5.22

A large coal fired power plant has an efficiency of 45% and produces net 1,500 MW of electricity. Coal releases 25 000 kJ/kg as it burns so how much coal is used per hour?

From the definition of the thermal efficiency and the energy release by the combustion called heating value HV we get

$$\dot{W} = \eta\, \dot{Q}_H = \eta \cdot \dot{m} \cdot HV$$

then

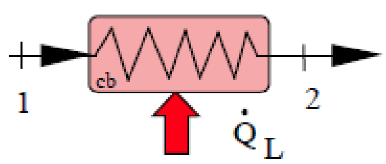
$$\dot{m} = \frac{\dot{W}}{\eta \times HV} = \frac{1500 \text{ MW}}{0.45 \times 25000 \text{ kJ/kg}} = \frac{1500 \times 1000 \text{ kJ/s}}{0.45 \times 25000 \text{ kJ/kg}}$$

$$= 133.33 \text{ kg/s} = \mathbf{480\ 000\ kg/h}$$

5.29

R-410A enters the evaporator (the cold heat exchanger) in an A/C unit at -20°C, x = 28% and leaves at -20°C, x = 1. The COP of the refrigerator is 1.5 and the mass flow rate is 0.003 kg/s. Find the net work input to the cycle.

Energy equation for heat exchanger



$$\dot{Q}_L = \dot{m}(h_2 - h_1) = \dot{m}[h_g - (h_f + x_1 h_{fg})]$$

$$= \dot{m}[h_{fg} - x_1 h_{fg}] = \dot{m}\,(1 - x_1)h_{fg}$$

$$= 0.003 \text{ kg/s} \times 0.72 \times 243.65 \text{ kJ/kg} = 0.5263 \text{ kW}$$

$$\beta = \text{COP} = \dot{Q}_L / \dot{W} \quad \Rightarrow \quad \dot{W} = \dot{Q}_L / \beta = 0.5263 / 1.5 = \mathbf{0.35\ kW}$$

5.31

An experimental power plant generates 130 MW of electrical power. It uses a supply of 1200 MW from a geothermal source and rejects energy to the atmosphere. Find the power to the air and how much air should be flowed to the cooling tower (kg/s) if its temperature cannot be increased more than 12°C.

Solution:

C.V. Total power plant.

Energy equation gives the amount of heat rejection to the atmosphere as

$$\dot{Q}_L = \dot{Q}_H - \dot{W} = 1200 - 130 = \mathbf{1070\ MW}$$

The energy equation for the air flow that absorbs the energy is

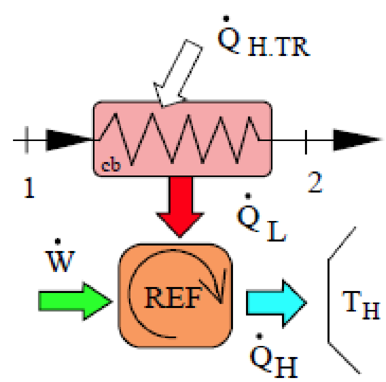
$$\dot{Q}_L = \dot{m}_{air}\, \Delta h = \dot{m}_{air}\, C_p\, \Delta T$$

$$\dot{m}_{air} = \frac{\dot{Q}_L}{C_p \Delta T} = \frac{1070 \times 1000}{1.004 \times 12} \frac{\text{MW}}{(\text{kJ/kg-K}) \times \text{K}} = \mathbf{88\ 811\ kg/s}$$

This is too large to make, so some cooling by liquid water or evaporative cooling should be used, see chapter 11.

5.32

A water cooler for drinking water should cool 25 L/h water from 18°C to 10°C while the water reservoir also gains 60 W from heat transfer. Assume a small refrigeration unit with a COP of 2.5 does the cooling. Find the total rate of cooling required and the power input to the unit.



The mass flow rate is

$$\dot{m} = \rho \dot{V} = \frac{25 \times 10^{-3}}{0.001002} \frac{1}{3600}\ \text{kg/s} = 6.93\ \text{g/s}$$

Energy equation for heat exchanger

$$\dot{Q}_L = \dot{m}(h_1 - h_2) + \dot{Q}_{H\ TR}$$

$$= \dot{m}\, C_P\, (T_1 - T_2) + \dot{Q}_{H\ TR}$$

$$= 6.93 \times 10^{-3}\ \text{kg/s} \times 4.18\ \text{kJ/kg-K} \times (18 - 10)\ \text{K} + 60\ \text{W}$$
$$= 291.8\ \text{W}$$

$$\beta = \text{COP} = \dot{Q}_L / \dot{W} \quad \Rightarrow \quad \dot{W} = \dot{Q}_L / \beta = 291.8 / 2.5 = \mathbf{116.7\ W}$$

5.36

Calculate the amount of work input a refrigerator needs to make ice cubes out of a tray of 0.25 kg liquid water at 10^oC. Assume the refrigerator has $\beta = 3.5$ and a motor-compressor of 750 W. How much time does it take if this is the only cooling load?

C.V. Water in tray. We neglect tray mass.

Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process : $P = \text{constant} = P_o$

$${}_1W_2 = \int P\, dV = P_o m(v_2 - v_1)$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(h_2 - h_1)$$

Tbl. B.1.1 : $h_1 = 41.99$ kJ/kg, Tbl. B.1.5 : $h_2 = -\ 333.6$ kJ/kg

$${}_1Q_2 = 0.25(-333.4 - 41.99\ ) = -\ 93.848 \text{ kJ}$$

Consider now refrigerator

$$\beta = Q_L/W$$

$$W = Q_L/\beta = -\ {}_1Q_2/\ \beta = 93.848/3.5 = \mathbf{26.81\ kJ}$$

For the motor to transfer that amount of energy the time is found as

$$W = \int \dot{W}\, dt = \dot{W}\, \Delta t$$

$$\Delta t = W/\dot{W} = (26.81 \times 1000)\text{J} /750 \text{ W} = \mathbf{35.75\ s}$$

Comment: We neglected a baseload of the refrigerator so not all the 750 W are available to make ice, also our coefficient of performance is very optimistic and finally the heat transfer is a transient process. All this means that it will take much more time to make ice-cubes.

5.45

An ideal (Carnot) heat engine has an efficiency of 40%. If the high temperature is raised 15% what is the new efficiency keeping the same low temperature?

Solution:

$$\eta_{TH} = W_{net} / Q_H = 1 - \frac{T_L}{T_H} = 0.4 \quad \Rightarrow \quad \frac{T_L}{T_H} = 0.6$$

so if T_H is raised 15% the new ratio becomes

$$\frac{T_L}{T_{H\,new}} = 0.6 / 1.15 = 0.5217 \quad \Rightarrow \quad \eta_{TH\,new} = 1 - 0.5217 = \mathbf{0.478}$$

5.49

A large heat pump should upgrade 4 MW of heat at 65°C to be delivered as heat at 145°C. What is the minimum amount of work (power) input that will drive this?

For the minimum work we assume a Carnot heat pump and $\dot{Q}_L = 4$ MW.

$$\beta_{HP} = \frac{\dot{Q}_H}{\dot{W}_{in}} = \frac{T_H}{T_H - T_L} = \frac{273.15 + 145}{145 - 65} = 5.227$$

$$\beta_{REF} = \beta_{HP} - 1 = \frac{\dot{Q}_L}{\dot{W}_{in}} = 4.227$$

Now we can solve for the work

$$\dot{W}_{in} = \dot{Q}_L / \beta_{REF} = 4/4.227 = \mathbf{0.946\ MW}$$

5.56

A refrigerator should remove 400 kJ from some food. Assume the refrigerator works in a Carnot cycle between -15^{o}C and 45^{o}C with a motor-compressor of 400 W. How much time does it take if this is the only cooling load?

Assume Carnot cycle refrigerator

$$\beta = \frac{\dot{Q}_L}{\dot{W}} = \dot{Q}_L / (\dot{Q}_H - \dot{Q}_L) \cong \frac{T_L}{T_H - T_L} = \frac{273 - 15}{45 - (-15)} = 4.3$$

This gives the relation between the low T heat transfer and the work as

$$\dot{Q}_L = \frac{Q}{t} = \beta\ \dot{W} = 4.3\ \dot{W}$$

$$t = \frac{Q}{\beta\ \dot{W}} = \frac{400 \times 1000}{4.3 \times 400}\ \frac{J}{W} = \mathbf{233}\ \text{s}$$

5.61

It is proposed to build a 1000-MW electric power plant with steam as the working fluid. The condensers are to be cooled with river water (see Fig. P5.61). The maximum steam temperature is 550°C, and the pressure in the condensers will be 10 kPa. Estimate the temperature rise of the river downstream from the power plant.

Solution:

$$\dot{W}_{NET} = 10^6 \text{ kW}, \quad T_H = 550°\text{C} = 823.3 \text{ K}$$

$$P_{COND} = 10 \text{ kPa} \rightarrow T_L = T_G\,(P = 10 \text{ kPa}) = 45.8°\text{C} = 319 \text{ K}$$

$$\eta_{TH\ CARNOT} = \frac{T_H - T_L}{T_H} = \frac{823.2 - 319}{823.2} = 0.6125$$

$$\Rightarrow \dot{Q}_{L\ MIN} = 10^6\left(\frac{1 - 0.6125}{0.6125}\right) = 0.6327 \times 10^6 \text{ kW}$$

But $\dot{m}_{H_2O} = \dfrac{60 \times 8 \times 10/60}{0.001} = 80\,000$ kg/s having an energy flow of

$$\dot{Q}_{L\ MIN} = \dot{m}_{H_2O}\,\Delta h = \dot{m}_{H_2O}\,C_{P\ LIQ\ H_2O}\,\Delta T_{H_2O\ MIN}$$

$$\Rightarrow \Delta T_{H_2O\ MIN} = \frac{\dot{Q}_{L\ MIN}}{\dot{m}_{H_2O} C_{P\ LIQ\ H_2O}} = \frac{0.6327 \times 10^6}{80000 \times 4.184}\,\frac{\text{kW}}{\text{kg/s} \times \text{kJ/kg-K}}$$

$$= \mathbf{1.9°C}$$

5.62

A certain solar-energy collector produces a maximum temperature of 100°C. The energy is used in a cyclic heat engine that operates in a 10°C environment. What is the maximum thermal efficiency? If the collector is redesigned to focus the incoming light, what should the maximum temperature be to produce a 25% improvement in engine efficiency?

Solution:

For $T_H = 100°C = 373.2$ K & $T_L = 283.2$ K

$$\eta_{th\ max} = \frac{T_H - T_L}{T_H} = \frac{90}{373.2} = \mathbf{0.241}$$

The improved efficiency is

$$\eta_{th\ max} = 0.241 \times 1.25 = 0.301$$

With the Carnot cycle efficiency

$$\eta_{th\ max} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H} = 0.301$$

Then

$$T_H = T_L / (1 - 0.301) = 405 \text{ K} = \mathbf{132°C}$$

5.79

A car engine with a thermal efficiency of 33% drives the air-conditioner unit (a refrigerator) besides powering the car and other auxiliary equipment. On a hot (35°C) summer day the A/C takes outside air in and cools it to 5°C sending it into a duct using 2 kW of power input and it is assumed to be half as good as a Carnot refrigeration unit. Find the rate of fuel (kW) being burned extra just to drive the A/C unit and its COP. Find the flow rate of cold air the A/C unit can provide.

$$\dot{W}_{extra} = \eta\, \dot{Q}_{H\ extra} \quad \Rightarrow \quad \dot{Q}_{H\ extra} = \dot{W}_{extra} / \eta = 2 \text{ kW} / 0.33 = \mathbf{6\ kW}$$

$$\beta = \frac{Q_L}{W_{IN}} = 0.5\ \beta_{Carnot} = 0.5\ \frac{T_L}{T_H - T_L} = 0.5\ \frac{5 + 273.15}{35 - 5} = 4.636$$

$$\dot{Q}_L = \beta\, \dot{W} = 4.636 \times 2 \text{ kW} = 9.272 \text{ kW} = \dot{m}_{air}\, C_{P\ air}\, \Delta T_{air}$$

$$\dot{m}_{air} = \dot{Q}_L / [C_{P\ air}\, \Delta T_{air}] = \frac{9.272 \text{ kW}}{1.004 \text{ kJ/kg-K} \times (35 - 5) \text{ K}} = \mathbf{0.308\ kg/s}$$