We can also find the relationship between Cp & CV & shown that

Cp – Cv = R ;   & 

**Enthalpy**: Consider a system undergoing a quasi equilibrium constant pressure process. We have from 1st law of thermodynamics for a non-flow process,

Q1-2 = U2 – U1 + W1-2

W1-2 =  pdv

Since pressure is constant W1-2 = p (V2 – V1)

∴Q1-2 = U2 – U1 + p (V2 – V1)

= (U2 + p2V2) – (U1 + p1V1)

i.e., heat transfer during the process is given in terms of the change in the quantity (U + pV) between initial and final states. Therefore, it find more convenient in thermodynamics to define this sum as a property called Enthalpy (H)

i.e., H = U + pV

∴In a constant pressure quasi equilibrium process, the heat transfer is equal to the change in enthalpy which includes both the change in internal energy and the work for this particular process.

The enthalpy of a fluid is the property of the fluid, since it consists of the sum of a property and the product of the two properties. Since enthalpy is a property, like internal energy, pressure, specific volume and temperature, it can be introduced into any problem whether the process is a flow or a non-flow process.

For a perfect gas, we have h = u + pV

= CV T + RT = (CV + R) T = CpT

i.e., h = CpT & H = mCpT

For any process, δQ = dH = mCpdT

∴For a process between states 1 & 2

Change in enthalpy = (H2 – H1) = mCp (T2 – T1)

**Specific heat at Constant Volume**:

When heat interaction takes place at constant volume, δW = 0 and from 1st law of thermodynamics, for unit mass, (δq)V = dU

The amount of heat supplied or removed per degree change in temperature, when the system is kept under constant volume, is called as the specific heat at constant volume,

Or CV =  ≅ 

Or dU = CV dT

**Specific heat at Constant pressure:**

When heat interaction is at constant pressure, (δq)p = dh

The amount of heat added or removed per degree change in temperature, when the system is kept under constant pressure, is called as the specific heat at constant pressure.

Or Cp =  ≅ 

Or dh = Cp. dT

**Application of 1st law of thermodynamics to non-flow or closed system**:

1. **Constant volume process (V = constant)**

Applying 1st law of thermodynamics to the process,

Q1-2 = U2 – U1 + W1-2

= U2 – U1 + 0

i.e., Q1-2 = CV (T2 – T1)

For mass ‘m’ of a substance, Q = mCV (T2 – T1)

1. **Constant pressure (p = Constant)**

Applying 1st law of thermodynamics to the process,

Q1-2 = u2 – u1 + W1-2

The work done, W1-2 = p dV = p (V2 – V1)

i.e., Q1-2 = u2 – u1 + p (V2 – V1) = (u2 + pV2) – (u1 + pV1)

= h2 – h1

i.e., Q = Cp (T2 – T1)

For mass ‘m’ of a substance, Q = mCp (T2 – T1)

1. **Constant temperature process (Isothermal process, T = constant)**

Applying 1st law of thermodynamics to the process,

Q1-2 = U2 – U1 + W1-2

= CV (T2 – T2) + W1-2

i.e., Q1-2 = W1-2 

Q1-2 = p1V1 lnV2/V1

= p1 V1 ln p1/p2

1. **Reversible adiabatic process (pVγ) = constant**

Applying 1st law of thermodynamics to the process,

Q1-2 = U2 – U1 + W1-2

O = u2 – U1 + W1-2 --- (1)

Or (U1 – U2) = 

(U1 – U2) = 

The above equation is true for an adiabatic process whether the process is reversible or not. In an adiabatic experiment, the work done W1-2 by the fluid is at the expense of a reduction in the internal energy of the fluid. Similarly in an adiabatic composition process, all the work done on the fluid goes to increase the internal energy of the fluid.

To derive pVγ = C: For a reversible adiabatic process

We have δq = du + δu

For a reversible process, δw = p dV

∴δq = du+ p dV

= O  For an adiabatic process δq = 0

Also for a perfect gas, pV= RT or p = 

∴dU + RT 

Also, u = CV T or du = CV dT

∴CV dT + RT 

or CV 

Int., CV ln T + R ln V = constant

Sub. T = pV/R

Cv ln = constant

Or ln  = constant

Also, CV = 

∴ln= constant

∴ln = constant

or ln = constant

i.e., ln = constant

or = econstant = constant

i.e., pVγ = constant

we have pV = RT

or p = 

sub. This value of p in pVγ = C

Vγ = C or TVγ-1 = constant --- (a)

Also, V = sub. This in equation pressureγ = C

p = constant

∴= constant or = constant --- (b)

∴For a reversible adiabatic process for a perfect gas between states 1 & 2, we can write

p1V1γ = p2V2γ or  --- (c)

T1V1γ-1 = T2V2γ-1 or  --- (d)

 or  --- (e)

The work done in an adiabatic process is W = u1 – u2

The gain in I.E. of a perfect gas, is u2 – u1 = CV (T2 – T1)

W = CV (T1 – T2)

But CV = 

∴W = 

Using pV = RT, W = 

1. **Poly tropic process (PVn = constant)**

Applying 1st law of thermodynamics, Q1-2 = u2 – u1 + W1-2

= (u2 – u1) + 

i.e., Q = - CV (T1 – T2)

Also CV =sub. & simplifying Q = 

In a poly tropic process, the index n depends on the heat and work quantities during the process.

**Problems**:

1. In a cyclic process, heat temperature are + 14.7 kJ, -25.2 kJ, -3.56 kJ and +31.5 kJ. What is the net work for this cyclic process.

Solution: 1st law of thermodynamics for a cyclic process is 

i.e., Net work = 14.7 – 25.2 -3.56 + 31.5

= 17.44 kJ

1. Consider a cyclic process in a closed system which includes three heat interactions, namely Q1 = 20 kJ, Q2 = -6kJ, and Q3 = -4 kJ and two work interactions for which W1 = 4500 N-m. Compute the magnitude of the second work interaction W2 in Nm.

Solution: We have for a closed system undergoing cyclic process,



20000 – 6000 – 4000 = 4500 + W2

∴W2 = 5500 Nm

1. When the state of a system changes from state 1 to state 3 along the path 1-2-3 as shown in figure, 80 kJ of heat flows into the system and the system does 30 kJ of work. (a) How much heat flows into the system along the path 1-4-3 if work done by the system is 10 kJ (b) when the state of the system is returned from state 3 to state 1 along the curved path, the work done on the system is 20 kJ. Does the system absorb or liberate heat? Find its magnitude. (c) If U1 = 0 and U4 = 40kJ, find the heat absorbed in the process 1-4 and 4-3 respectively.

Solution:

1

2

3

4

p

V

A

a) Along the path 1-2-3,

From 1st law of thermodynamics, Q1-3 = U3-U1 + W1-3

From the data given, 80 = (U3 – U1) + 30

∴(U3 – U1) = 50 kJ

Along the path 1-4-3, we have

Q1-3 = U3 – U1 + W1-3

From the data given, Q1-3 = 50 + 10

= 60 kJ U is property of a system

i.e., Work is done by the system

b) Along the path 3-A-1,

(U1 – U3) = Q3-1 – W3-1

Or Q3-1 = (U1 – U3) + W3-1

= -50 -20 = -70 kJ

Negative sign indicates that heat is liberated from the system.

c) Along the path 1-4

Q1-4 = U4 – U1 + W1-4

= 40-0+10 (since W1-4-3 = W1-4 + W4-3 = 10 + 0 = 10)

= 50 kJ

Positive sign indicates heat is absorbed by the system

Along the path 4-3

Q4-3 = U3 – U4 + W4-3

= 50 – 40 + 0 = 10 kJ

1. A domestic refrigerator is loaded with food and the door closed. During a certain period the machine consumes 1 kWh of energy and the internal energy of the system drops by 5000 kJ. Find the net heat transfer for the system.

Solution: W1-2 = 1kWhr = -1 x3600 kJ U2 – U1 = -5000 kJ

From 1st law, Q1-2 = (U2-U1) + W1-2

= -5000 -3600 = -8600 kJ = - 8.6 MJ

1. For the following process in a closed system find the missing data (all in kJ)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Process | Q | W | U1 | U2 | ∆U |
| a) | 35 | 20 | -10 | 5 | 15 |
| b) | 15 | -6 | -27 | -6 | 21 |
| c) | -7 | 10 | 20 | 3 | -17 |
| d) | -27 | -7 | 28 | 8 | -20 |

Solution: Process (a): Q = ∆U + W

= U2 – U1 + W1-2 but U2-U1 = 15 ∴U2 = 5

= 15 + 20 = 35 kJ

Process (b): Q = U2 – U1 + W

15 = -6-U1-6

27 = -U1 ∴U1 = -27 kJ

∴∆U = U2 – U1 = - 6 + 27 = 21 kJ

Process (c) - 7 = U2 – 20 + 10

∴U2 = 3 kJ ∴∆U = 3-20 = -17 kJ

Process (d) ∆U = U2 – U1 = - 20

= 8 – U1 = - 20 ∴U1 = 28 kJ

A = 8 – 28 – 7 = - 27 kJ

1. A fluid system, contained in a piston and cylinder machine, passes through a complete cycle of four processes. The sum of all heat transferred during a cycle is -340 kJ. The system completes 200 cycles minutes. Complete the following table showing the method for each item, and compute the net rate of work output in kW.

|  |  |  |  |
| --- | --- | --- | --- |
| Process | Q (kJ/min) | W (kJ/min) | ∆E (kJ/min) |
| 1-2 | 0 | 4340 | -4340 |
| 2-3 | 42000 | 0 | 42000 |
| 3-4 | -4200 | 69000 | -73200 |
| 4-1 | -105800 | -141340 | 35540 |

Solution: Given = -340 kJ, No. of cycle = 200 cycles / min

**Process 1-2**: Q1-2 = (E2 – E1) + W1-2

0 = ∆E + W1-2

∴∆E = -4340 kJ/min

**Process 2-3**: 42000 = ∆E + 0

∴Q1-2 = 42000 kJ/min

**Process 3-4**: -4200 = -73200 + W3-4

∴W3-4 = 69000 kJ/min

**Process 4-1**:  = -340 kJ

The system completes 200 cycle/min

∴ = -340 x 200 = - 68000 kJ / min

But, Q1-2 + Q2-3 + Q3-4 + Q4-1 = -68000

∴Q4-1 = - 68000 – 0 – 42000 + 4200

= - 105800 kJ/min

Also, ∫dE = 0, since cyclic integral of any property is zero

∴(∆E)1-2 + (∆E)­2-3 + (∆E)3-4 + (∆E)4-1 = 0

-4340 + 42000 – 73200 + (∆E)4-1 =0

∴(∆E)4-1 = 35540 kJ/min

Therefore Q4-1 = (∆E)4-1 + W4-1

- 105800 = 35540 + W4-1

∴W4-1 = -141340 kJ/min

Since 

= - 68000 kJ/min

∴Rate of work output = = 1133.33 kW

**First Law of Thermodynamics to open system**:

In the case of closed system there is only energy transfer across the system boundary. But in many engineering applications we come across open systems where in both mass and energy transfer takes place. The energies that cross the system boundary are as follows.

1. **Internal energy**: Each kg of matter has the internal energy ‘u’ and as the matter crosses the system boundary the energy of the system changes by ‘u’ for every kg mass of the matter that crosses the system boundary.
2. **Kinetic energy**: Since the matter that crosses the system boundary will have some velocity say  each kg of matter carries a K.E. () thus causing the energy of the system to change by this amount for every kg of matter entering the system boundary.
3. **Potential energy**: P.E. is measured with reference to some base. Thus ‘Z’ is the elevation of the matter that is crossing the system boundary, then each kg of matter will possess a P.E. of gZ.
4. **Flow energy or Flow work**: This energy is not directly associated with the matter crossing the system boundary. But it is associated with the fact that there must be some pumping process which is responsible for the movement of the matter across the system boundary. Thus external to the system there must be some force which forces the matter across the system boundary and the energy associated with this is called flow energy.

**Flow Work:** Consider a flow process in which a fluid of mass dm1 is pushed into the system at section 1 and a mass dm2 is forced out of the system at section 2 as shown in fig.

**p1**

**p2,**

**A1**

**F1**

**dm1**

**dm2**

**F2**

**1**

**1**

**2**

**2**

**dl1**

**dl2**

In order to force the fluid to flow across the boundary of the system against a pressure p1, work is done on the boundary of the system. The amount of work done is δW = - F1.dl1,

Where F1 is the force and dl1 is the infinitesimal displacement, but F1 = p1A1

∴δW = - p1A1 dl1 = - p1dv1

i.e., the flow work at section 1 = - p1v1

Similarly, the work done by the system to force the fluid out of the system at section 2 = + p2v2

Hence net flow work = p2V2 – p1V1

For unit mass, the flow work is (p2V2 – p1V1). Flow work is expressed entirely in terms properties of the system. The net flow work depends out on the end state of the fluid and it is a thermodynamics property. Also the fluid contains energies like internal energy, potential energy and due to the motion of the fluid, kinetic energy, in addition to the flow work. When a fluid enters an open system, these properties will be carried into the system. Similarly when the fluid leaves the system, it carries these energies out of the system. Thus in an open system, there is a change in energy of the system.

**5. Control Volume**: The first and most important step in the analysis of an open system is to imagine a certain region enclosing the system. This region having imaginary boundary is called control volume, which can be defined as follows.

A C.V. is any volume of fixed shape, and of fixed position and orientation relative to the observer. Across the boundaries of the C.V. apart from mass flow, energy transfer in the form of heat and work can take place just as similar to the energy transfer across the boundaries of a system.

Thus the difference between C.V. and system are

1. The system boundary may and usually does change shape, position, orientation relative to the observer. The C.V. does not by definition.
2. Matter may and usually does flow across the system boundary of the C.V. No such flow takes place across the system boundary by definition.

**First law of thermodynamics for an open system (Flow process)**:

We have 1st law of thermodynamics to a closed system as,

δQ – δW = dU + d(KE) + d (PE)

= d [E]0

The subscript O refers to the states of the system within the boundary. In the case of open system, energy is transferred into & out of the system not only by heat and work but also by the fluid that enters into and leaves the boundary of the system in the form of internal energy, gravitational potential energy, kinetic energy in addition to the energy in the flow work. Thus, when the first law is applied to an open system, the energy entering into the system must be equal to the energy leaving the system in addition to any accumulation of energy within the system.

**δQ**

**δW**

**d[E]0**

The flow process is shown in fig. This analysis can be expressed mathematically as,



 --- (1)

Where state (1) is the entering condition and state (2) is the leaving condition of the fluid. This is a general equation of the first law of thermodynamics applied to open system.

**Note:** The equation is valid to both open and closed system. For closed system, dm1=0 & dm2 =0

**Energy Equation for open system**: The general form of first law of thermodynamics applied to an open system is called steady-flow energy equation (SFEE) i.e., the rate at which the fluid flows through the C.V. is constant or steady flow. SFEE is developed on the basis of the following assumptions.

1. The mass flow rate through the C.V. is constant, i.e., mass entering the C.V. / unit time = mass leaving the C.V. /unit time. This implies that mass within the C.V. does not change.
2. The state and energy of a fluid at the entrance and exit do not vary with time, i.e., there is no change in energy within the C.V.
3. The rates of heat and work transfer into or out of the C.V. do not vary with time.

For a steady flow process,  & d(E)0 = 0 as Q ≠ f (T) & W ≠ f (T)

**SFEE on the basis unit mass:**

Energy entering to the system = energy leaving the system

i.e.,  

or 

or 

Where Q = heat transfer across the C.V, W = shaft work across the C.V, h = Enthalpy,

V = velocity, Z = elevation and g = gravitational acceleration

**SFEE on the basis of unit time**:



Where = heat transfer/unit time;  = shaft work / unit time,  =mass flow rate / unit time

Hence it can be written as,

 = 

Where  Where ρ = density A = cross sectional area

But 



This is the Steady Flow Energy Equation

**Displacement work for a flow process (open system)**:

From SFEE, when changes in kinetic & potential energies are neglected, δq – δW = dh

Or δW = δq – dh --- (1)

From the 1st law of thermodynamics, we have δq – δW = du

For a rev. process, δW = Pdv

∴δq = du + Pdv

Also, from the definition of enthalpy, h = u + pv

Or dh = du + d (pv)

Sub δq & dh in equation (i)

δW = [du + p.dv] – [du + d (pv)]

= p.dv – p.dv – v.dp ∴W = - ∫vdp

Note: With negligible PE & KE, for a non-flow rev. process, the work interaction is equal to  where as for a steady-flow rev. process, it is equal to 

**Application of SFEE**:

1. **Nozzle and Diffuser**: Nozzle is a duct of varying c/s area in which the velocity increases with a corresponding drop in pressure. Since the flow through the nozzle occurs at a very high speed, there is hardly any time for a fluid to gain or loose heat and hence flow of the fluid is assumed to be adiabatic. And also there is no work interaction during the process, i.e., Ws = 0, Q = 0, Z1 = Z2

**V1**

**V2**

**Z1**

**Z2 = Z1**

We have from SFEE, Q –W = Δh + ΔPE + ΔKE

0 = h2 – h1 + 



i.e., the gain in KE during the process is equal to the decrease in enthalpy of the fluid. Diffuser is a device to increase the pressure of a fluid during flow with a corresponding decrease in KE. Thus its function is reverse to that of a nozzle. As final velocity V2 in a diffuser is very small, it is very often negligible.

1. **Turbine and Compressor (rotary)**: Turbine is a device which produces work by expanding a high pressure fluid to a low pressure. The fluid is first accelerated in a set of nozzle and then directed through curved moving blades which are fixed on the rotor shaft. The direction of the fluid changes which it flows through the moving blades, due to which there is a change in momentum and a force exerted on the blades producing torque on the rotor shaft. Since the velocity of flow of the fluid through the turbine is very high, the flow process is generally assumed to be adiabatic, hence heat transfer q = 0. The change in PE is neglected as it is negligible.

**V1**

**V2**

**Z1**

**Z2 = Z1**

**W1-2**

∴SFEE is W1-2 = (h1 – h2) – ½ (V22 – V12)

If mass flow rate is  then,



i.e., power developed by the turbine

Compressor is a device in which work is done on the fluid to raise its pressure. A rotary compressor can be regarded as a reversed turbine. Since work is done on the system, the rate of work in the above equation is negative and the enthalpy after compression h2 will be greater than the enthalpy before compression h1.

1. **Throttling Process**: When a fluid steadily through restricted passages like a partially closed valve, orifice, porous plug etc., the pressure of the fluid drops substantially and the process is called throttling. In a throttling process, expansion of the fluid takes place so rapidly that no heat transfer is possible between the system and the surroundings. Hence the process is assumed to occur adiabatically. The work transfer in this process is zero.

**1**

**1**

**2**

**2**

SFEE is Q1-2 – W1-2 = Δh + ΔKE + ΔPE

We have, Q = 0; W = 0; Z1 = Z2, V1 ≅ V2

∴0 – 0 = h2 – h1 + 0 + 0 i.e., h1 = h2

∴In a throttling process, the enthalpy remains constant. The throttling process is irreversible because when a fluid is throttled, it passes through a series of non-equilibrium states.

1. **Heat Exchanger**: A heat exchanger is a device in which heat is transferred from one fluid to another. It is used to add or reduced heat energy of the fluid flowing through the device. Radiator in an automobile, condenser in a steam power and refrigeration plants, evaporator in a refrigerator are examples of heat exchangers. There will be no work interaction during the flow of the fluid through any heat exchanger.

Eg: i) Steam condenser: Used to condense the steam. It a device in which steam loses heat as it passes over the tubes through which water is flowing.

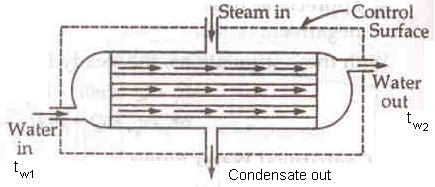
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Figure: Heat Exchanger

We have ΔKE = 0, ΔPE = 0 (as their values are very small compared to enthalpies)

W = 0 (since neither any work is developed nor absorbed)

∴SFEE is Q = h2 – h1

i.e., h1 – Q = h2 --- (1)

Where Q = heat lost by 1 kg of steam passing through the condenser.

Assuming there are no other heat interactions except the heat transfer between steam and water, then Q = heat gained by water passing through the condenser.



Substituting Q in the above equation (1),



Where  = mass of cooling water passing through the condenser

Cw = specific heat of water

In a condenser there are 2 steady flow streams namely (i) Vapour that losses heat (ii) The coolant (water) that receives heat.

Let  = mass flow rate of coolant

 = mass flow rate of steam

h1w = Enthalpy-coolant entry

h1s = Enthalpy-steam entry

h2w, h2s = Enthalpy of coolant, steam at exit

 h1w +  h1s =  h2w +  h2s

or 

**ii)** **Evaporator:** An evaporator is a component of a refrigeration system and is used to extract heat from the chamber which is to be kept at low temperature. The refrigerating liquid enters the evaporator, absorbs latent heat from the chamber at constant pressure and comes out as a vapour. SFEE is

h1 +  = h2 Since  = 0, ΔKE = ΔPE = 0

∴ =  (h2 – h1)

 is taken as positive because heat flows from the chamber to the evaporator coil.

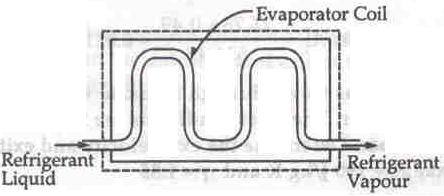
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Figure: Evaporator

1. **Boiler**: It is equipment used for the generation of the steam. Thermal energy released by combustion of fuel is transferred to water which vaporizes and gets converted into steam at the desired pressure and temperature. The steam thus generated is used for
   1. Producing mechanical work by expanding it in steam engine or steam turbine.
   2. Heating the residential and industrial buildings in cold weather and
   3. Performing certain processes in the sugar mills, chemical and textile industries.

1. Velocity change is negligible V1 = V2

2. Change in elevation is also negligible Z2 = Z1

3. Work done = 0

∴SFEE is h1 + q = h2

∴q = h2 – h1

= (u2 – u1) + (p2 v2 – p1 v1)

**Problems**:

1. 12 kg of a fluid per minute goes through a reversible steady flow process. The properties of fluid at the inlet are p1 = 1.4 bar, ρ1 = 25 kg/m3, V1 = 120 m/s & u1 = 920 kJ/kg and at the exit are p2 = 5.6 bar, ρ2 = 5 kg/m3, V2 = 180 m/s and u2 = 720 kJ/kg. During the passage, the fluid rejects 60 kJ/s and raises through 60m. Determine i) the change in enthalpy ii) work done during the process.

Solution: i) Change in enthalpy Δh = Δ(u + pV)

= (720 x 103 – 920 x 103) + (5.6 x 105 x 1/5 – 1.4 x 105 x 1/25)

= - 93.6 kJ

ii) SFEE for unit time basis is  --- (1)

 = 9000 J = 9 kJ/kg

ΔPE = g (Z2 – Z1) = 9.81 (60) = 0.589 kJ/kg

∴Substituting in equation (1), - 60  = 12/60 [- 93.6 + 9 + 0.589]

 = - 43.2 kW

Negative sign indicates work is done on the fluid in the reversible steady flow process.

1. In the turbine of a gas turbine unit the gases flow through the turbine at 17 kg/s and the power developed by the turbine is 14000 kW. The enthalpies of the gases at inlet and outlet are 1200 kJ/kg and 360 kJ/kg respectively, and the velocities of the gases at inlet and outlet are 60 m/s and 150 m/s respectively. Calculate the rate at which the heat is rejected from the turbine. Find also the area of the inlet pipe given that the specific volume of the gases at inlet is 0.5 m3/kg.

Solution:  = 17 kg/s v1 = 0.45 m3/kg

P = 1400kW ∴Work done  = 823.53 kJ/kg

h1 = 1200kJ/kg h2 = 360kJ/kg V1 = 60m/s V2 = 150 m/s

We have SFEE, Q –W = Δh + ΔPE + ΔKE





ΔPE = 0

Substituting in SFEE equation,

∴ Q – 823.53 = – 840 + 0 + 9.45

∴Q = - 7.02 kJ/kg

i.e., heat rejected = 7.02 x 17 = 119.34 kW

Also, we have 

 ∴A1 = 0.142 m2

1. Air flows steadily at the rate of 0.4 kg/s through an air compressor entering at 6 m/s with a pressure of 1 bar and a specific volume of 0.85 m3/kg, and leaving at 4.5 m/s with a pressure of 6.9 bar and a specific volume of a 0.16 m3/kg. The internal energy of air leaving is 88 kJ/kg greater than that of the air entering. Cooling water in a jacket surrounding the cylinder absorbs heat from the air at the rate of 59 kJ/s. Calculate the power required to drive the compressor and the inlet and outlet pipe cross sectional areas.

Solution:  = 0.4 kg/s V1 = 6m/s p1 = 1 x 105Pa

v1 = 0.85 m3/kg V2 = 4.5 m/s P2 = 6.9 x 105Pa v2 =0.16m3/kg

Δu = 88 kJ/kg Q = - 59 kJ/s 

Δpv = 6.9 x 105 x 0.16 – 1 x 105 x 0.85 = 25.4 kJ/kg

Δu = 88 kJ/kg

∴Δh = Δ (u + pv) = 113.4 kJ/kg

SFEE for unit time basis is given by,





ΔPE = 0

Substituting in the SFEE equation,





Negative sign indicates work is done in the air compressor i.e., power input to the compressor.

ii) We have 







1. A turbine operating under steady flow conditions receives steam at the following state. pressure 13.8 bar, specific volume 0.143 m3/kg, i.e., 2590 kJ/kg, velocity 30 m/s. The state of the steam leaving the turbine is pressure 0.35 bar, specific volume 4.37 m3/kg, i.e., 2360 kJ/kg, velocity 90 m/s. Heat is lost to the surroundings at the rate of 0.25 kJ/s. If the rate of steam flow is 0.38 kg/s, what is the power developed by the turbine? (102.8 kW).
2. At the inlet to a certain nozzle the enthalpy of the fluid is 3025 kJ/kg and the velocity is 60 m/s. At the exit from the nozzle the enthalpy is 2790 kJ/kg. The nozzle is horizontal and there is negligible heat loss from it. i) Find the velocity at the nozzle exit. ii) If the inlet area is 0.1 m2 and specific volume at inlet is 0.19 m3/kg, find the rate of flow of fluid. iii) If the specific volume at the nozzle exit is 0.5 m3/kg, find the exit area of the nozzle.

Solution: h1 = 3025 kJ/kg V1 = 60 m/s h2 = 2790 kJ/kg Z2 = Z1 Q = 0

SFEE is Q – W = Δh + ΔPE + ΔKE

For a nozzle, W = 0, Q = 0, ΔPE = 0

Substituting in SFEE, we get



or 2 (h2 – h1) = 

= 688.2 m/s

ii) 



iii) 

 ∴A2 = 0.0229 m2

1. In a steam power plant 1.5 kg of water is supplied per second to the boiler. The enthalpy and velocity of water entering the boiler are 800 kJ/kg and 10 m/s. Heat at the rate of 2200 kJ/kg of water is supplied to the water. The steam after passing through the turbine comes out with a velocity of 50 m/s and enthalpy of 2520kJ/kg. The boiler inlet is 5m above the turbine exit. The heat loss from the boiler is 1800 kJ/m and from the turbine 600 kJ/min. Determine the power capacity of the turbine, considering boiler and turbine as single unit.

Solution: = 1.5 kg/s h1 = 800 kJ/kg V1 = 10 m/s Q = 2200 kJ/kg

V2 = 50 m/s h2 = 2520 kJ/kg Z1 = 5 m Z2 = 0 W = ?

Heat loss from boiler and turbine is 1800 + 600 = 2400 kJ/min

= 40 kJ/sec = = 26.67 kJ/kg

Net heat added to the water in the boiler Q = 2200 – 26.67 = 2173.33 kJ/kg

SFEE is Q - W = Δh + ΔKE + ΔPE --- (1)

Δh = h2 – h1 = 2500 – 800 = 1720 kJ/kg



ΔPE = g (Z2 – Z1) = 9.81 (0-5) = - 49.05 J/kg = -49.05 x 10-3kJ/kg

∴Substituting in (1), 2173.33 – W = 1720 + 1.2 – 49.05 x 10-3

∴W = 452.18 kJ/kg

∴Power capacity of the turbine P = 452.18 x 1.5 = 678.27 kW

1. A centrifugal air compressor used in gas turbine receives air at 100 KPa and 300 K and it discharges air at 400 KPa and 500 K. The velocity of air leaving the compressor is 100 m/s. Neglecting the velocity at the entry of the compressor, determine the power required to drive the compressor if the mass flow rate is 15 kg/sec. Take Cp(air) = 1 kJ/kgK, and assume that there is no heat transfer from the compressor to the surroundings.

Solution: p1 = 100 x 103N/m2 T1 = 300 K p2 = 400 x 103N/m2 T2 = 500K

V2 = 100 m/s W = ? = 15 kg/s Cp = 1kJ/kgK Q = 0

SFEE is Q – W = Δh + ΔKE + ΔPE

Δh = Cp (T2 – T1) = 15 (1) (500 – 300)

= 3000 kJ/s = 3000 / 15 = 200 kJ/kg



Substituting in SFEE we have

0 – W = 200 + 5 = 205 kJ/kg

i.e., W = - 205 kJ/kg = - 205 x 15 kJ/s = - 3075 kW

Negative sign indicates work is done on the centrifugal air compressor

∴Power required = 3075 kW

1. In a water cooled compressor 0.5 kg of air is compressed/sec. A shaft input of 60 kW is required to run the compressor. Heat lost to the cooling water is 30% of input and 10% of the input is lost in bearings and other frictional effects. Air enters the compressor at 1 bar and 200C. Neglecting the changes in KE & PE, determine the exit air temperature. Take Cp = 1kJ/kg0C air.

Solution:  = 0.5 kg/s W = 60 kW HL = (30% + 10%) input = 40% input

p1 = 1 x 105N/m2 t1 = 200C

SFEE is Q – W = Δh + ΔKE + ΔPE

ΔKE = 0, ΔPE = 0

W = 60 kW = 60 kJ/sec = 120 kJ/kg

Heat lost to the surroundings = 40% (input) = 0.4 (120)

= 48 kJ/kg

Substituting in SFEE we have

- 48 – (-120) = Δh

But Δh = Cp (t2 – t1)

∴- 48 + 120 = Cp (t2 – t1)

i.e., 72 = 1 (t2 – 20)

∴t2 = 920C

1. A petrol engine develops 50 kW brake power. The fuel and air flow rates are 10 kg and 107 kg/hr. The temperature of fuel air mixture entering the engine is 200C and temperature of gases leaving the engine is 5000C. The heat transfer rate from the engine to the cooling water circulated is 50kJ/s and that to the surroundings 10 kJ/s. Evaluate the increase in the specific enthalpy of the mixture as it flows through the engine.

Solution: W = 50 kW = 50 kJ/s = 1538.46 kJ/kg  = (10 + 107)kg/hr = 0.0325 kg/s

t1 = 200C t2 = 5000C QL = 50 + 10 = 60 kJ/s = 1846.15 kJ/kg

SFEE is QL – W = Δh + ΔKE + ΔPE but ΔKE = ΔPE = 0

Substituting in SFEE, we have

- 1846.15 – 1538.46 = Δh

∴Δh = - 3384.61 kJ/kg

= - 109.99 kJ/sec

Negative sign indicates there is decrease in enthalpy of the mixture.

1. Air at a temperature of 150C passes through a heat exchanger at a velocity of 30 m/s where its temperature is raised to 8000C. It then enters a turbine with the same velocity of 30 m/s and expands until the temperature falls to 6500C. On leaving the turbine, the air is taken at a velocity of 60 m/s to a nozzle where it expands until the temperature has fallen to 5000C. If the air flow rate is 2 kg/s, calculate i) the rate of heat transfer to the air, ii) the power output from the turbine assuming no heat loss, and iii) the velocity at exit from the nozzle, assuming no heat loss. Take the enthalpy of air as h = Cpt, where Cp = 1.005 kJ/kg0C.

Solution: t1 = 150C, V1 = 30 m/s, t2 = 8000C V2 = 30 m/s t3 = 6500C

V3 = 60 m/s t4 = 5000C  = 2 kg/s

i) Heat exchanger: Q = ?

Q – W = (Δh + ΔKE + ΔPE) but ΔKE = ΔPE = 0

∴Q = Cp (t2 – t1)

= 1.005 (800 – 15) = 788.93 kJ/kg

or Q = 1577.85 kJ/s

ii) Turbine: W = ?

Q – W = Δh + ΔKE + ΔPE, but Q = 0, ΔPE = 0

Δh = Cp (t3 – t2) = (650 – 800) 1.005 = - 150.75 kJ/kg



Substituting in SFEE, we have

∴- W = - 150.75 + 1.35

∴W = 149.4 kJ/kg

= 149.4 x 2 = 298.8 kW

iii) Nozzle: V4 =?

Q – W = Δh + ΔKE + ΔPE, but Q = 0, W = 0, ΔPE = 0

Substituting in SFEE, we have

(h3 – h4) = 

i.e., 2Cp (t3 – t4) = 

∴2 (1.005) (650 – 500) + 602 = V42

∴V4 = 552.36 m/s

1. A 260 mm dia cylinder fitted with a frictionless leak pro of piston contains 0.02 kg of steam at a pressure of 6 x 105 N/m2 and a temperature of 2000C. As the piston moves slowly outwards through a distance of 305 mm the steam undergoes a fully resisted expansion according to the law pVn = a constant to a final pressure 1 x 105N/m2. Determine i) value of the index n ii) work done by the steam iii) Magnitude and sign of heat transfer.

Solution: d = 0.26 m, m = 0.02 kg p1 = 6 x 105Pa t1 = 2000C

l = 0.305 m, pVn = C p2 = 1 x 105Pa

Stroke volume = 

Considering steam as a perfect gas, p1V1 = mRT1,



∴Final volume = V2 = V1 + stroke volume

= 4.525 x 10-3 + 0.016193

= 0.020693m3

i) n =? p1 V1n = p2V2n



ii) 

iii) For reversible polytropic process, 

= 4.453 kJ

1. Air flows steadily at the rate of 0.5 kg/s through an air compressor, entering at 7 m/s velocity, 100 KPa pressure, 0.95 m3/kg volume, and leaving at 5 m/s velocity, 700 KPa pressure and 0.19 m3/kg. The internal energy of the air leaving is 93 kJ/kg greater than that of the air entering. Cooling water in the compressor jackets absorbs heat from the air at the rate of 58 kW. i) compute the rate of shaft work in kW ii) find the ratio of the inlet pipe dia to outlet pipe diameter.

Solution:  = 0.5 kg/s V1 = 7 m/s p1 = 100 x 103Pa V1 = 0.95 m3/kg

V2 = 5 m/s p2 = 700 x 103Pa v2 = 0.19 m3/kg (u2 – u1) = 93 kJ/kg

QL = 58 kJ/s  Z1 = Z2

Q – W = Δh + ΔKE + ΔPE --- (1)

Δh = Δ(U + pV) = (U2 – U1) + (p2V2 – p1V1)

= 93 x 103 + [700 x 103 x 0.19 – 100 x 103 x 0.95]

= 131000 J/kg = 131 kJ/kg



ΔPE = 0

∴Equation (1) becomes, - 116 – W = 131 – 12 x 10-3

∴W = - 246.99 kJ/kg

= - 246.99 x 0.5 = - 123.49 kW

Negative sign indicates shaft work done on the compressor.

ii) = ρ1A1V1 = ρ2A2V2





1. A gas flows into a turbine with an initial pressure of 7 bar, specific volume 0.2 m3 and velocity 150 m/s. The corresponding values of pressure, specific volume and velocity at the exit are 3.5 bar, 0.5 m3 and 300 m/s respectively. During the expansion of gas in the turbine its internal energy decreases by 92 kJ/kg and loss due to radiation was 13 kJ/kg. What amount of shaft work is developed per kg of gas flow.
2. The compressor of a large gas turbine receives air from the surroundings at 95 KPa and 200C. The air is compressed to 800 KPa according to the relation pV1.3 = constant. The inlet velocity is negligible and the outlet velocity is 100 m/s. The power input to the compressor is 2500 kW, 20% of which is removed as heat from the compressor. What is the mass flow rate of the air? Take Cp = 1.01 kJ/kg0K for air.

Solution: p1 = 95 x 103N/m2 T1 = 293 k p2 = 800 x 103N/m2

pV1-3 = C V2 = 100 m/s W = - 2500 kW  = - 0.2 (2500) = -500 kW

 = ? Cp = 1.01 kJ/kg0K

we have 



- 500 + 2500 

∴ = 10.365 kg/sec

1. The steam supply to an engine is comprised of two streams which mix before entering the engine. One stream is supplied at the rate of 0.01 kg/s with an enthalpy of 2950 kJ/kg and a velocity of 20 m/s. The other stream is supplied at the rate of 0.1 kg/s with an enthalpy of 2569 kJ/kg and a velocity of 120 m/s. At the exit from the engine the fluid leaves as two streams, one of water at the rate of 0.001 kg/s with an enthalpy of 420 kJ/kg and the other of steam. The fluid velocity at the exit are negligible. The engine develops a shaft power of 25 kW. The heat transfer is negligible. Evaluate the enthalpy of the second exit stream. (Ans. 2462 kJ/kg)
2. A perfect gas flows through a nozzle where it expands in a reversible adiabatic manner. The inlet conditions are 22 bar, 5000C, 38 m/s. At exit the pressure is 2 bar. Determine the exit velocity and exit area if the flow rate is 4 kg/s. Take R = 190 J/kg-0k and γ = 1.35

[hint: 

p2v2 = RT2 ∴v2 = 0.3933 m3/kg   = ρ2A2V2 ]

Ans.: V2 = 726 m/s , A2 = 0.002167 m2

1. A steam turbine operate under steady flow conditions receiving steam at the following state: Pressure 15 bar, internal energy 2700 kJ/kg, velocity 300 m/s, specific volume 0.17 m3/kg and velocity 100 m/s.

The exhaust of steam from the turbine is at 0.1 bar with internal energy 2175 kJ/kg, specific volume 15m3/kg and velocity 300 m/s. The intake is 3 m above the exhaust. The turbine develops 35 kW and heat loss over the surface of turbine is 20kJ/kg. Determine the steam flow rate through the turbine. [Ans.: 0.0614 kg/s]

1. Determine the power required to drive a pump which raises the water pressure from 1 bar at entry to 25 bar at exit and delivers 2000 kg/hr of water. Neglect changes in volume, elevation and velocity and assume specific volume of water to be 0.001045m3/kg.

Solution: We have 

 ΔKE = 0, ΔPE = 0

Substituting in the SFEE equation,



Δu = 0  Water does not experience any change in temperature



 but v1 = v2



∴ = - 1.393 kW

1. In a conference hall comfortable temperature conditions are maintained in winter by circulating hot water through a piping system. The water enters the piping system at 3 bar pressure and 500C temperature (enthalpy = 240 kJ/kg) and leaves at 2.5 bar pressure and 300C temperature (enthalpy = 195 kJ/kg). The exit from the piping system is 15 m above the entry. If 30 MJ/hr of heat needs to be supplied to the hall, make calculation for the quantity of water circulated through the pipe per minute. Assume that there are no pumps in the system and that the change in KE is negligible.

Solution: Q – W = (Δh + ΔKE + ΔPE)

W = 0, ΔKE = 0

Q = (195 – 240) + 

= - 44.853 kJ/kg

∴Mass of water to be circulated = 

**Unsteady flow process**: In a steady flow process we have assumed that the mass and energy within the system remain constant and do not vary with time. In an unsteady flow process, mass and energy within the control volume vary continuously. The fluid flow into and out of the system.

Example: Filling or evacuation of a tank, (internal energy as well as mass of the tank changes with time), the condition of water in the cylinder jacket of an I.C. engine (is time dependant)

**Analysis**: Consider the flow of a fluid through a pipe line into the cylinder. Let m1 be the mass of the fluid initially in the cylinder at pressure p1, temperature t1 and m2 the final mass in the cylinder at pressure p2, temperature t2. The mass that flows into the cylinder is thus (m2 – m1).

There are two ways for solving problems involving unsteady flow (i) Closed system analysis (ii) Control volume analysis

* + 1. **Closed system analysis**:

**Pipe line**

**System Boundary**

**Cylinder**

**(System)**

Since no mass crosses the boundary of the system, the boundary of the system is selected in such a way that it includes not only the cylinder but also that portion of the fluid in the pipe line which will be introduced eventually into the cylinder as shown in figure. That means the system has variable boundaries which at the final state will be the same as that of the cylinder. Initially energy of the system E1 is composed of the internal energy of the mass initially in the cylinder, m1u1 plus the energy of the fluid which will eventually flow the pipe line into the cylinder, (m2 – m1)  where the subscript ‘p’ refers to the condition of the fluid in the pipe line. At the final state, energy E2 of the fluid in the system will be equal to m2u2.

Neglecting the change in PE, the change in energy is,

E2 – E1 = m2u2 - 

To find out work done on the system, consider a mass in the pipe line (m2 – m1) which is subjected to a controlled pressure Pp. The flow work due to the flow of mass (m2 – m1) into the cylinder from the (m2 – m1) vp in the pipe line to a zero volume is

W = Pp [0 – (m2 – m1) vp] = - (m2 – m1) Pp vp

Where vp is the specific volume of the fluid in the pipeline.

Applying 1st law of thermodynamics,



But hp = up + Ppvp,

∴Above equation becomes,

 --- (1)

* + 1. **Control Volume analysis**:

**Pipe line**

**C.V Boundary**

**Cylinder**

**(Control Volume)**

The cylinder itself is taken as the control volume as shown in figure. In this case, there is no work interaction. Using the general equation 1st law and considering no mass flows out of the control volume and neglecting the change in PE, as in the earlier case we have



or  --- (2)

If the tank would have been thermally insulated and initially empty, Q = 0 and m1 = 0 substituting into equation (1) and simplifying, we get  --- (3)

Also if KE in the pipe line is not appreciable, hp = u2 i.e., the specific enthalpy of the fluid in the pipe line is equal to the specific internal energy of the fluid in the cylinder at the final state.

**Note**: The tank emptying process is the reverse of filling process i.e., there is flow of fluid from the tank (cylinder) to the surroundings.

Analogous to filling process, applying 1st law, of thermodynamics, we have

 --- (4)

Where hp and Vp are the specific enthalpy and velocity of leaving fluid.

For no heat transfer and negligible exit velocity,

(m1 – m2) hp = m1u1 – m2u2

Further if the tank is to be fully emptied (m2 = 0)

i.e., m1hp = m1u1

or hp = u1

i.e., the specific enthalpy of the fluid in the cylinder is equal to the specific internal energy of the fluid in the pipe line at the final state.

**Problems**:

1. A household gas cylinder initially evacuated is filled by 15 kg gas supply of enthalpy 625 kJ/kg. After filling, the gas in the cylinder has the following parameters: pressure 10 bar, enthalpy 750 kJ/kg and specific volume 0.0487 m3/kg. Evaluate the heat received by the cylinder from the surroundings.

Solution: Given: m2 = 15 kg hp = 625 kJ/kg P2 = 10 bar h2 = 750 kJ/kg

v2 = 0.0487 m3/kg

SFEE to the filling process is

Q = m2u2 – m1u1 – (m2 – m1) 

The cylinder is initially evacuated i.e., m1 = 0, also 

i.e., Q = m2u2 – m2hp

= m2 [(h2 – p2v2) – hp]



= 1144.5 kJ

1. An insulated and rigid tank contains 5 m3 of air at 10 bar and 425 K. The air is then let off to atmosphere through a valve. Determine the work obtainable by utilizing the KE of the discharge air. Take Cp = 1 kJ/kg K, CV = 0.714 kJ/kg0-K atmosphere pressure = 1 bar.

Solution: Given: V1 = V2 = 5 m3 P1 = 10 bar T1 = 425 K

The situation corresponds to emptying process, for which the energy balance equation is,

Q + (m1 – m2) 

Insulated and rigid tank i.e., Q = 0

 Suffix ‘p’ refers to discharge condition.

Or 

= m1CVT1 – m2CVT2 – (m1 – m2) CpT2 --- (1)

We have,  p2 = 1 bar, R = Cp – CV = 0.286 kJ/kg K

Also, p1V1 = m1RT1 

& p2V2 = m2RT2 

Substitute in equation (1) on RHS, we have

 = 41.14 (0.714) (425) – 7.95 (0.714) (220)

- (41.14 – 7.95) (1.0) (220)

= 3933.35 kJ

1. A vessel of constant volume 0.3 m3 contains air at 1.5 bar and is connected via a valve, to a large main carrying air at a temperature of 380C and high pressure. The valve is opened allowing air to enter the vessel and raising the pressure there in to 7.5 bar. Assuming the vessel and valve to be thermally insulated, find the mass of air entering the vessel.

Solution: The situation corresponds to filling process, for which the energy balance equation is,



With thermally insulated and neglecting KE of air,

(m2 – m1)hp = m2u2 – m1u1

or (m2 – m1) CpTp = m2CVT2 – m1CVT1

Air is a perfect gas, i.e., pV = mRT









= 1.44 kg

= Mass of the air entering

1. After the completion of exhaust stroke of an I.C. engine the piston cylinder assembly remains filled up with 1 x 10-4kg of combustible products at 800 K. During the subsequent suction stroke, the piston moves outward and 16 x 10-4 kg of air at 290 K is sucked inside the cylinder. The suction process occurs at constant pressure and heat interaction is negligible. Evaluate the temperature of gases at the end of suction stroke. For air and gases, take Cp = 1kJ/kg

Solution: The energy equation for the filling process is,



With no heat interaction and negligible KE of air in the supply line, above equation reduces to,

(m2 – m1) hp = m2u2 – m1u1 + W

The suction occurs at constant pressure i.e., 

= p (m2v2 – m1v1)

= m2 (p2v2 – p1v1)

Substituting in the above equation for W, we have

(m2 – m1) hp = m2u2 – m1u1 + m2 (p2v2 – p1v1)

= m2 (u2 + p2v2) – m1 (u1 + p1v1)

= m2h2 – m1h1

Or (m2 – m1) CpTp = m2CpT2 – m1CpT1

Or (m2 – m1) Tp = m2T2 – m1T1

Substitute the given data, we get

(16 x 10-4 – 1 x 10-4) 290 = 16 x 10-4 x T2 – 1 x 10-4 x 800

T2 = 321.87 K (Temperature of gas at the end of suction stroke)

1. An air receiver of volume 6 m3 contains air at 15 bar and 40.50C. A valve is opened and some air is allowed to blow out to atmosphere. The pressure of the air in the receiver drops rapidly to 12 bar when the valve is then closed. Calculate the mass of air which has left the receiver.

Solution: The situation correspond to emptying process for which the energy balance equation is,



But Q = 0, Vp = 0

i.e., (m1- m2) hp = m1u1 – m2u2

Or (m1 – m2) CpTp = m1CVT1 – m2CVT2

From perfect gas equation, p1V1 = m1RT1 

∴Above equation becomes,



i.e., Mass of air left the receiver, 



= 14.3 kg

Also, 

∴m2 = 85.74 kg

1. The internal energy of air is given, at ordinary temperature by, u = u0 + 0.718t. Where u is in kJ/kg, u0 is any arbitrary value of u at 00C, kJ/kg and t is temperature in 0C. Also for air, pv = 0.287 (t + 273) where p is in KPa and v is in m3/kg.
2. An evacuated bottle is fitted with a valve through which air from the atmosphere, at 760 mm oxygen and 250C, is allowed to flow slowly to fill the bottle. If no heat transfer to or from the air in the bottle, what will its temperature be when the pressure in the bottle reaches 760 mm Hg?
3. If the bottle initially contains 0.03 m3 of air at 400 mm Hg and 250C, what will the temperature be when the pressure in the bottle reaches 760 mm of Hg?

Solution: u = u0 + 0.718t

pv = 0.287 (t + 273)

Using above equation determine Cv, Cp i.e., Cv = du/dt = 0.718 kJ/kg -0k

 = 1.005 kJ/kg-0k

i) Situation corresponds to filling process, for which the energy balance equation is,



Heat transfer Q = 0, evacuated bottle, m1 = 0 and negligible KE, Vp = 0

∴m2hp = m2u2

Or hp = u2

i.e., CpTp = CVT2



= γTp = 1.4 (298)

= 417.120K or 144.120C

ii) Energy balance equation is, (m2 – m1) hp = m2 u2 – m1 u1

i.e., (m2 – m1) CpTp = m2CVT2 – m1CVT1

Using perfect gas equation, p1V1 = m1RT1

But p1 = ωh

= 9810 (13.6) (400 x 10-3) = 53366.4 N/m2



Similarly p2V2 = m2RT2

P2 = ωh = 9810 (13.6) (760 x 10-3)

= 101396.2 N/m2



Substituting in energy balance equation,



Solving, T2 = 344.920K or 71.920C

1. The internal energy of air is given by u = u0 + 0.718 t also for air, pv = 0.287 (t + 273). A mass of air is stirred by a paddle wheel in an insulated constant volume tank. The velocities due to stirring make a negligible contribution to the internal energy of the air. Air flows out through a small valve in the tank at a rate controlled to keep the temperature in the tank constant. At a certain instant the conditions are as follows: tank volume 0.12m3, pressure 1 MPa, temperature 1500C and power to paddle wheel 0.1 kW. Find the rate of flow of air out of the tank at this instant.

Solution: The energy balance equation for emptying process is,

Q – Ws + (m1 – m2) 

Insulated tank, Q = 0, there is no change in i.e., of air in the tank. Internal energy, u = 0 and

KE = 0

∴Above equation becomes,

- Ws + (m1 – m2) hp = 0

i.e., (m1 – m2) = Ws/hp

Or rate of flow of air out of the tank at this instant

= 2.3412 x 10-4 kg/s

= 0.843 kg/hr

1. A certain water heater operates under steady flow conditions receiving 4.2 kg/s of water at 750C temperature, enthalpy 314 kJ/kg. The water is heated by mixing with steam which is supplied to the heater at temperature 1000C and enthalpy 2676 kJ/kg. The mixture leaves the heater as liquid water at temperature 1000C and enthalpy 419 kJ/kg. How much steam must be supplied to the heater per hour.

Solution: Energy entering = energy leaving





By the nature of the process,  ΔKE = 0 ΔPE = 0 

i.e., 





= 705 kg/hr

1. In a water cooling tower air enters at a height of 1 m above the ground level with velocity of 20 m/s and leaves the tower at a height of 7 m above the ground level with a velocity of 30 m/s. Water enters the tower at a height of 8 m above the ground level with a velocity of 3 m/s and leaves the tower at a height of 0.8 m with a velocity of 1 m/s. Water temperatures at inlet and exit are 800C and 500C respectively, while the inlet and exit temperatures of air are 300C and 700C respectively. The cooling tower is well insulated and a of 2.25 kW drives the air through the cooling tower. Determine the mass flow rate of air required if the mass flow rate of water is 1.5 kg/s.

Assume that for air Cp = 1.005 kJ/kg-0K and for water C = 4.187 kJ/kg-0K