8.1 What is the maximum thermal efficiency of an engine that operates between a heat source at 850°C and a heat sink at 35°C?

Find: Maximum thermal efficiency η_{th} of the engine.

Known: Temperature of heat source T_H = 850°C, temperature of heat sink T_C = 35°C.

Assumptions: Engine operates on a Carnot cycle.

The maximum thermal efficiency of the engine can be found if we assume that the engine operates on a Carnot cycle, and use the definition of thermal efficiency of a Carnot engine:

$$\eta_{th} = 1 - \frac{T_C}{T_H} = 1 - \frac{(35 + 273.15)\ \text{K}}{(850 + 273.15)\ \text{K}} = 0.72564.$$

The maximum efficiency of the engine is 72.6%.

8.2 Ocean Thermal Energy Conversion (OTEC) plants use the temperature difference between cold water near the ocean floor and warmer surface water to run a heat engine. What is the maximum efficiency of such a plant operating between deep water at 5°C and surface water at 25°C?

Find: Maximum thermal efficiency η_{th} of the OTEC plants.

Known: Temperature of surface water T_H = 25°C, temperature of deep water T_C = 5°C.

Assumptions: Engine operates on a Carnot cycle.

The maximum thermal efficiency of the engine can be found under the assumption that the plants operate on a Carnot cycle, and use the definition of thermal efficiency of a Carnot engine:

$$\eta_{\text{th}} = 1 - \frac{T_C}{T_H} = 1 - \frac{278.15\ \text{K}}{298.15\ \text{K}} = 0.067080.$$

The maximum efficiency of the OTEC plants is 6.7%.

8.8 A car engine has a power output of 95 kW and a thermal efficiency of 25%. If gasoline gives a heat output of 47 MJ/kg when burned, find the rate of fuel consumption in kg/h.

Find: Rate of fuel consumption $\dot{m}$ in the car engine (kg/h).

Known: Power output $\dot{W}$ = 95 kW, thermal efficiency of engine η_{th} = 25%, enthalpy change for gasoline combustion Δh = 47 MJ/kg.

The rate of heat addition to the engine can be found with the definition of thermal efficiency,

$$\dot{Q}_H = \frac{\dot{W}}{\eta_{th,Carnot}} = \frac{95\ \text{kW}}{0.25} = 380\ \text{MW}$$

$$\dot{m}_{fuel} = \frac{380\ \text{kJ/s}}{47 \times 10^3\ \text{kJ/kg}} = 8.1 \times 10^{-3}\ \text{kg/s=29.1 kg/h}$$

Then the rate of consumption of fuel is

$$Q_H = \dot{m}\Delta h,$$

$$\dot{m} = \frac{380\ \text{kJ/s}}{47 \times 10^3\ \text{kJ/kg}} = 8.0851 \times 10^{-3}\ \text{kg/s} = 29.106\ \text{kg/h}.$$

The car engine consumes fuel at a rate of 29.1 kg/h.

8.12 A Carnot engine with a power output of 20 kW takes 60 kW of heat from a high temperature reservoir at 800 K. What is the temperature of the heat sink?

Find: Temperature T_C of the heat sink for the Carnot engine.

Known: Carnot engine, power output $\dot{W}$ = 20 kW, rate of heat input $\dot{Q}_H$ = 60 kW, temperature of heat source T_H = 800 K.

The temperature of the heat sink can be found from the definition of thermal efficiency of a Carnot cycle,

$$\eta_{th} = \frac{\dot{W}}{\dot{Q}_H} = 1 - \frac{T_C}{T_H},$$

$$T_C = T_H\left(1 - \frac{\dot{W}}{\dot{Q}_H}\right) = 800\ \text{K} \times \left(1 - \frac{20\ \text{kW}}{60\ \text{kW}}\right) = 533.33\ \text{K}.$$

The temperature of the heat sink is 533 K.

8.13 A nuclear power plant generates 80 MW when taking heat from a reactor at 615 K. Heat is discarded to a river at 298 K. If the thermal efficiency of the plant is 73% of the maximum possible value, how much heat is discarded to the river?

Find: Rate of heat rejected $\dot{Q}_C$ from nuclear plant into river.

Known: Power output of nuclear plant $\dot{W}$ = 80 MW, temperature of heat source T_H = 615 K, temperature of river T_C = 298 K, thermal efficiency of plant η_{th} = 73% of maximum possible value.

Assumptions: Temperature of the river remains constant.

The maximum possible efficiency of the nuclear plant would be if the cycle was a Carnot cycle,

$$\eta_{th,\max} = 1 - \frac{T_C}{T_H} = 1 - \frac{298\ \text{K}}{615\ \text{K}} = 0.515447.$$

then the actual efficiency of the nuclear plant can be found:

$$\eta_{th} = 0.73\eta_{th,\max} = 0.73 \times 0.515447 = 0.376276.$$

The heat input to the plant can be found using the definition of thermal efficiency,

$$\eta_{th} = \frac{\dot{W}}{\dot{Q}_H},$$

$$\dot{Q}_H = \frac{\dot{W}}{\eta_{th}} = \frac{80\ \text{MW}}{0.376276} = 212.610\ \text{MW},$$

and the heat rejected to the river can be found using an energy balance,

$$\dot{W} = \dot{Q}_H - \dot{Q}_C,$$

$$\dot{Q}_C = \dot{Q}_H - \dot{W} = 212.620\ \text{MW} - 80\ \text{MW} = 132.610\ \text{MW}.$$

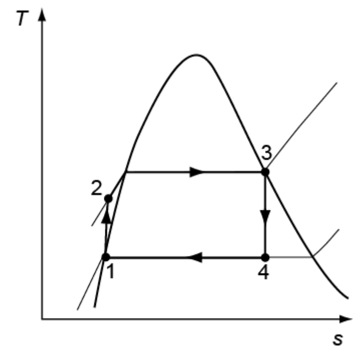
The nuclear plant rejects heat to the river at a rate of 132.6 MW.

9.1. Steam enters the turbine in an ideal Rankine cycle at 8 MPa and leaves at 10 kPa. What is the work done by the turbine per kilogram of steam?

Find: Work output w_t of the turbine per unit mass (kg) of steam.

Known: Ideal Rankine cycle using water, pressure of steam at turbine inlet $P_3 = 8$ MPa, pressure at turbine outlet $P_4 = 10$ kPa.

Properties: Specific enthalpy of saturated water at 8 MPa for gas $h_3 = 2758.0$ kJ/kg (A8*b*), specific entropy of saturated water at 8 MPa for gas $s_3 = 5.7432$ kJ/kgK (A8*b*), specific enthalpy for saturated water at 10 kPa for fluid $h_f = 191.83$ kJ/kg and has $h_g = 2584.7$ kJ/kg (A8*b*), specific entropy for saturated water at 10 kPa for fluid $s_f = 0.6493$ kJ/kgK and gas $s_g = 8.1502$ kJ/kgK (A8*b*).



The steam goes through an ideal Rankine cycle, so expansion through the turbine is isentropic and $s_4 = s_3 = 5.7432$ kJ/kgK. The quality of the steam leaving the turbine can then be found,

$$x_4 = \frac{s_4 - s_f}{s_g - s_f} = \frac{5.7432 \text{ kJ/kgK} - 0.6493 \text{ kJ/kgK}}{8.1502 \text{ kJ/kgK} - 0.6493 \text{ kJ/kgK}} = 0.679105.$$

The enthalpy at the turbine exit is then

$$h_4 = h_f + x_4(h_g - h_f),$$

$$h_4 = 191.83 \text{ kJ/kg} + 0.679105 \times \ (2584.7 \text{ kJ/kg} - 191.83 \text{ kJ/kg}) = 1816.84 \text{ kJ/kg}.$$

and the work output of the turbine can be found:

$$w_t = (h_3 - h_4) = 2758.0 \text{ kJ/kg} - 1816.84 \text{ kJ/kg} = 941.160 \text{ kJ/kg}.$$

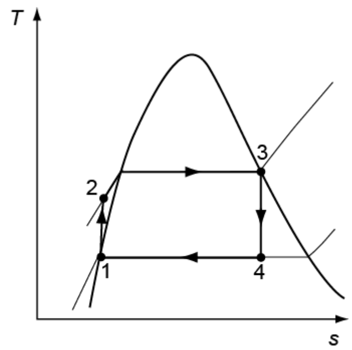
The turbine does 941.2 kJ/kg of work on the surroundings.

9.2. An ideal Rankine cycle has a condenser operating at a pressure of 50 kPa. If the steam quality at the outlet of the turbine is required to be 80%, what should the boiler pressure be?

Find: Boiler pressure $P_2 = P_3$ required to produce the necessary steam quality exiting the turbine.

Known: Ideal Rankine cycle using water, pressure of condenser $P_4 = P_1 = 50$ kPa, quality of steam exiting turbine $x_4 = 80\%$.

Properties: Specific entropy of saturated water at 50 kPa for fluid $s_f = 1.0910$ kJ/kgK and gas $s_g = 7.5939$ kJ/kgK (A8*b*).



The process occurs on an ideal Rankine cycle, so the pressure of the boiler can be found in state 2 or 3, so we will use the isentropic expansion through the turbine to find $s_3 = s_4$, using the given quality of steam exiting the turbine:

$$s_4 = s_f + x_4(s_g - s_f),$$

$$s_4 = 1.0910 \text{ kJ/kgK} + 0.80 \times (7.5939 \text{ kJ/kgK} - 1.0910 \text{ kJ/kgK}) = 6.2933 \text{ kJ/kgK}.$$

The pressure of the boiler can then be interpolated from Appendix 8*b* using entropy of saturated gas, since state 3 is saturated vapour:

$$\frac{P_3 - 2.25 \text{ MPa}}{2.50 \text{ MPa} - 2.25 \text{ MPa}} = \frac{6.2933 \text{ kJ/kgK} - 6.2575 \text{ kJ/kgK}}{6.2972 \text{ kJ/kgK} - 6.2575 \text{ kJ/kgK}},$$

$$P_3 = 2.2746 \text{ MPa}.$$

The boiler is required to be at a pressure of 2.27 MPa to achieve the desired quality.

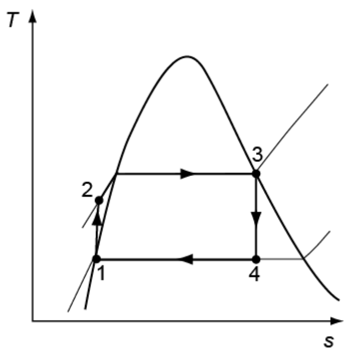
9.5. Two thermal reservoirs are available, a high temperature heat source at 350°C and a low temperature heat sink at 20°C. Calculate the maximum efficiency of *a*) a Carnot cycle, and *b*) an ideal Rankine cycle using water as a working fluid operating between these two reservoirs.

Find: Maximum efficiency *a*) η_C of a Carnot cycle, *b*) η_R of an ideal Rankine cycle.

Known: Temperature of high temperature reservoir T_H = 350°C, temperature of low temperature reservoir T_C = 20°C, Carnot cycle, ideal Rankine cycle using water.

Assumptions: Water is incompressible.

Properties: Saturation pressure of water at 350°C $P_2 = P_3$ = 16.513 MPa (A8*a*), specific enthalpy of saturated water at 350°C for gas h_3 = 2563.9 kJ/kg (A8*a*), specific entropy of saturated water at 20°C for gas s_3 = 5.2112 kJ/kgK (A8*a*), saturation pressure of water at 20°C $P_4 = P_1$ = 0.002339 MPa (A8*a*), specific enthalpy of saturated water at 20°C for fluid h_f = 83.96 kJ/kg and gas h_g = 2538.1 kJ/kg (A8*a*), specific entropy of saturated water at 20°C for fluid s_f = 0.2966 kJ/kgK and gas s_g = 8.6672 kJ/kgK (A8*a*), specific volume of saturated water at 20°C for fluid v_1 = 0.001002 m^3/kg (A8*a*).



a) The thermal efficiency of a Carnot cycle operating between these temperatures is

$$\eta_C = 1 - \frac{T_C}{T_H} = 1 - \frac{293.15\text{ K}}{623.15\text{ K}} = 0.52957.$$

b) The specific enthalpy at the turbine inlet is that of saturated water vapour at T_3 = 350°C, h_3 = 2563.9 kJ/kg. Since the cycle operates on an ideal Rankine cycle, expansion through the turbine is isentropic, so $s_4 = s_3$ = 5.2112 kJ/kgK and the quality of the steam exiting the turbine is

$$x_4 = \frac{s_4 - s_f}{s_g - s_f} = \frac{5.2112\text{ kJ/kgK} - 0.2966\text{ kJ/kgK}}{8.6672\text{ kJ/kgK} - 0.2966\text{ kJ/kgK}} = 0.58713.$$

The specific enthalpy at the turbine exit can then be found,

$$h_4 = h_f + x_4(h_g - h_4),$$

$$h_4 = 83.96\text{ kJ/kg} + 0.58713 \times (2538.1\text{ kJ/kg} - 83.96\text{ kJ/kg}) = 1524.9\text{ kJ/kg}.$$

The specific enthalpy at the condenser exit is that of saturated liquid water at T_1 = 20°C, $h_1 = h_f$ = 83.96 kJ/kg. The specific enthalpy of the fluid at the pump exit

$$h_2 = h_1 + w_p = h_1 + v_1(P_2 - P_1),$$

$$h_2 = 83.96 \text{ kJ/kgK} + 0.001002 \text{ m}^3/\text{kg} \times (16513 \text{ kPa} - 2.339 \text{ kPa}) = 100.50 \text{ kJ/kg}.$$

The thermal efficiency of a Rankine cycle is then

$$\eta_R = 1 - \frac{(h_4 - h_1)}{(h_3 - h_2)} = 1 - \frac{1524.9 \text{ kJ/kg} - 83.96 \text{ kJ/kg}}{2563.9 \text{ kJ/kg} - 100.50 \text{ kJ/kg}} = 0.41506.$$

The maximum efficiency of the *a*) Carnot cycle is 53.0%, and *b*) of the ideal Rankine cycle is 41.5%.