THERMODYNAMICS
TUTORIAL 3 – THERMODYNAMIC SYSTEMS

This tutorial is set at Level QCF 3

- Explain and use the First Law of Thermodynamics.
- Solve problems involving various kinds of thermodynamic systems.

Contents

1. *Energy Transfer*

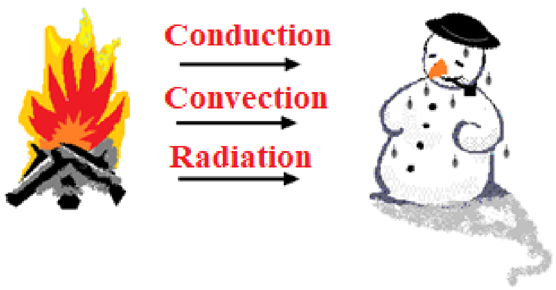
When you complete section one you should be able to explain and calculate the following.

- Heat transfer.
- Heat transfer rate.
- Work transfer
- Work transfer rate (Power)

There are two ways to transfer energy in and out of a system, by means of work and by means of heat. Both may be regarded as a quantity of energy transferred in Joules or energy transfer per second in Watts.

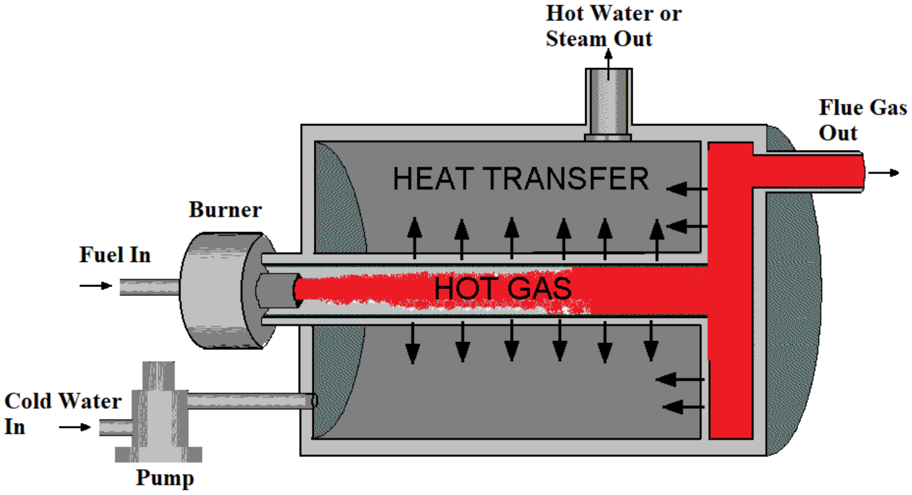
1.1 Heat Transfer

Heat transfer occurs because one place is hotter than another. Under normal circumstances, heat will only flow from a hot body to a cold body by virtue of the temperature difference. There are 3 mechanisms for this, ***Conduction, Convection and Radiation***. You do not need to study the laws governing conduction, convection and radiation in this tutorial.



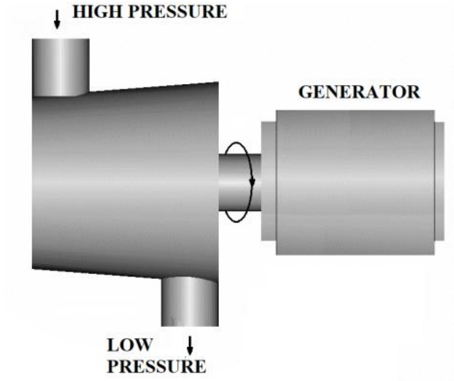
A quantity of energy transferred as heat is given the symbol Q and its basic unit is the Joule. The quantity transferred in one second is the heat transfer rate and this has the symbol Φ and the unit is the Watt.

An example of this is when heat passes from the furnace of a steam boiler through the walls separating the combustion chamber from the water and steam. In this case, conduction, convection and radiation all occur together. There will be more on heat transfer using specific heats in the next tutorial.



1.2 Work Transfer

Energy may be transported from one place to another mechanically. An example of this is when the output shaft of a car engine transfers energy to the wheels. A quantity of energy transferred as work is 'W' Joules but the work transferred in one second is the Power 'P' Watts.



An example of power transfer is the shaft of a steam turbine used to transfer energy from the steam to the generator in an electric power station. It is useful to remember that the power transmitted by a shaft depends upon the torque and angular velocity.

The formulae used are $P = \omega T$ or $P = 2\pi NT$

ω is the angular velocity in radian per second and N is the angular velocity in revolutions per second.

WORKED EXAMPLE No. 1

A duct has a cross section of 0.2 m × 0.4 m. Steam flows through it at a rate of 3 kg/s with a pressure of 2 bar. The steam has a dryness fraction of 0.98. Calculate all the individual forms of energy being transported.

SOLUTION

Cross sectional area = 0.2 × 0.4 = 0.08 m^2.

Volume flow rate = m x v_g at 2 bar

Volume flow rate = 3 × 0.98 × 0.8856 = 2.6 m^3/s.

velocity = c = Volume/area = 2.6/0.08 = 32.5 m/s.

Kinetic Energy being transported = $mc^2/2 = 3 \times 32.5^2 /2$ = 1 584 Watts.

Enthalpy being transported = $m(h_f + x\ h_{fg})$

H= 3(505 + 0.98 × 2 202) = 7 988.9 kW

Flow energy being transported = pressure x volume

Flow Energy = $2 \times 10^5 \times 2.6$ = 520 000 Watts

Internal energy being transported = $m(u_f + x\ u_{fg})$

U = 3(505 + 0.98 × 2 025) = 7 468.5 kW

Check flow energy = H - U = 7 988.9 – 7 468.5 = 520 kW

SELF ASSESSMENT EXERCISE No. 1

1. 1 kg/s of steam flows in a pipe 40 mm bore at 200 bar pressure and 400°C.

   i. Look up the specific volume of the steam and determine the mean velocity in the pipe. (7.91 m/s)

   ii. Determine the kinetic energy being transported per second. (31.3 W)

   iii. Determine the enthalpy being transported per second. (2 819 W)

2. The shaft of a steam turbine produces 600 Nm torque at 50 rev/s.
   Calculate the work transfer rate from the steam.
   (188.5 W)

3. A car engine produces 30 kW of power at 3 000 rev/min. Calculate the torque produced.
   (95.5 Nm)

2. *The First Law of Thermodynamics*

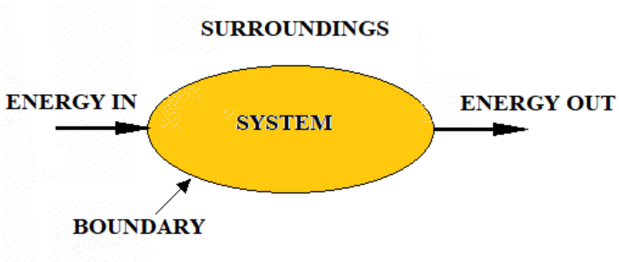
When you have completed this section, you should be able to explain and use the following terms.

- The First Law of Thermodynamics.
- Closed systems.
- The Non-Flow Energy Equation.
- Open systems.
- The Steady Flow Energy Equation.

2.1 Thermodynamic Systems

In order to do energy calculations, we identify our system and draw a boundary around it to separate it from the surroundings. We can then keep account of all the energy crossing the boundary. The first law simply states that

The nett energy transfer = nett energy change of the system.



Energy transfer into the system = E(in)

Energy transfer out of system = E (out)

Nett change of energy inside system = E(in) - E (out) = ΔE

This is the fundamental form of the first law.

Thermodynamic systems might contain only static fluid in which case they are called ***Non-Flow* or *Closed Systems*.**

Alternatively, there may be a steady flow of fluid through the system in which case it is known as a ***Steady Flow* or *Open System*.**

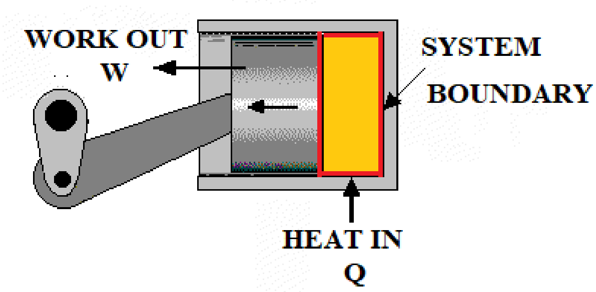
The energy equation is fundamentally different for each because most energy forms only apply to a fluid in motion. We will look at non-flow systems first.

2.2 Non-Flow Systems

The rules governing non-flow systems are as follows.

- The volume of the boundary may change.
- No fluid crosses the boundary.
- Energy may be transferred across the boundary.

When the volume enlarges, work (-W) is transferred from the system to the surroundings. When the volume shrinks, work (+W) is transferred from the surroundings into the system. Energy may also be transferred into the system as heat (+Q) or out of the system (-Q). This is best shown with the example of a piston sliding inside a cylinder filled with a fluid such as gas.



The only energy possessed by the fluid is internal energy (U) so the net change is ΔU. The energy equation becomes

$$\mathbf{Q + W = \Delta U}$$

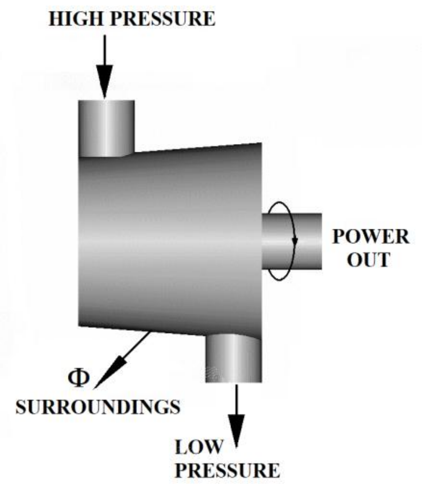
This is known as the ***Non-Flow Energy Equation*** **(N. F. E. E.)**

2.3 Steady Flow Systems

The laws governing this type of system are as follows.

- Fluid enters and leaves through the boundary at a steady rate.
- Energy may be transferred into or out of the system.

A good example of this system is a steam turbine. Energy may be transferred out as a rate of heat transfer Φ or as a rate of work transfer P.



The fluid entering and leaving has potential energy (PE), kinetic energy (KE) and enthalpy (H).

The first law becomes Φ + P = Nett change in energy of the fluid.

$$\mathbf{\Phi + P = \Delta(PE)/s + \Delta(KE)/s + \Delta(H)/s}$$

This is called the ***Steady Flow Energy Equation*** **(S. F. E. E.)**

Again, we will use the convention of positive for energy transferred into the system.

Note that the term Δ means '*change of*' and if the inlet is denoted point (1) and the outlet point (2). The change is the difference between the values at (2) and (1). For example ΔH means (H_2-H_1).

WORKED EXAMPLE No. 3

A steam turbine is supplied with 30 kg/s of superheated steam at 80 bar and 400^{o}C with negligible velocity. The turbine shaft produces 200 kNm of torque at 3 000 rev/min. There is a heat loss of 1.2 MW from the casing. Determine the thermal power remaining in the exhaust steam.

SOLUTION

Shaft Power = $2\pi NT = 2\pi(3\ 000/60) \times 200\ 000 = 62.831 \times 10^6$ W = 62.831 MW

Thermal power supplied = H at 80 bar and 400^{o}C

H = 30(3 139) = 94 170 kW = 94.17 MW

Total energy flow into turbine = 94.17 MW

Energy flow out of turbine = 94.17 MW = SP + Loss + Exhaust.

Thermal Power in exhaust = 94.17 -1.2 - 62.831 = **30.14 MW**

SELF ASSESSMENT EXERCISE No. 2

1. A non-flow system receives 80 kJ of heat transfer and loses 20 kJ as work transfer. What is the change in the internal energy of the fluid?
(60 kJ)

2. A non-flow system receives 100 kJ of heat transfer and also 40 kJ of work is transferred to it. What is the change in the internal energy of the fluid?
(140 kJ)

3. A steady flow system receives 500 kW of heat and loses 200 kW of work. What is the net change in the energy of the fluid flowing through it?
(300 kW)

4. A steady flow system loses 2 kW of heat also loses 4 kW of work. What is the net change in the energy of the fluid flowing through it?
(-6 kW)

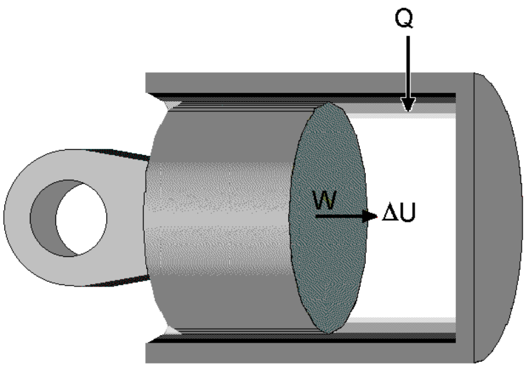
5. A steady flow system loses 3 kW of heat also loses 20 kW of work. The fluid flows through the system at a steady rate of 70 kg/s. The velocity at inlet is 20 m/s and at outlet it is 10 m/s. The inlet is 20 m above the outlet. Calculate the following.

   i. The change in K. E/s (-10.5 kW)
   ii. The change in P. E/s (-13.7 kW)
   iii. The change in enthalpy/s (1.23 kW)

3. *More Examples of Thermodynamic Systems*

When we examine a thermodynamic system, we must first decide whether it is a non-flow or a steady flow system. First, we will look at examples of non-flow systems.

3.1 Piston in a Cylinder



There may be heat and work transfer. The N. F. E. E. is, $Q + W = \Delta U$

Sometimes there is no heat transfer (e.g. when the cylinder is insulated). $Q = 0$

$$W = \Delta U$$

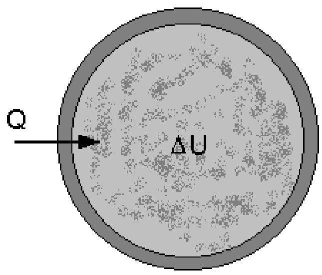
If the piston does not move, the volume is fixed and no work transfer occurs. In this case

$$Q = \Delta U$$

For a GAS ONLY the change in internal energy is $\Delta U = mC_V\Delta T$.

C_V is called the specific heat at constant volume and is explained later.

3.2. Sealed Evaporator or Condenser.



Since no change in volume occurs, there is no work transfer so

$$\mathbf{Q = \Delta U}$$

WORKED EXAMPLE No. 4

30 g of gas inside a cylinder fitted with a piston has a temperature of 15°C. The piston is moved with a mean force of 200 N so that that it moves 60 mm and compresses the gas. The temperature rises to 21°C as a result.

Calculate the heat transfer given c_V = 718 J/kg K.

SOLUTION

This is a non flow system so the law applying is $Q + W = \Delta U$
The change in internal energy is $\Delta U = mc_V \Delta T = 0.03 \times 718 \times (21 - 15)$
$\Delta U = 129.24$ J

The work is transferred into the system because the volume shrinks.

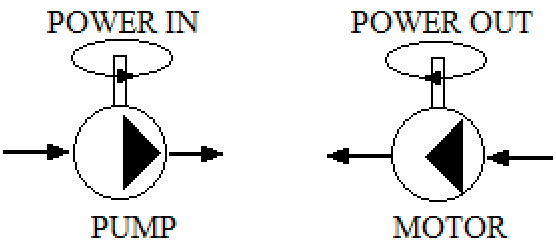
W = force × distance moved = 200 × 0.06 = 12 J

Q = ΔU - W = 117.24 J

Now we will look at examples of steady flow systems.

3.3. Pumps and Fluid Motors

The diagram shows graphical symbols for hydraulic pumps and motors.



The S. F. E. E. states,

$$\Phi + P = \Delta KE/s + \Delta PE/s + \Delta H/s$$

In this case, especially if the fluid is a liquid, the velocity is the same at inlet and outlet and the kinetic energy is ignored. If the inlet and outlet are at the same height, the PE is also neglected. Heat transfer does not usually occur in pumps and motors so Φ is zero.

The S. F. E. E. simplifies to $\mathbf{P = \Delta H/s}$

Remember that enthalpy is the sum of internal energy and flow energy. The enthalpy of gases, vapours and liquids may be found. In the case of liquids, the change of internal energy is small and so the change in enthalpy is equal to the change in flow energy only.

The equation simplifies further to $P = \Delta FE/s$

Since FE = pV and V is constant for a liquid, this becomes $\mathbf{P = V\Delta p}$

WORKED EXAMPLE No. 5

A pump delivers 20 kg/s of oil of density 780 kg/m^3 from atmospheric pressure at inlet to 800 kPa gauge pressure at outlet. The inlet and outlet pipes are the same size and at the same level. Calculate the theoretical power input.

SOLUTION

Since the pipes are the same size, the velocities are equal and the change in kinetic energy is zero. Since they are at the same level, the change in potential energy is also zero. Neglect heat transfer and internal energy.

$P = V\,\Delta p$ $\qquad$ $V = m/\rho = 20/780 = 0.0256\ \text{m}^3/\text{s}$ $\qquad$ $\Delta p = 800 - 0 = 800\ \text{kPa}$

$$\mathbf{P = 0.0256 \times 800\,000 = 20\,480\ W\ or\ 20.48\ kW}$$

WORKED EXAMPLE No. 6

A feed pump on a power station pumps 20 kg/s of water. At inlet the water is at 1 bar and 120^{o}C. At outlet it is at 200 bar and 140^{o}C. Assuming that there is no heat transfer and that PE and K. E. are negligible, calculate the theoretical power input.

In this case the internal energy has increased due to frictional heating.

The S F E E reduces to $\qquad$ $P = \Delta H/s = m(h_2 - h_1)$

The h values may be found from tables. $\qquad$ $h_1 = 504$ kJ/kg

This is near enough the value of h_f at 120^{o}C bar in steam tables.

$h_2 = 602$ kJ/kg

P = 20 (602 - 504) = 1 969 kW or 1.969 MW

If water tables are not to hand the problem may be solved using $\qquad$ $\Delta h = \Delta u + \Delta f.e.$

c = 4.18 kJ/kg K for water $\quad$ $\Delta u = c\,\Delta T = 4.18\,(140 - 120) = 83.6$ kJ/kg

$\Delta f.e. = V\Delta p$

The volume of water is normally around 0.001 m^3/kg

$\Delta f.e. = 0.001 \times (200 - 1) \times 10^5 = 19\,900$ J/kg or 19.9 kJ/kg

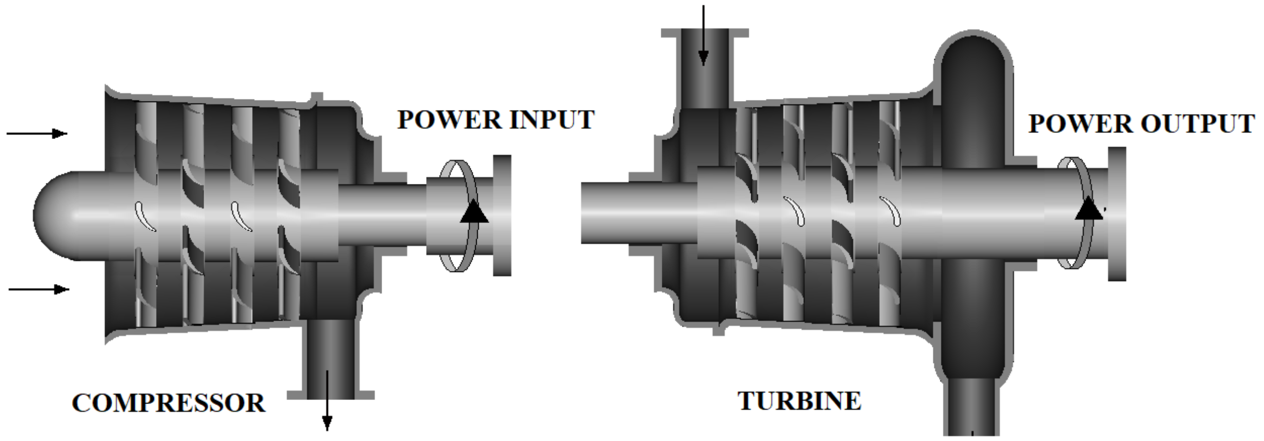
hence $\quad$ $\Delta h = \Delta u + \Delta fe = 83.6 + 19.9 = 103.5$ kJ/kg

$$\mathbf{P = m\Delta h = 20 \times 103.5 = 2070\ kW\ or\ 2.07\ MW}$$

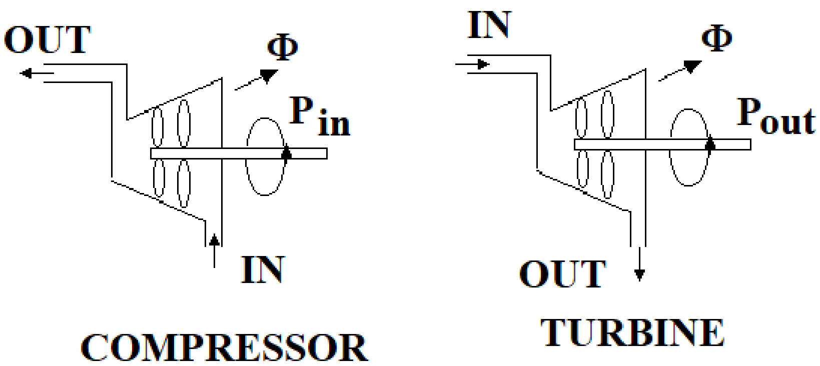
The discrepancies between the answers are slight and due to the fact the value of the specific heat and of the specific volume are not accurate at 200 bar.

3.4. Gas Compressors and Turbines.

The Diagrams shows the basic construction of an axial flow compressor and turbine. These have rows of aerofoil blades on the rotor and in the casing. The turbine passes high pressure hot gas or steam from left to right making the rotor rotate. The compressor draws in gas and compresses it in stages



Compressing a gas normally makes it hotter but expanding it makes it colder. This is because gas is compressible and unlike the cases for liquids already covered, the volumes change dramatically with pressure. This might cause a change in velocity and hence kinetic energy. Often both kinetic and potential energy are negligible. The internal energy change is not negligible. Figure 11 shows graphical symbols for turbines and compressors. Note the narrow end is always the high pressure end.



WORKED EXAMPLE No. 7

A gas turbine uses 5 kg/s of hot air. It takes it in at 6 bar and 900^oC and exhausts it at 450^oC. The turbine loses 20 kW of heat from the casing. Calculate the theoretical power output given that c_p = 1 005 J/kg K.

First identify this as a steady flow system for which the equation is

$$\Phi + P = \Delta K.E./s + \Delta P.E./s + \Delta H/s$$

For lack of further information we assume K. E. and PE to be negligible. The heat transfer rate is -20 kW.

The enthalpy change for a gas is $\Delta H = mC_p\Delta T$

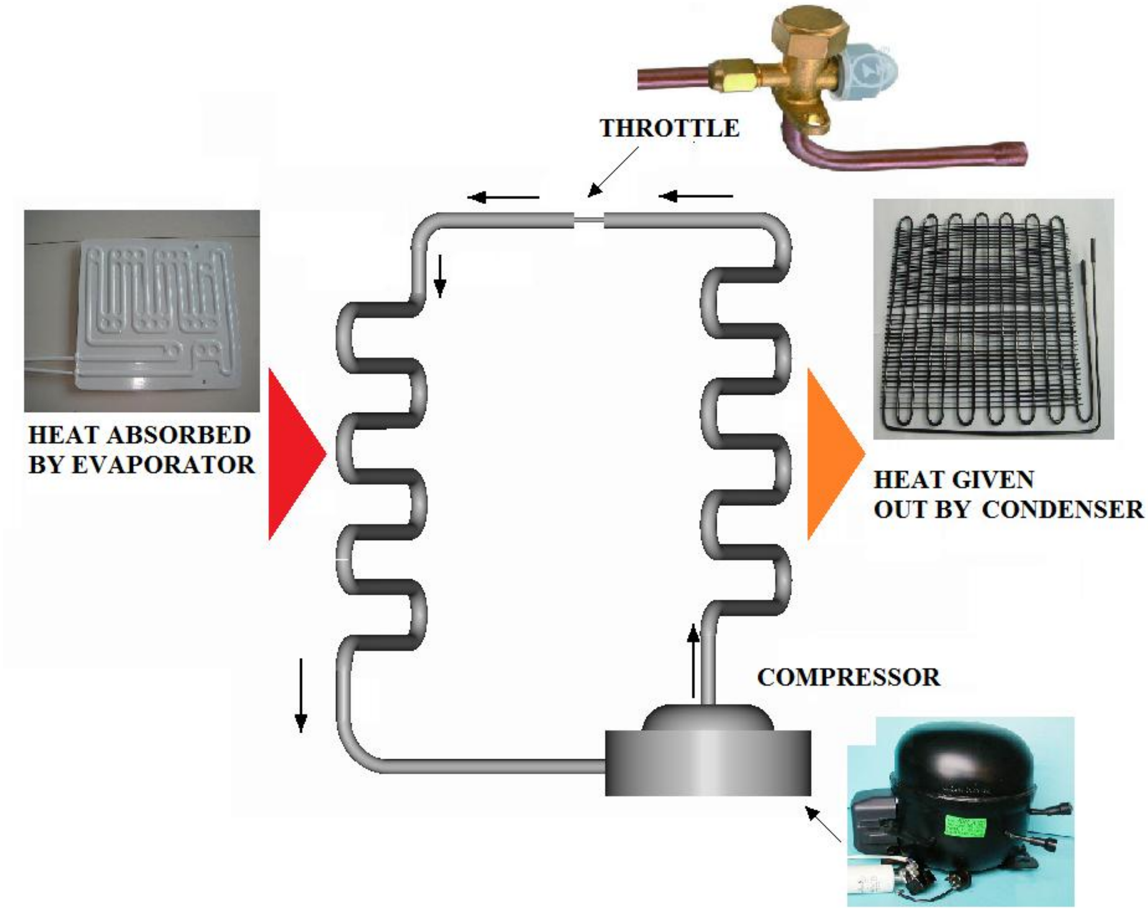
$\Delta H = 5 \times 1\,005 \times (450 - 900) = -2\,261\,000$ W or -2.261 MW

$P = \Delta H - \Phi = -2\,261 - (-20) = -2\,241$ kW

The minus sign indicates that the power is leaving the turbine. Note that if this was a steam turbine, you would look up the h values in the steam tables.

7.5 Steady Flow Evaporators and Condensers

A refrigerator is a good example of a thermodynamic system. In particular, it has a heat exchanger inside that absorbs heat at a cold temperature and evaporates the liquid into a gas. The gas is compressed and becomes hot. The gas is then cooled and condensed on the outside in another heat exchanger.



For both the evaporator and condenser, there is no work transferred in or out. K.E. and P.E. are not normally a feature of such systems so the S. F. E. E. reduces to

$$\mathbf{\Phi = \Delta H/s}$$

On steam power plant, boilers are used to raise steam and these are examples of large evaporators working at high pressures and temperatures. Steam condensers are also found on power stations. The energy equation is the same, whatever the application.

WORKED EXAMPLE No. 8

A steam condenser takes in wet steam at 8 kg/s and dryness fraction 0.82. This is condensed into saturated water at outlet. The working pressure is 0.05 bar.
Calculate the heat transfer rate.

SOLUTION

$\Phi = \Delta H/s = m(h_2 - h_1)$

$h_1 = h_f + x\, h_{fg}$ at 0.05 bar

from the steam tables we find that

$h_1 = 138 + 0.82(2\,423) = 2\,125$ kJ/kg

$h_2 = h_f$ at 0.05 bar = 138 kJ/kg

hence **$\Phi = 8(138 - 2\,125) = -15\,896$ kW**

The negative sign indicates heat transferred from the system to the surroundings.

SELF ASSESSMENT EXERCISE No. 4

1. Gas is contained inside a cylinder fitted with a piston. The gas is at 20°C and has a mass of 20 g. The gas is compressed with a mean force of 80 N which moves the piston 50 mm. At the same time 5 Joules of heat transfer occurs out of the gas. Calculate the following.

   i. The work done.(4 J)
   ii. The change in internal energy. (-1 J)
   iii. The final temperature. (19.9°C)

   Take c_v as 718 J/kg K

2. A steady flow air compressor draws in air at 20°C and compresses it to 120°C at outlet. The mass flow rate is 0.7 kg/s. At the same time, 5 kW of heat is transferred into the system. Calculate the following.

   i. The change in enthalpy per second. (70.35 kW)
   ii. The work transfer rate. (65.35 kW)

   Take c_p as 1005 J/kg K.

3. A steady flow boiler is supplied with water at 15 kg/s, 100 bar pressure and 200°C. The water is heated and turned into steam. This leaves at 15 kg/s, 100 bar and 500°C. Using your steam tables, find the following.

   i. The specific enthalpy of the water entering. (856 kJ/kg)
   ii. The specific enthalpy of the steam leaving. (3 373 kJ/kg)
   iii. The heat transfer rate. (37.75 kW)

4. A pump delivers 50 dm^3/min of water from an inlet pressure of 100 kPa to an outlet pressure of 3 MPa. There is no measurable rise in temperature. Ignoring K.E. and P.E, calculate the work transfer rate. (2.42 kW)

5. A water pump delivers 130 dm^3/minute (0.13 m^3/min) drawing it in at 100 kPa and delivering it at 500 kPa. Assuming that only flow energy changes occur, calculate the power supplied to the pump. (860 W)

6. A steam condenser is supplied with 2 kg/s of steam at 0.07 bar and dryness fraction 0.9. The steam is condensed into saturated water at outlet. Determine the following.

   i. The specific enthalpies at inlet and outlet. (2 331 kJ/kg and 163 kJ/kg)
   ii. The heat transfer rate. (4 336 kW)

7. 0.2 kg/s of gas is heated at constant pressure in a steady flow system from 10°C to 180°C. Calculate the heat transfer rate Φ. (37.4 kW)
   C_p = 1.1 kJ/kg K

8. 0.3 kg of gas is cooled from 120°C to 50°C at constant volume in a closed system. Calculate the heat transfer. (-16.8 kJ)
   C_v = 0.8 kJ/kg.