Unit code: K/601/1443 QCF level: 5 Credit value: 15

OUTCOME 3 - TUTORIAL 1

3 Heat transfer equipment

Recuperators**:** concentric tube (parallel and counter flow, cross flow, shell and tube, plate, extended surface)

Heat transfer performance**:** steady state performance; overall heat transfer coefficient; LMTD; effectiveness; pressure drop; fouling factors

Fluids: water; oil; air; refrigerants; steam

Applications: specification of suitable recuperator and fluids for given applications such as oil cooling and heat recovery; calculation of heat transfer rates given fluid and recuperator data

You should judge your progress by completing the self assessment exercises. On completion of this tutorial the student should be able to do the following.

This is the third tutorial in the series on heat transfer and covers some of the advanced theory of convection. The tutorials are designed to bring the student to a level where he or she can solve problems involving practical heat exchangers.

On completion of this tutorial the student should be able to do the following.

- Explain the logarithmic mean temperature difference.
- Describe the basic designs of heat exchangers.
- Parallel, Counter and Cross Flow Heat Exchangers.
- Explain the factors involved in heat transfer.
- Solve heat transfer problems for heat exchangers.

Note – a recuperator is another name for a heat exchanger in which heat is transferred from one fluid to another through a barrier that separates the fluids. In this tutorial the 'term heat exchanger' is preferred.

It is assumed that the student is familiar with fluid properties and the use of steam and other fluid tables. If not, this should be studied first and this may be found in other tutorials on thermodynamics.

INTRODUCTION

Most heat exchanges make use of forced convection. Heat exchangers use a variety of surfaces a typical one being a tube with fins. The effectiveness of the heat exchanger depends on many things such as the following.

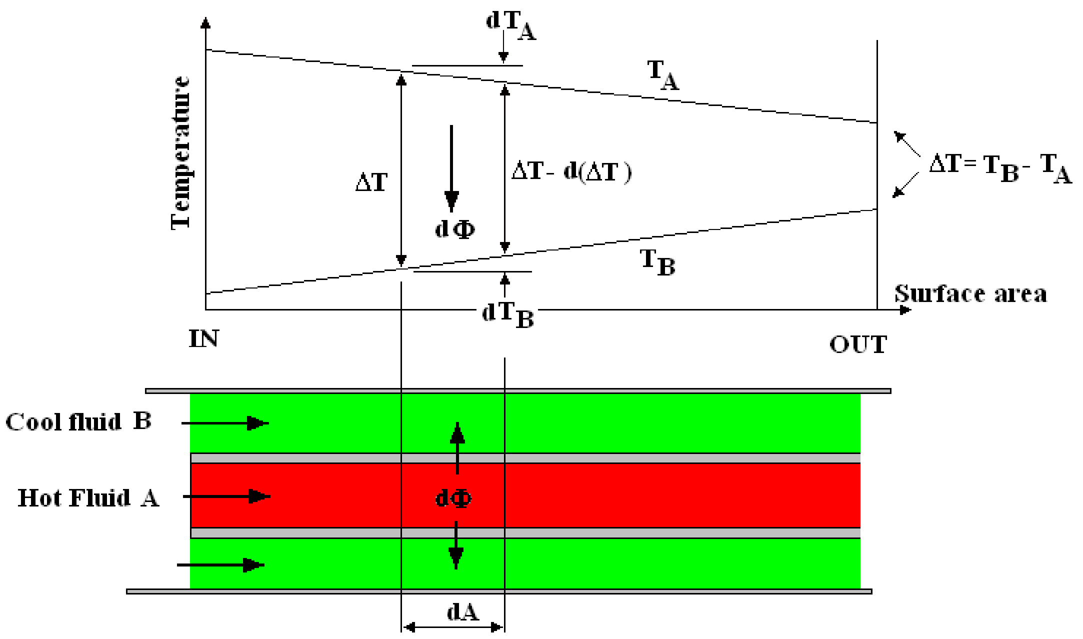
- The shape of the surface.
- The texture of the surface.
- The orientation to the direction of flow.
- The properties of the fluids.

In outcome 2 you studied heat transfer coefficients for a variety of circumstances. This can be applied to heat exchangers.

Many heat exchangers take the form of tubes with a fluid on both sides. The formulae used in previous tutorials needs modifying to take account of the temperature change as the fluids travel through the heat exchangers.

HEAT TRANSFER THROUGH A LONG TUBE

Consider a hot fluid (A) flowing through a long tube exchanging heat with a cooler fluid (B) flowing in a parallel direction on the outside of the tube. As the fluids flow from inlet to outlet, fluid (A) cools and fluid (B) is heated. The net heat exchange is Φ. The temperature of the two fluids varies with the surface area or path length as shown.



Consider a short length with surface area dA. The temperature difference at any point is:-

$$\Delta T = T_B - T_A.$$

The heat exchange is dΦ over this small area.

The heat lost or gained by a fluid over the small length is given by $d\Phi = mc_p dT$

m is the mass flow rate and c_p the specific heat capacity and this is assumed to be constant in this work.

dT is the change in temperature over the path length.

Heat lost by fluid A $d\Phi = m_A\, c_{pA}\, dT_A$ $dT_A = \dfrac{d\Phi}{m_A c_{pA}}$

Heat gained by fluid B $d\Phi = m_B\, c_{pB}\, dT_B$ $dT_B = \dfrac{d\Phi}{m_B c_{pB}}$

$$dT_B + dT_A = d(\Delta T) = \frac{d\Phi}{m_B c_{pB}} + \frac{d\Phi}{m_A c_{pA}} \qquad d\Phi = \frac{d(\Delta T)}{\left(\dfrac{1}{m_B c_{pB}} + \dfrac{1}{m_A c_{pA}}\right)} \text{...........(i)}$$

Integrate between the outlet and inlet and $\Phi = \dfrac{\Delta T_o - \Delta T_i}{\dfrac{1}{m_B c_{pB}} + \dfrac{1}{m_A c_{pA}}}$ ....(ii)

Now consider the change in the temperature difference over the short path length.

In terms of the overall heat transfer coefficient $d\Phi = U\, dA\, \Delta T$............(iii)
Equate (i) and (iii)

$$d\Phi = U\, dA\, \Delta T = \frac{d(\Delta T)}{\left(\dfrac{1}{m_B c_{pB}} + \dfrac{1}{m_A c_{pA}}\right)} \qquad U\left(\frac{1}{m_B c_{pB}} + \frac{1}{m_A c_{pA}}\right) dA = \frac{d(\Delta T)}{\Delta T}$$

Integrating over the whole path $U\left(\dfrac{1}{m_B c_{pB}} + \dfrac{1}{m_A c_{pA}}\right) A = \ln\left(\dfrac{\Delta T_o}{\Delta T_i}\right)$

$$\left(\frac{1}{m_B c_{pB}} + \frac{1}{m_A c_{pA}}\right) = \frac{\ln\left(\dfrac{\Delta T_o}{\Delta T_i}\right)}{U\, A} \text{......................(iv)}$$

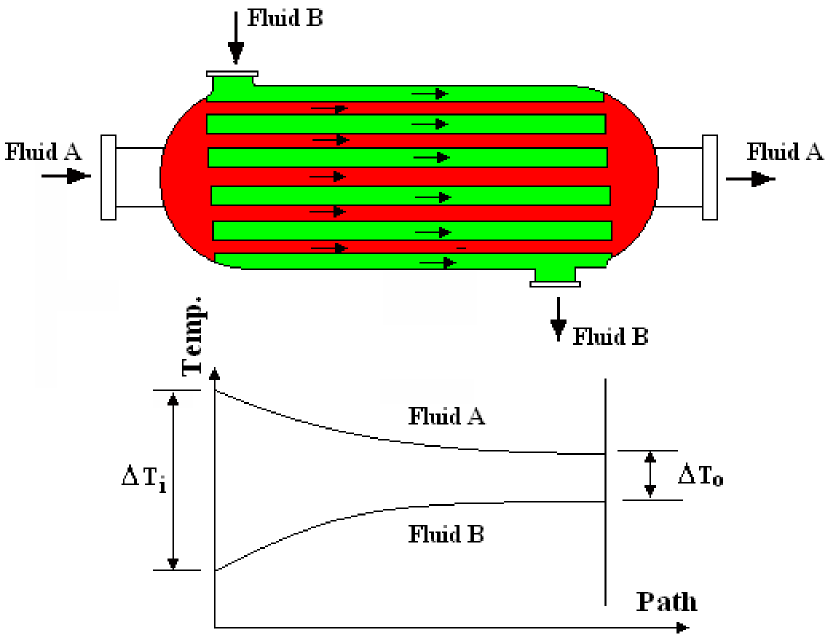
Substitute (iv) into (ii) $\Phi = \dfrac{U\, A(\Delta T_o - \Delta T_i)}{\ln\left(\dfrac{\Delta T_o}{\Delta T_i}\right)}$

For the whole system we may use $\Phi = U\, A\, \Delta T_m$ where ΔT_m is a mean temperature difference.

Comparing it is apparent that $\Delta T_m = \dfrac{(\Delta T_o - \Delta T_i)}{\ln\left(\dfrac{\Delta T_o}{\Delta T_i}\right)}$

This is called the logarithmic mean temperature difference. If we did the same analysis for the fluids flowing in opposite directions, we would get the same result.
Next let's discuss the basic types of heat exchangers.

PARALLEL FLOW HEAT EXCHANGERS



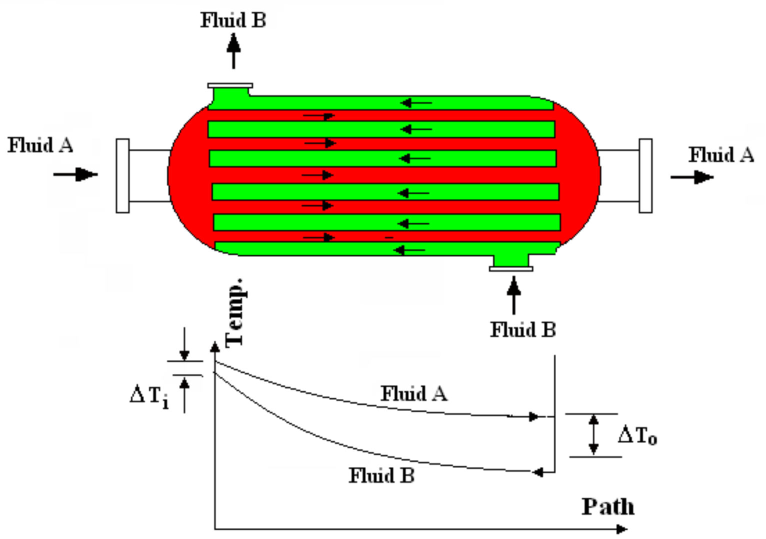
The fluid being heated and the fluid being cooled flow in the same parallel direction as shown. The heat is convected to the wall of the tube, then conducted to the other side and then convected to the other fluid. If the tube wall is thin, the heat transfer rate is

$$\Phi = UA\frac{\Delta T_o - \Delta T_i}{\ln\left(\frac{\Delta T_o}{\Delta T_i}\right)}$$

A is the surface are of the tubes.

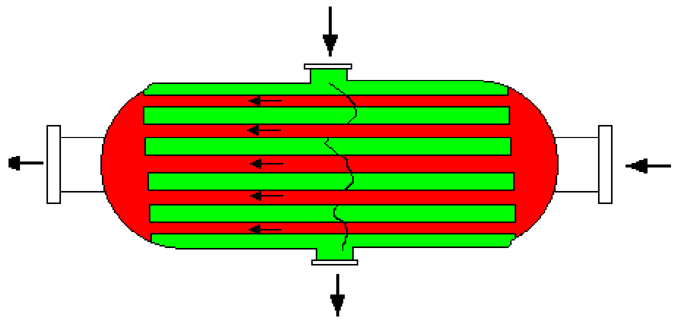
The diagram shows typically how the temperature of the two fluids varies with the path length. Fluid 'B' gets hotter and fluid 'A' gets cooler so the temperature difference is greatest at inlet.

COUNTER FLOW



The fluids flow in opposite but parallel directions as shown. The temperature of the fluid being heated can be raised to near the inlet temperature of the fluid being cooled. This is important for exchangers that heat up air for combustion such as the exhaust gas heat exchangers on gas turbines. For a given heat transfer the surface area is less. The heat transfer formula is the same.

CROSS FLOW



The fluids flow at right angles to each other as shown. This design is often the result of the plant layout and is common in industrial boilers where the hot gasses flow in a path normal to the water and steam. (superheaters, recuperators and economisers).

The tubes are often finned to improve the efficiency. Sooty deposits on the outside are more likely to be dislodged in this configuration. Large steam condensers also use this style.

CONDENSING AND EVAPORATING

If one of the fluids is evaporating or condensing during the process the temperature is constant so long as it does not completely evaporate or condense.

WORKED EXAMPLE No. 1

A heat exchanger transfers heat from hot carbon dioxide to superheated steam.

The steam flows inside tubes and the gas flows over the outside in a parallel direction.

The steam is at 200 bar pressure and is heated from 375°C to 500°C respectively.

The carbon dioxide is cooled from 750°C to 600°C and flows at 0.35 kg/s.

The tubes are thin walled and 40 mm diameter. The total length is 250 m.

Determine the following.

(i) The flow rate of the steam.
(ii) The logarithmic mean temperature.
(iii) The effective heat transfer coefficient for the unit.

SOLUTION

The mean temperature of the gas is (750 + 600)/2 = 675°C
From the fluids tables the specific heat is 1.11 kJ/kg K
Heat Transfer rate from gas = $m_g c_p \Delta T$ = 0.35 x 1.11 (750 - 600) = 58.275 kW

From the steam tables
The enthalpy of the steam at 200 bar and 500°C is 3239 kJ/kg = hs_2
The enthalpy of the steam at 200 bar and 375°C is 2605 kJ/kg = hs_1
Heat Transfer rate to steam = $m_s(hs_2 - hs_1)$ = 58.275

$$m_s = \frac{58.275}{3239 - 2605} = 0.0927 \text{ kg/s}$$

ΔT_i = 750 – 375 = 375
ΔT_o = 600 – 500 = 100

$$\Delta T_m = \frac{(\Delta T_o - \Delta T_i)}{\ln\left(\frac{\Delta T_o}{\Delta T_i}\right)} = \frac{(100 - 375)}{\ln\left(\frac{100}{375}\right)} = 208^\circ\text{C}$$

$A = \pi DL = \pi \text{ x } 0.04 \text{ x } 250 = 31.416 \text{ m}^2$

$$U = \frac{\Phi}{A T_m} = \frac{58275}{31.416 \text{ x } 208} = 8.918 \text{ W/m}^2\text{ K}$$

WORKED EXAMPLE No. 2

An exhaust pipe is 75 mm diameter and it is cooled by surrounding it with a water jacket. The exhaust gas enters at 350°C and the water enters at 10°C. The surface heat transfer coefficients for the gas and water are 300 and 1500 W/m^2 K respectively. The wall is thin so the temperature drop due to conduction is negligible. The gasses have a mean specific heat capacity c_p of 1130 J/kg K and they must be cooled to 100°C. The specific heat capacity of the water is 4190 J/kg K. The flow rate of the gas and water is 200 and 1400 kg/h respectively.

Calculate the required length of pipe for (a) parallel flow and (b) contra flow.

SOLUTION

Overall Heat Transfer Coefficient is U where $\frac{1}{U} = \frac{1}{h_g} + \frac{1}{h_w} + \frac{x}{k}$

The wall is very thin so ignore conduction $\frac{1}{U} = \frac{1}{h_g} + \frac{1}{h_w} = \frac{1}{0.3} + \frac{1}{1.5} = 4 \quad U = 0.25$

PARALLEL FLOW

Heat lost by the gas is

$\Phi = mC_p\Delta T = 200 \times 1.13\ (350 - 100)$

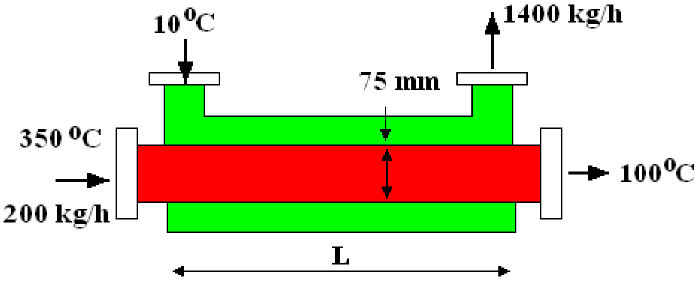
$\Phi = 56500$ kJ/h

Heat Gained by water

$\Phi = 56500 = mC_p\Delta T$

$56500 = 1400 \times 4.19 \times (\theta - 10)$

$\theta = 19.63°C$

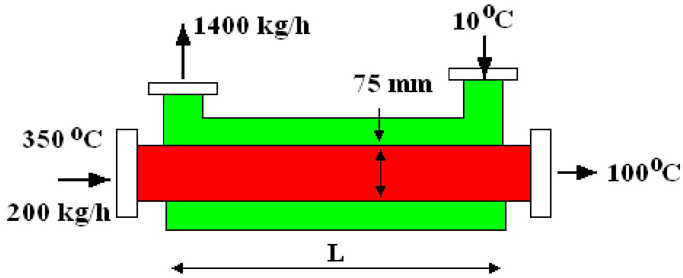


$\Delta T_i = 340$ K $\Delta T_o = 80.34$ K $\quad \Phi = UA\frac{\Delta T_o - \Delta T_i}{\ln\left(\frac{\Delta T_o}{\Delta T_i}\right)} = \frac{56500}{3600}$ kW

$15.694 = 0.25A\frac{80.34 - 340}{\ln\left(\frac{80.34}{340}\right)} = \frac{64.915A}{1.443} = 45A \quad A = 0.349\ m^2 \quad A = \pi DL$

$L = 0.349/(\pi \times 0.075) = 1.48$ m

CONTRA FLOW



$\Delta T_i = 330.4$ K $\Delta T_o = 90$ K

$\Phi = 15.694 = UA\frac{\Delta T_o - \Delta T_i}{\ln\left(\frac{\Delta T_o}{\Delta T_i}\right)}$

$15.694 = 0.25A\frac{90 - 330.4}{\ln\left(\frac{90}{330.4}\right)} \quad A = 0.34\ m^2$

$15.694 = \frac{60.1A}{1.3} = 46.23A$

$A = \pi DL \quad L = 0.34/(\pi \times 0.075) = 1.44$ m

FOULING FACTOR

Many heat exchanger surfaces become fouled due to deposits forming on them such as lime scale with hard water and sooty scale with burned gasses. This produces a resistance to the conducting path and the temperature change through the wall of the tube is no longer negligible. To compensate for this a heat transfer coefficient U_f used where U_f is equivalent to k/x. This is called the fouling factor. This will vary with the type of deposit and the time taken to build up. Cleaning the tubes is highly desirable. This especially applies to fossil fuel boilers in the water walls, superheaters and feed water heaters. The feed water heaters in particular are subject to build up of soot on the cooling fins and this is cleaned by mechanical scrapers and blasting with steam.

If the flow rates and inlet temperatures are unchanged, the heat transfer rate will be reduced and the temperatures of both fluids change at exit.

WORKED EXAMPLE No. 3

Repeat worked example No.2 but this time there is a fouling factor U_f of 120 W/m^2 K

SOLUTION

Overall Heat Transfer Coefficient is U where $\frac{1}{U} = \frac{1}{h_g} + \frac{1}{h_w} + \frac{1}{U_f}$

The wall is very thin so ignore conduction $\frac{1}{U} = \frac{1}{h_g} + \frac{1}{h_w} = \frac{1}{0.3} + \frac{1}{1.5} + \frac{1}{0.12} = 0.1233$

U = 81.08 kW/m^2 K

PARALLEL FLOW

Heat lost by the gas is

$\Phi = mC_p\Delta T = 200 \times 1.13\,(350 - 100)$

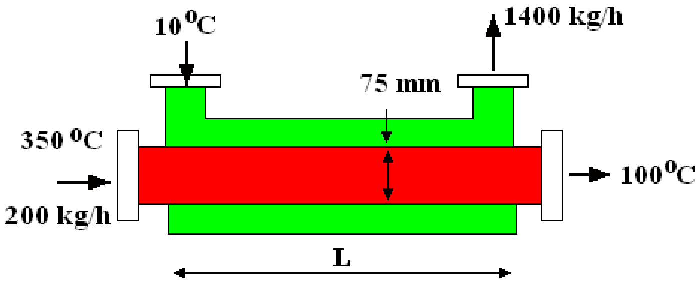
$\Phi = 56500$ kJ/h

Heat Gained by water

$\Phi = 56500 = mC_p\Delta T$

$56500 = 1400 \times 4.19 \times (\theta - 10)$

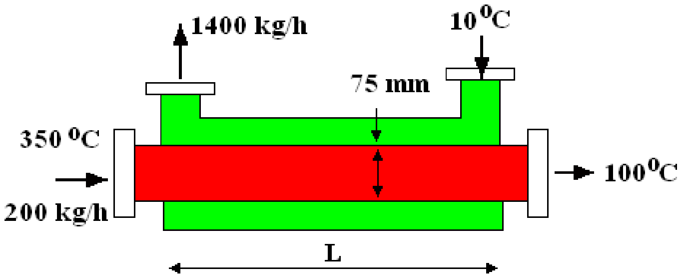
$\theta = 19.63^\circ C$



$\Delta T_i = 340$ K $\Delta T_o = 80.34$ K $\qquad \Phi = UA\frac{\Delta T_o - \Delta T_i}{\ln\left(\frac{\Delta T_o}{\Delta T_i}\right)} = \frac{56500}{3600}$ kW

$15.694 = 81.08A\frac{80.34 - 340}{\ln\left(\frac{80.34}{340}\right)}$ A = 1.075 m^2 A = πDL L = 1.075/(π x 0.075) = 4.56 m

CONTRA FLOW



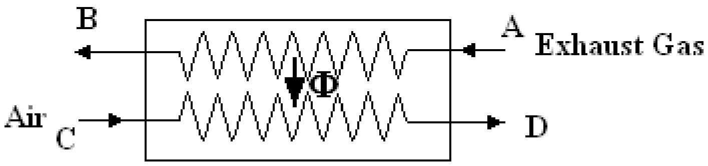
$\Delta T_i = 330.4$ K $\Delta T_o = 90$ K

$\Phi = 15.694 = UA\frac{\Delta T_o - \Delta T_i}{\ln\left(\frac{\Delta T_o}{\Delta T_i}\right)}$

$15.694 = 81.08A\frac{90 - 330.4}{\ln\left(\frac{90}{330.4}\right)}$ A = 1.047 m^2 A = πDL L = 1.047/(π x 0.075) = 4.44 m

THERMAL RATIO AND EFFECTIVENESS

These are terms often used with exhaust gas heat exchangers on gas turbines. Consider the heat exchanger in the diagram. Ideally the $T_A = T_B$ and $T_C = T_B$ and the maximum possible heat transfer would be obtained.



The effectiveness is defined as the ratio of the heat transfer to the air and from the hot gas. This is not efficiency but simply a way to calculate the temperatures. The ratio may be given a symbol E.

$$E = \frac{m_a c_{pa}(T_D - T_C)}{m_g c_{pg}(T_B - T_A)}$$

If the specific heats and mass flow are the same (often assumed in a gas turbine problem) this simplifies to $E = \frac{(T_D - T_C)}{(T_B - T_A)}$

It is also often taken that $T_B = T_C$ so it further reduces to $E = \frac{(T_D - T_B)}{(T_B - T_A)}$ and this is usually called the thermal ratio.

The same principles may be applied to recuperators that preheat the incoming air for combustion on a boiler burning fossil fuel.

WORKED EXAMPLE No.4

A gas turbine exhausts gas at 950 K and this is passed through an exhaust gas heat exchanger to the air being supplied to the combustion process. The air enters at 503 K. The effectiveness of the exchanger is 0.88. The mass flow of both are the same but the specific heat of the air is 1.005 kJ/kg K and the specific heat of the exhaust gas is 1.15 kJ/kg K. Calculate the temperature of the air entering the combustion chamber.

SOLUTION

Note that working in absolute temperatures is normal for gas turbines but working in ^oC gives the same answers.

$$0.88 = \frac{c_{pa}(T_D - T_B)}{c_{pg}(T_B - T_A)} = \frac{1.005(T_D - 503)}{1.15(950 - 503)}$$

$T_D = 894.4\ K$

In ^oC $\theta = 894.4 - 273 = 621.4\ ^oC$

SELF ASSESSMENT EXERCISE No.1

1. An oil cooler consists of a coiled tube inside a shell through which cooling water is circulated. The oil flows at 0.17 kg/s. The inlet and exit temperatures are 80°C and 30°C respectively. The cooling water enters at 12°C and is required to be heated to 18°C. Calculate the flow rate of water required.
   The specific heat of water is 4.2 kJ/kg K and 2.2 kJ/kg K for oil. (0.742 kg/s)

2. A power station burns fossil fuel and the air for combustion is preheated by a recuperator. The air enters at 5°C and is heated by hot flue gases entering at 180°c and exiting at 120°C. The effectiveness is 0.75. Calculate the temperature of the preheated air. Take the specific heats for the air and burned gas as 1.005 and 1.105 kJ/kg K respectively. The mass flow of both is the same.
   (Answer 54.5°C)

3. A contra flow heat exchanger transfers heat from refrigerant 134a to water. The refrigerant passes through tubes surrounded by a water jacket.
   The refrigerant enters at 20°C as dry saturated vapour and leaves as wet vapour with dryness fraction 0.6.
   The water flows at 0.2 kg/s. It enters at 10°C and leaves at 16°C. The specific heat of water is 4190 J/kg K.
   The tubes are thin walled and 15 mm diameter. The total length is 5 m.
   (i) The heat transfer rate. (5028 W)
   (ii) The flow rate of the refrigerant. (0.068 kg/s)
   (iii) The logarithmic mean temperature. (6.548°C)
   (iv) The effective heat transfer coefficient for the unit. (3.259 kW/m^2 K)

4. A recuperator consists of a shell with parallel pipes 25 mm diameter. Hot gas enters the pipes at 420 °C and it is cooled by water flowing through the shell on the outside of the pipes. The water temperature is 15°C at inlet. The surface heat transfer coefficients for the gas and water are 250 and 1700 W/m^2 K respectively. The wall is thin so the temperature drop due to conduction is negligible. The gases have a mean specific heat capacity c_p of 1020 J/kg K and they must be cooled to 150°C. The specific heat capacity of the water is 4200 J/kg K. The flow rate of the gas and water is 0.055 kg/s and 0.4 kg/s respectively.

   Calculate the heat transfer rate, the water exit temperature and the required length of pipe for both parallel and contra flow configuration.

   (Answers 15.147 kW, 24°C, 3.7 m and 3.65 m)

5. The parallel flow recuperator described in question 4 becomes fouled over a period of time resulting in the gas temperature rising at outlet to 200°C. If the water flow rate is unchanged, calculate the new heat transfer rate, the exit temperature of the water and the fouling factor.
   (12.34 kW, 22.35°C and 522.6 W/m^2 K)