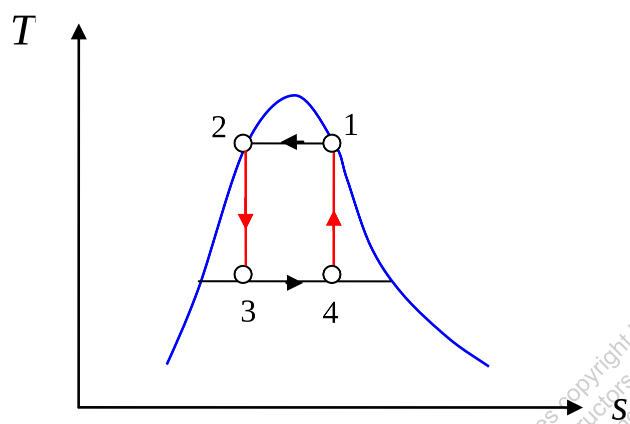
10-1-1 [OXC] A Carnot vapor refrigeration cycle uses R-134a as the working fluid. The refrigerant enters the condenser as saturated vapor at 30°C and leaves as saturated liquid. The evaporator operates at a temperature of -5°C. Determine, in kJ per kg of refrigerant flow, (a) the work input to the compressor, (b) the work developed by the turbine, (c) the heat transfer to the refrigerant passing through the evaporator and (d) the coefficient of performance of the cycle. (e) What-if Scenario: What would the answer in part (d) and (c) be if R-134a were replaced with R-12?

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@30°\text{C}} = 266.10\frac{\text{kJ}}{\text{kg}};\; s_1 = s_{g@30°\text{C}} = 0.9162\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $T_2 = T_1, x_2$):

$$h_2 = h_{f@30°\text{C}} = 92.81\frac{\text{kJ}}{\text{kg}};\; s_2 = s_{f@30°\text{C}} = 0.3446\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-3 (given $T_3, s_3 = s_2$):

$$h_{f@-5°\text{C}} = 44.34\frac{\text{kJ}}{\text{kg}};\; h_{fg@-5°\text{C}} = 202.02\frac{\text{kJ}}{\text{kg}};\; s_{f@-5°\text{C}} = 0.1764\frac{\text{kJ}}{\text{kg}\cdot\text{K}};\; s_{fg@-5°\text{C}} = 0.7533\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$x_3 = \frac{s_3 - s_{f@-5°\text{C}}}{s_{fg@-5°\text{C}}} = \frac{0.3446 - 0.1764}{0.7533} = 0.223$$

$$h_3 = h_{f@-5°\text{C}} + x_3 h_{fg@-5°\text{C}} = 44.34 + (0.223)(202.02) = 89.39\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $T_4 = T_3, s_4 = s_1$):

$$h_{f@-5°C} = 44.34\frac{kJ}{kg};\; h_{fg@-5°C} = 202.02\frac{kJ}{kg};\; s_{f@-5°C} = 0.1764\frac{kJ}{kg\cdot K};\; s_{fg@-5°C} = 0.7533\frac{kJ}{kg\cdot K}$$

$$x_4 = \frac{s_4 - s_{f@-5°C}}{s_{fg@-5°C}} = \frac{0.9162 - 0.1764}{0.7533} = 0.982$$

$$h_4 = h_{f@-5°C} + x_4 h_{fg@-5°C} = 44.34 + (0.982)(202.02) = 242.72\frac{kJ}{kg}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $q_H = h_1 - h_2 = 266.10 - 92.81 = 173.29\frac{kJ}{kg}$

Device-B (2-3): $w_T = h_2 - h_3 = 92.81 - 89.39 = 3.42\frac{kJ}{kg}$

Device-C (3-4): $q_C = h_4 - h_3 = 242.72 - 89.39 = 153.33\frac{kJ}{kg}$

Device-D (4-1): $w_C = h_1 - h_4 = 266.10 - 242.72 = 23.38\frac{kJ}{kg}$

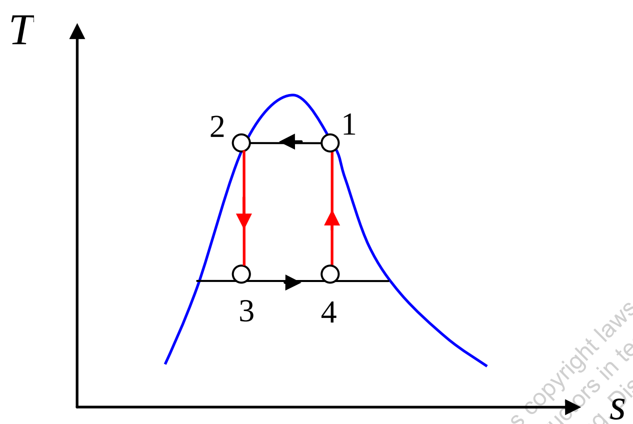
Therefore, the COP can be obtained as

$$COP_{R,Carnot} = \frac{q_C}{q_H - q_C} = \frac{153.33}{173.29 - 153.33} = 7.68$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-2 [OXV] Refrigerant R-22 is the working fluid in a Carnot vapor refrigeration cycle for which the evaporator temperature is 0^oC. Saturated vapor enters the condenser at 40^oC, and saturated liquid exits at the same temperature. The mass flow rate of refrigerant is 4 kg/min. Determine (a) the rate of heat transfer (Q_C) to the refrigerant passing through the evaporator, (b) the net power input (W_{net}) (magnitude only) to the cycle in kW and (c) the coefficient of performance (COP_R). (d) What-if Scenario: What would the answer in part (a) be if the mass flow rate were 1 kg/min?

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@40°C} = 261.15\frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@40°C} = 0.8746\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $T_2 = T_1, x_2$):

$$h_2 = h_{f@40°C} = 94.27\frac{\text{kJ}}{\text{kg}};\ s_2 = s_{f@40°C} = 0.3417\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-3 (given $T_3, s_3 = s_2$):

$$h_{f@0°C} = 44.59\frac{\text{kJ}}{\text{kg}};\ h_{fg@0°C} = 205.36\frac{\text{kJ}}{\text{kg}};\ s_{f@0°C} = 0.1751\frac{\text{kJ}}{\text{kg}\cdot\text{K}};\ s_{fg@0°C} = 0.7518\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$x_3 = \frac{s_3 - s_{f@0°C}}{s_{fg@0°C}} = \frac{0.3417 - 0.1751}{0.7518} = 0.222$$

$$h_3 = h_{f@0°C} + x_3 h_{fg@0°C} = 44.59 + (0.222)(205.36) = 90.18\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $T_4 = T_3, s_4 = s_1$):

$$h_{f@0°C} = 44.59\,\frac{\text{kJ}}{\text{kg}};\; h_{fg@0°C} = 205.36\,\frac{\text{kJ}}{\text{kg}};\; s_{f@0°C} = 0.1751\,\frac{\text{kJ}}{\text{kg}\cdot\text{K}};\; s_{fg@0°C} = 0.7518\,\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$x_4 = \frac{s_4 - s_{f@0°C}}{s_{fg@0°C}} = \frac{0.8746 - 0.1751}{0.7518} = 0.930$$

$$h_4 = h_{f@0°C} + x_4 h_{fg@0°C} = 44.59 + (0.930)(205.36) = 235.57\,\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{Q}_H = \dot{m}(h_1 - h_2) = (0.067)(261.15 - 94.27) = 11.18\text{ kW}$

Device-B (2-3): $\dot{W}_T = \dot{m}(h_2 - h_3) = (0.067)(94.27 - 90.18) = 0.27\text{ kW}$

Device-C (3-4): $\dot{Q}_C = \dot{m}(h_4 - h_3) = (0.067)(235.57 - 90.18) = 9.74\text{ kW}$

Device-D (4-1): $\dot{W}_C = \dot{m}(h_1 - h_4) = (0.067)(261.15 - 235.57) = 1.71\text{ kW}$

Therefore, the COP can be obtained as

$$\text{COP}_{\text{R,Carnot}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C} = \frac{9.74}{11.18 - 9.74} = 6.76$$

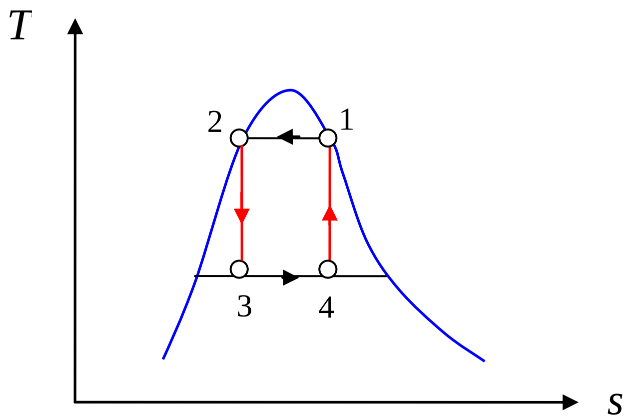
The magnitude of net power input

$$\left|\dot{W}_{\text{net}}\right| = \left|\dot{W}_T - \dot{W}_C\right| = |0.27 - 1.71| = 1.44\text{ kW}$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-3 [OXQ] A Carnot vapor refrigeration cycle operates between thermal reservoirs at 40°F and 100°F. For (a) R-12, (b) R-134a, (c) water, (d) R-22 and (e) ammonia as the working fluid, determine the operating pressures in the condenser and evaporator, in lbf/in^2, and the coefficient of performance.

SOLUTION



For R-12 as the working fluid:

State-1 (given T_1, x_1):

$$h_1 = h_{g@100°F} = 87.03\frac{\text{Btu}}{\text{lbm}};\ s_1 = s_{g@100°F} = 0.1632\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

$$p_{\text{sat}@100°F} = 131.83\ \text{psia}\ (\text{condenser})$$

State-2 (given $T_2 = T_1, x_2$):

$$h_2 = h_{f@100°F} = 31.11\frac{\text{Btu}}{\text{lbm}};\ s_2 = s_{f@100°F} = 0.0632\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

State-3 (given $T_3, s_3 = s_2$):

$$h_{f@40°F} = 17.27\frac{\text{Btu}}{\text{lbm}};\ h_{fg@40°F} = 64.17\frac{\text{Btu}}{\text{lbm}};\ s_{f@40°F} = 0.0375\frac{\text{Btu}}{\text{lbm}\cdot\text{R}};\ s_{fg@40°F} = 0.1282\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

$$x_3 = \frac{s_3 - s_{f@40°F}}{s_{fg@40°F}} = \frac{0.0632 - 0.0375}{0.1282} = 0.200$$

$$h_3 = h_{f@40°F} + x_3 h_{fg@40°F} = 17.27 + (0.200)(64.17) = 30.10\frac{\text{Btu}}{\text{lbm}}$$

$$p_{\text{sat}@40°F} = 51.64\ \text{psia}\ (\text{evaporator})$$

State-4 (given $T_4 = T_3, s_4 = s_1$):

$$h_{f@40°F} = 17.27\frac{\text{Btu}}{\text{lbm}};\ h_{fg@40°F} = 64.17\frac{\text{Btu}}{\text{lbm}};\ s_{f@40°F} = 0.0375\frac{\text{Btu}}{\text{lbm}\cdot\text{R}};\ s_{fg@40°F} = 0.1282\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

$$x_4 = \frac{s_4 - s_{f@40°F}}{s_{fg@40°F}} = \frac{0.1632 - 0.0375}{0.1282} = 0.981$$

$$h_4 = h_{f@40°F} + x_4 h_{fg@40°F} = 17.27 + (0.981)(64.17) = 80.22\frac{\text{Btu}}{\text{lbm}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $q_H = h_1 - h_2 = 87.03 - 31.11 = 55.92\frac{\text{Btu}}{\text{lbm}}$

Device-B (2-3): $w_T = h_2 - h_3 = 31.11 - 30.10 = 1.01\frac{\text{Btu}}{\text{lbm}}$

Device-C (3-4): $q_C = h_4 - h_3 = 80.22 - 30.10 = 50.12\frac{\text{Btu}}{\text{lbm}}$

Device-D (4-1): $w_C = h_1 - h_4 = 87.03 - 80.22 = 6.81\frac{\text{Btu}}{\text{lbm}}$

Therefore, the COP can be obtained as

$$\text{COP}_{\text{R,Carnot}} = \frac{q_C}{q_H - q_C} = \frac{50.12}{55.92 - 50.12} = 8.64$$

Note that the COP is more precisely determined via the use of TESTcalcs since the manual calculations round and are less precise, skewing enthalpy values. Alternatively, using the temperatures for a more precise value, an answer is obtained that agrees more closely with the TESTcalc:

$$\text{COP}_{\text{R,Carnot}} = \frac{T_C}{T_H - T_C} = \frac{499.67}{559.67 - 499.67} = 8.33$$

Using the same process and the TEST-code on thermofluids.net, the process it repeated for the other working fluids:

R-134a:
Evaporator: 138.87 lbf/in^2
Condenser: 49.87 lbf/in^2
COP: 8.33

Water:
Evaporator: 0.95 lbf/in^2
Condenser: 0.12 lbf/in^2
COP: 8.33

R-22:
Evaporator: 210.54 lbf/in^2

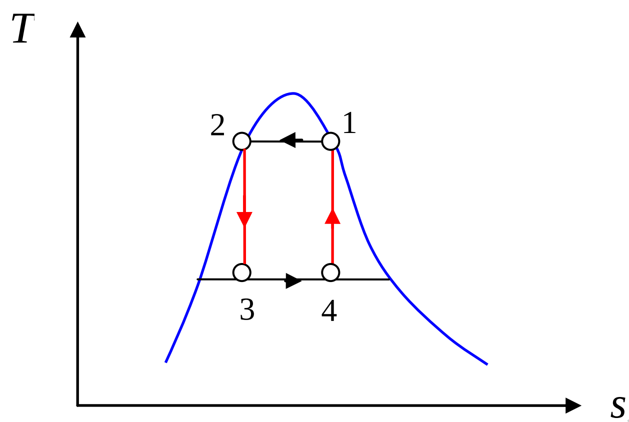
Condenser: 83.15 lbf/in^2
COP: 8.33

Ammonia:
Evaporator: 211.87 lbf/in^2
Condenser: 73.28 lbf/in^2
COP: 8.33

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-4 [OXT] A Carnot vapor refrigeration cycle is used to maintain a cold region at 0°F where the ambient temperature is 75°F. Refrigerant R-134a enters the condenser as saturated vapor at 100 lbf/in^2 and leaves as saturated liquid at the same pressure. The evaporator pressure is 20 lbf/in^2. The mass flow rate of refrigerant is 12 lbm/s. Calculate (a) the compressor and turbine power, in Btu/min and (b) the coefficient of performance.

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@100\text{lbf/in}^2} = 113.56\frac{\text{Btu}}{\text{lbm}};\; s_1 = s_{g@100\text{lbf/in}^2} = 0.2191\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

State-2 (given $p_2 = p_1, x_2$):

$$h_2 = h_{f@100\text{lbf/in}^2} = 37.51\frac{\text{Btu}}{\text{lbm}};\; s_2 = s_{f@100\text{lbf/in}^2} = 0.0780\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

State-3 (given $p_3, s_3 = s_2$):

$$h_{f@20\text{lbf/in}^2} = 11.03\frac{\text{Btu}}{\text{lbm}};\; h_{fg@20\text{lbf/in}^2} = 91.10\frac{\text{Btu}}{\text{lbm}};\; s_{f@20\text{lbf/in}^2} = 0.0251\frac{\text{Btu}}{\text{lbm}\cdot\text{R}};\; s_{fg@20\text{lbf/in}^2} = 0.1994\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

$$x_3 = \frac{s_3 - s_{f@20\text{lbf/in}^2}}{s_{fg@20\text{lbf/in}^2}} = \frac{0.0780 - 0.0251}{0.1994} = 0.265$$

$$h_3 = h_{f@20\text{lbf/in}^2} + x_3 h_{fg@20\text{lbf/in}^2} = 11.03 + (0.265)(91.10) = 35.17\frac{\text{Btu}}{\text{lbm}}$$

State-4 (given $p_4 = p_3, s_4 = s_1$):

$$h_{f@20\text{lbf/in}^2} = 11.03\frac{\text{Btu}}{\text{lbm}};\ h_{fg@20\text{lbf/in}^2} = 91.10\frac{\text{Btu}}{\text{lbm}};\ s_{f@20\text{lbf/in}^2} = 0.0251\frac{\text{Btu}}{\text{lbm}\cdot\text{R}};\ s_{fg@20\text{lbf/in}^2} = 0.1994\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

$$x_4 = \frac{s_4 - s_{f@20\text{lbf/in}^2}}{s_{fg@20\text{lbf/in}^2}} = \frac{0.2191 - 0.0251}{0.1994} = 0.973$$

$$h_4 = h_{f@20\text{lbf/in}^2} + x_4 h_{fg@20\text{lbf/in}^2} = 11.03 + (0.973)(91.10) = 99.67\frac{\text{Btu}}{\text{lbm}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{Q}_H = \dot{m}(h_1 - h_2) = (12)(113.56 - 37.51) = 912.60\frac{\text{Btu}}{\text{s}} = 54756.00\frac{\text{Btu}}{\text{min}}$

Device-B (2-3): $\dot{W}_T = \dot{m}(h_2 - h_3) = (12)(37.51 - 35.17) = 28.08\frac{\text{Btu}}{\text{s}} = 1684.80\frac{\text{Btu}}{\text{min}}$

Device-C (3-4): $\dot{Q}_C = \dot{m}(h_4 - h_3) = (12)(99.67 - 35.17) = 774.00\frac{\text{Btu}}{\text{s}} = 46440\frac{\text{Btu}}{\text{min}}$

Device-D (4-1): $\dot{W}_C = \dot{m}(h_1 - h_4) = (12)(113.56 - 99.67) = 116.68\frac{\text{Btu}}{\text{s}} = 10000.80\frac{\text{Btu}}{\text{min}}$

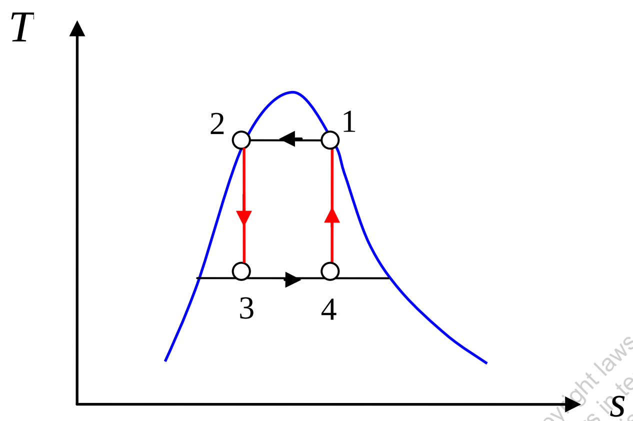
Therefore, the COP can be obtained as

$$\text{COP}_{\text{R,Carnot}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C} = \frac{774.00}{912.60 - 774.00} = 5.58$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-5 [OXY] A steady-flow Carnot refrigeration cycle uses refrigerant-134a as the working fluid. The refrigerant changes from saturated vapor to saturated liquid at 30°C in the condenser as it rejects heat. The evaporator pressure is 120 kPa. (a) Show the cycle on a *T*-*s* diagram relative to saturation lines, determine (b) the coefficient of performance (COP_R), (c) the amount of heat absorbed from the refrigerated space per kg of flow (q_C) and (d) the net work input per kg of flow (w_{net}).

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@30°C} = 266.10\frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@30°C} = 0.9162\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $T_2 = T_1, x_2$):

$$h_2 = h_{f@30°C} = 92.81\frac{\text{kJ}}{\text{kg}};\ s_2 = s_{f@30°C} = 0.3446\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-3 (given $T_3, s_3 = s_2$):

$$h_{f@120\text{kPa}} = 21.61\frac{\text{kJ}}{\text{kg}};\ h_{fg@120\text{kPa}} = 213.94\frac{\text{kJ}}{\text{kg}};\ s_{f@120\text{kPa}} = 0.0891\frac{\text{kJ}}{\text{kg}\cdot\text{K}};\ s_{fg@120\text{kPa}} = 0.8536\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$x_3 = \frac{s_3 - s_{f@120\text{kPa}}}{s_{fg@120\text{kPa}}} = \frac{0.3446 - 0.0891}{0.8536} = 0.299$$

$$h_3 = h_{f@120\text{kPa}} + x_3 h_{fg@120\text{kPa}} = 21.61 + (0.299)(213.94) = 85.58\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $T_4 = T_3, s_4 = s_1$):

$$h_{f@120\text{kPa}} = 21.61\frac{\text{kJ}}{\text{kg}};\ h_{fg@120\text{kPa}} = 213.94\frac{\text{kJ}}{\text{kg}};\ s_{f@120\text{kPa}} = 0.0891\frac{\text{kJ}}{\text{kg}\cdot\text{K}};\ s_{fg@120\text{kPa}} = 0.8536\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$x_4 = \frac{s_4 - s_{f@120\text{kPa}}}{s_{fg@120\text{kPa}}} = \frac{0.9162 - 0.0891}{0.8536} = 0.969$$

$$h_4 = h_{f@120\text{kPa}} + x_4 h_{fg@120\text{kPa}} = 21.61 + (0.969)(213.94) = 228.92\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $q_H = h_1 - h_2 = 266.10 - 92.81 = 173.29\frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $w_T = h_2 - h_3 = 92.81 - 85.58 = 7.23\frac{\text{kJ}}{\text{kg}}$

Device-C (3-4): $q_C = h_4 - h_3 = 228.92 - 85.58 = 143.34\frac{\text{kJ}}{\text{kg}}$

Device-D (4-1): $w_C = h_1 - h_4 = 266.10 - 228.92 = 37.18\frac{\text{kJ}}{\text{kg}}$

Therefore, the COP can be obtained as

$$\text{COP}_{\text{R,Carnot}} = \frac{q_C}{q_H - q_C} = \frac{143.34}{173.29 - 143.34} = 4.79$$

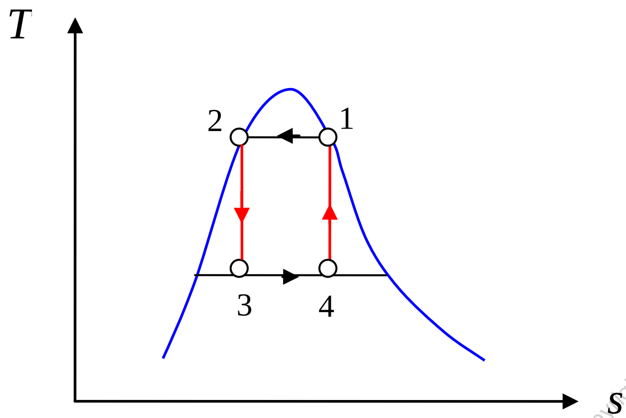
The magnitude of net work input per unit mass

$$|w_{\text{net}}| = |w_T - w_C| = |7.23 - 37.18| = 29.95\frac{\text{kJ}}{\text{kg}}$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-6 [OXF] Refrigerant R-134a enters the condenser of a steady-flow Carnot refrigerator as a saturated vapor at 100 psia, and it leaves as saturated liquid. The heat absorption from the refrigerated space takes place at a pressure of 30 psia and the mass flow rate is 1 kg/s. (a) Show the cycle on a *T-s* diagram relative to saturation lines, determine (b) the coefficient of performance (COP_R), (c) the quality at the beginning of the heat-absorption process and (d) the net work input.

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@100\text{psia}} = 113.56\frac{\text{Btu}}{\text{lbm}};\ s_1 = s_{g@100\text{psia}} = 0.2191\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

State-2 (given $p_2 = p_1, x_2$):

$$h_2 = h_{f@100\text{psia}} = 37.51\frac{\text{Btu}}{\text{lbm}};\ s_2 = s_{f@100\text{psia}} = 0.0780\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

State-3 (given $p_3, s_3 = s_2$):

$$h_{f@30\text{psia}} = 16.58\frac{\text{Btu}}{\text{lbm}};\ h_{fg@30\text{psia}} = 88.19\frac{\text{Btu}}{\text{lbm}};\ s_{f@30\text{psia}} = 0.0370\frac{\text{Btu}}{\text{lbm}\cdot\text{R}};\ s_{fg@30\text{psia}} = 0.1857\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

$$x_3 = \frac{s_3 - s_{f@30\text{psia}}}{s_{fg@30\text{psia}}} = \frac{0.0780 - 0.0370}{0.1857} = 0.221$$

$$h_3 = h_{f@30\text{psia}} + x_3 h_{fg@30\text{psia}} = 16.58 + (0.221)(88.19) = 36.07\frac{\text{Btu}}{\text{lbm}}$$

State-4 (given $p_4 = p_3, s_4 = s_1$):

$$h_{f@30\text{psia}} = 16.58\frac{\text{Btu}}{\text{lbm}};\ h_{fg@30\text{psia}} = 88.19\frac{\text{Btu}}{\text{lbm}};\ s_{f@30\text{psia}} = 0.0370\frac{\text{Btu}}{\text{lbm}\cdot\text{R}};\ s_{fg@30\text{psia}} = 0.1857\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

$$x_4 = \frac{s_4 - s_{f@30\text{psia}}}{s_{fg@30\text{psia}}} = \frac{0.2191 - 0.0370}{0.1857} = 0.981$$

$$h_4 = h_{f@30\text{psia}} + x_4 h_{fg@30\text{psia}} = 16.58 + (0.981)(88.19) = 103.09\frac{\text{Btu}}{\text{lbm}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{Q}_H = \dot{m}(h_1 - h_2) = (2.205)(113.56 - 37.51) = 167.69\frac{\text{Btu}}{\text{s}} = 176.92\text{ kW}$

Device-B (2-3): $\dot{W}_T = \dot{m}(h_2 - h_3) = (2.205)(37.51 - 36.07) = 3.18\frac{\text{Btu}}{\text{s}} = 3.36\text{ kW}$

Device-C (3-4): $\dot{Q}_C = \dot{m}(h_4 - h_3) = (2.205)(103.09 - 36.07) = 147.78\frac{\text{Btu}}{\text{s}} = 155.92\text{ kW}$

Device-D (4-1): $\dot{W}_C = \dot{m}(h_1 - h_4) = (2.205)(113.56 - 103.09) = 23.07\frac{\text{Btu}}{\text{s}} = 24.34\text{ kW}$

Therefore, the COP can be obtained as

$$\text{COP}_{\text{R,Carnot}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C} = \frac{147.78}{167.69 - 147.78} = 7.42$$

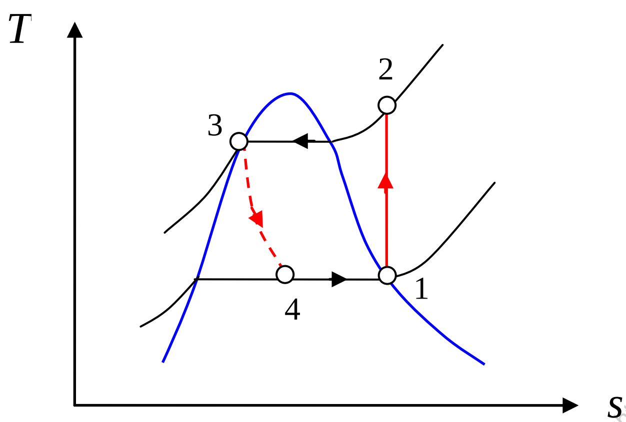
The magnitude of net power input

$$\left|\dot{W}_{\text{net}}\right| = \left|\dot{W}_T - \dot{W}_C\right| = \left|3.36 - 24.34\right| = 20.98\text{ kW}$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-7 [OXD] A refrigerator uses R-12 as the working fluid operates on an ideal vapor compression refrigeration cycle between 0.15 MPa and 1 MPa. If the mass flow rate is 0.04 kg/s, determine (a) the tonnage of the system, (b) compressor power and (c) the COP_R. (d) What-if Scenario: What would the COP be if R-12 were replaced with R-134a, a more environmentally benign refrigerant?

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.15\text{MPa}} = 178.67 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = s_{g@0.15\text{MPa}} = 0.7088 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 212.67 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@1\text{MPa}} = 76.26 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 76.26 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}(h_2 - h_1) = (0.04)(212.67 - 178.67) = 1.36 \text{ kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.04)(212.67 - 76.26) = 5.46 \text{ kW}$

Device-C (4-1): $\dot{Q}_C = \dot{m}(h_1 - h_4) = (0.04)(178.67 - 76.26) = 4.10 \text{ kW} = 1.165 \text{ ton}$

Therefore, the COP can be obtained as

$$\mathrm{COP_R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{4.10}{1.36} = 3.01$$

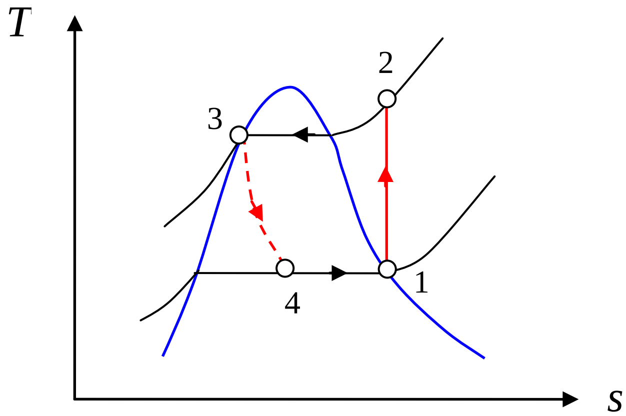
The magnitude of net power input

$$\left|\dot{W}_{\mathrm{net}}\right| = \left|\dot{W}_T - \dot{W}_C\right| = \left|3.36 - 24.34\right| = 20.98\ \mathrm{kW}$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-8 [OXM] A refrigerator uses R-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.15 MPa and 1 MPa. For a cooling load of 10 kW, determine the mass flow rate of the refrigerant through the evaporator.

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.15\text{MPa}} = 238.79 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = s_{g@0.15\text{MPa}} = 0.9382 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 278.41 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@1\text{MPa}} = 106.61 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 106.61 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 278.41 - 238.79 = 39.62 \frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_H = h_2 - h_3 = 278.41 - 106.61 = 171.80 \frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_C = h_1 - h_4 = 238.79 - 106.60 = 132.19 \frac{\text{kJ}}{\text{kg}}$

Given the cooling load, the mass flow through the evaporator

$$\dot{m} = \frac{\dot{Q}_C}{q_C} = \frac{10}{132.19} = 0.076 \frac{\text{kg}}{\text{s}}$$

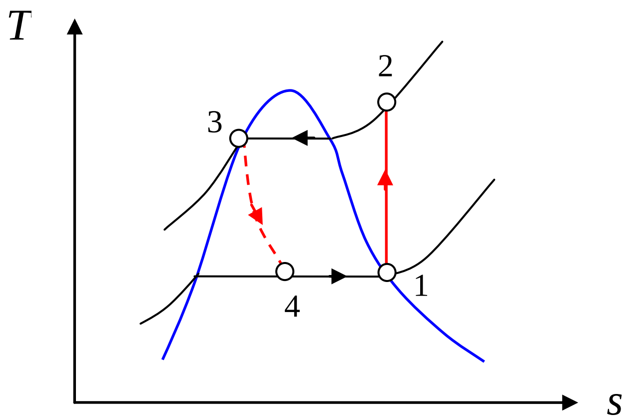
The magnitude of net power input

$$|\dot{W}_{\text{net}}| = |\dot{W}_T - \dot{W}_C| = |3.36 - 24.34| = 20.98 \text{ kW}$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-9 [OXJ] Refrigerant R-134a enters the compressor of an ideal vapor-compression refrigeration system as saturated vapor at -10°C and leaves the condenser as saturated liquid at 35°C. For a cooling capacity of 20 kW, determine (a) the mass flow rate, (b) the compressor power in kW and (c) the coefficient of performance (COP_R).

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@-10°C} = 243.30\frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@-10°C} = 0.9328\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$p_1 = p_{\text{sat}@-10°C} = 201.70 \text{ kPa}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 274.16\frac{\text{kJ}}{\text{kg}}$$

State-3 (given T_3, x_3):

$$h_3 = h_{f@35°C} = 100.12\frac{\text{kJ}}{\text{kg}}$$

$$p_3 = p_{\text{sat}@35°C} = 887.60 \text{ kPa}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 100.12\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 274.16 - 243.30 = 30.86\frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_H = h_2 - h_3 = 274.16 - 100.12 = 174.04 \dfrac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_C = h_1 - h_4 = 243.30 - 100.12 = 143.18 \dfrac{\text{kJ}}{\text{kg}}$

Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{q_C}{w_C} = \frac{143.18}{30.86} = 4.64$$

Given the cooling load, the mass flow through the evaporator

$$\dot{m} = \frac{\dot{Q}_C}{q_C} = \frac{20}{143.18} = 0.140 \frac{\text{kg}}{\text{s}}$$

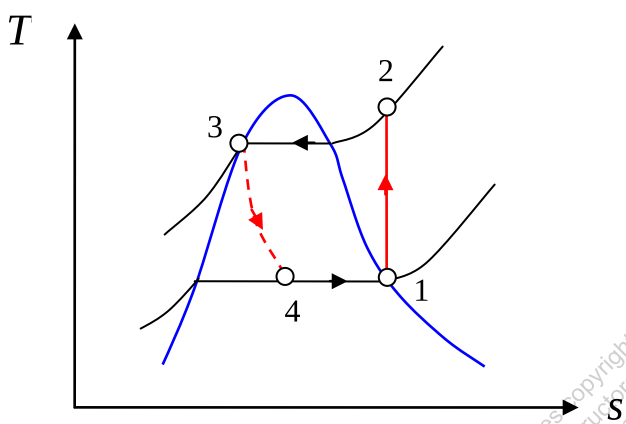
The compressor power

$$\dot{W}_C = \dot{m} w_C = (0.140)(30.86) = 4.32 \text{ kW}$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-10 [OXW] A refrigerator uses R-12 as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.15 MPa and 0.8 MPa. The mass flow rate of the refrigerant is 0.04 kg/s. (a) Show the cycle on a T-s diagram with respect to saturation lines. Determine (b) the rate of heat removal from the refrigerated space, (c) the power input to the compressor, (d) the rate of heat rejection to the environment and (e) the coefficient of performance (COP_R). (f) What-if Scenario: What would the answer in part (b) and (c) be if the mass flow rate were doubled?

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.15\text{MPa}} = 178.67 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = s_{g@0.15\text{MPa}} = 0.7088 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 208.31 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@0.8\text{MPa}} = 67.30 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 67.30 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}(h_2 - h_1) = (0.04)(208.31 - 178.67) = 1.19 \text{ kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.04)(208.31 - 67.30) = 5.64 \text{ kW}$

Device-C (4-1): $\dot{Q}_C = \dot{m}\left(h_1 - h_4\right) = \left(0.04\right)\left(178.67 - 67.30\right) = 4.45\ \text{kW}$

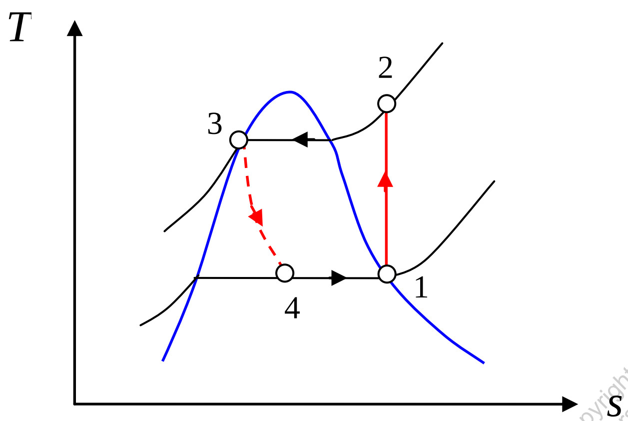
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{4.45}{1.19} = 3.74$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-11 [OCR] An ideal vapor-compression refrigeration cycle operates at steady state with Refrigerant R-134a as the working fluid. Saturated vapor enters the compressor at -5°C, and saturated liquid leaves the condenser at 35°C. The mass flow rate of refrigerant is 5 kg/min. Determine (a) the compressor power in kW, (b) the refrigerating capacity in tons and (c) the coefficient of performance (COP_R). (d) What-if Scenario: What would the COP be if the condenser operated at 50°C?

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@-5°C} = 246.36 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = s_{g@-5°C} = 0.9297 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 273.19 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given T_3, x_3):

$$h_3 = h_{f@35°C} = 100.12 \frac{\text{kJ}}{\text{kg}}$$

$$p_3 = p_{\text{sat}@35°C} = 887.60 \text{ kPa}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 100.12 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}(h_2 - h_1) = (0.083)(273.19 - 246.36) = 2.23 \text{ kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.083)(273.19 - 100.12) = 14.36 \text{ kW}$

Device-C (4-1): $\dot{Q}_C = \dot{m}\left(h_1 - h_4\right) = \left(0.083\right)\left(246.36 - 100.12\right) = 12.14 \text{ kW} = 3.45 \text{ ton}$

Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{12.14}{2.23} = 5.44$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

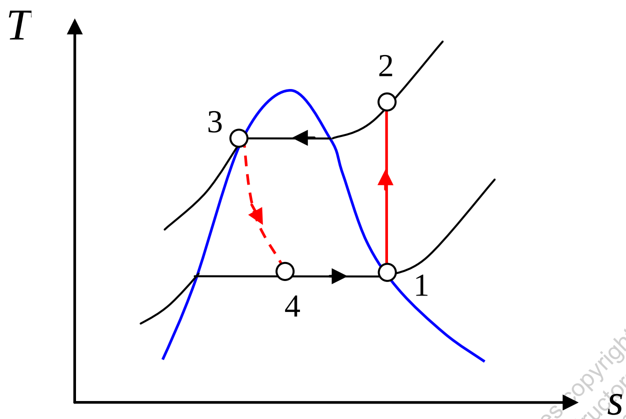
10-1-12 [OCO] Repeat problem 10-1-11 [OCR] by varying the condenser exit temperature from 0^oC through 60^oC. Plot how the COP and the Carnot COP (based on maximum and minimum temperature of the cycle) vary with the condenser exit temperature.

SOLUTION

Use the PC vapor-compression cycle TESTcalc to find the COP and Carnot COP at the condenser exit temperature varies in the given range. Then input the values from the TESTcalc into an Excel spreadsheet to generate a plot of the parametric study.

10-1-13 [OCS] A large refrigeration plant is to be maintained at -18^{o}C, and it requires refrigeration at a rate of 200 kW. The condenser of the plant is to be cooled by liquid water, which experiences a temperature rise of 8^{o}C as it flows over the coils of the condenser. Assuming the plant operates on the ideal vapor-compression cycle using Refrigerant-134a as the working fluid between the pressure limits of 120 kPa and 700 kPa, determine (a) the mass flow rate of the refrigerant, (b) the power input to the compressor and (c) the mass flow rate of cooling water.

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@120\text{kPa}} = 235.55\frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@120\text{kPa}} = 0.9427\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 272.18\frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@120\text{kPa}} = 87.99\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 87.99\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 272.18 - 235.55 = 36.63\frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_H = h_2 - h_3 = 272.18 - 87.99 = 184.19 \frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_C = h_1 - h_4 = 235.55 - 87.99 = 147.56 \frac{\text{kJ}}{\text{kg}}$

The mass flow rate of the refrigerant

$$\dot{m} = \frac{\dot{Q}_C}{q_C} = \frac{200}{147.56} = 1.355 \frac{\text{kg}}{\text{s}}$$

The power input to the compressor

$$\dot{W}_C = \dot{m} w_C = (1.355)(36.63) = 49.63 \text{ kW}$$

The mass flow rate of the cooling water

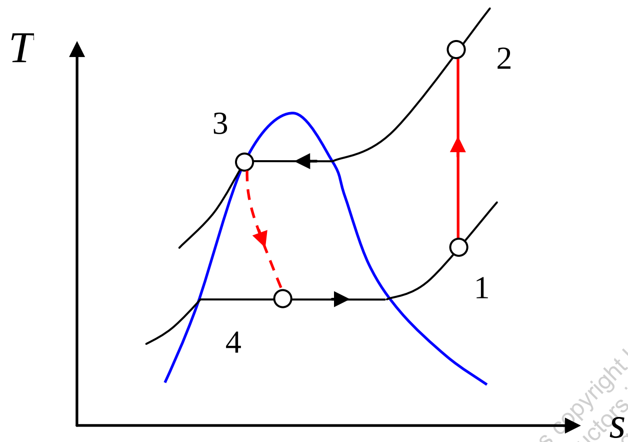
$$\dot{Q}_H = \dot{m} q_H = (1.355)(184.19) = 249.58 \text{ kW}$$

$$\dot{m}_W = \frac{\dot{Q}_H}{c_p \Delta T} = \frac{249.58}{(4.184)(8)} = 7.456 \frac{\text{kg}}{\text{s}}$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-14 [OCH] An ideal vapor-compression refrigeration system operates at steady state with Refrigerant R-12 as the working fluid. Superheated vapor enters the compressor at 25 lbf/in^2, 10^{o}F and saturated liquid leaves the condenser at 200 lbf/in^2. The refrigeration capacity is 5 tons. Determine (a) the compressor power in horsepower, (b) the rate of heat transfer from the working fluid passing through the condenser, in Btu/min, and (c) the coefficient of performance (COP_R). (d) What-if Scenario: What would the compressor power be if the refrigeration capacity were 10 tons?

SOLUTION



State-1 (given p_1, T_1):

$$h_1 = 78.64 \frac{\text{Btu}}{\text{lbm}}; \; s_1 = 0.1710 \frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 95.05 \frac{\text{Btu}}{\text{lbm}}$$

State-3 (given p_3, x_3):

$$h_3 = h_{f@200\text{lbf/in}^2} = 39.00 \frac{\text{Btu}}{\text{lbm}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 39.00 \frac{\text{Btu}}{\text{lbm}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 95.05 - 78.64 = 16.41 \frac{\text{Btu}}{\text{lbm}}$

Device-B (2-3): $q_H = h_2 - h_3 = 95.05 - 39.00 = 56.05 \frac{\text{Btu}}{\text{lbm}}$

Device-C (4-1): $q_C = h_1 - h_4 = 78.64 - 39.00 = 39.64 \dfrac{\text{Btu}}{\text{lbm}}$

The mass flow rate of refrigerant

$$5 \text{ ton} = 1000 \frac{\text{Btu}}{\text{min}}$$

$$\dot{m} = \frac{\dot{Q}_C}{q_C} = \frac{1000}{39.64} = 25.23 \frac{\text{lbm}}{\text{min}}$$

The compressor power

$$\dot{W}_C = \dot{m} w_C = (25.23)(16.41) = 414.02 \frac{\text{Btu}}{\text{min}} = 9.76 \text{ hp}$$

The rate of heat transfer from the working fluid passing through the condenser

$$\dot{Q}_H = \dot{m} q_h = (25.23)(56.05) = 1414.14 \frac{\text{Btu}}{\text{min}}$$

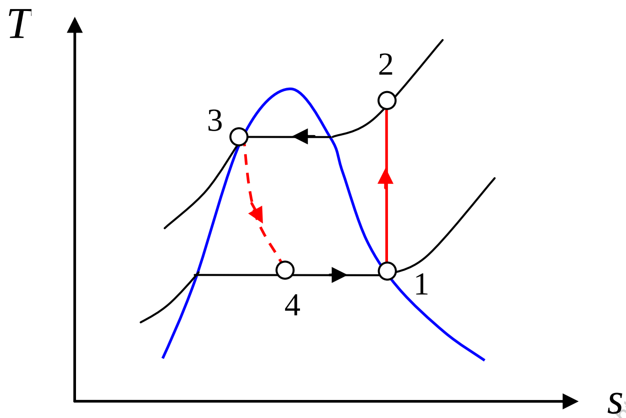
The COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{1000}{414.02} = 2.42$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-15 [OCB] Refrigerant R-12 enters the compressor of an ideal vapor-compression refrigeration system as saturated vapor at -10°C with a volumetric flow rate of 1 m^3/min. The refrigerant leaves the condenser at 35°C and 10 bar. Determine (a) the compressor power, in kW, (b) the refrigerating capacity in tons and (c) the coefficient of performance (COP$_R$).

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@-10°\text{C}} = 183.19 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = s_{g@-10°\text{C}} = 0.7019 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$v_1 = h_{g@-10°\text{C}} = 0.07665 \frac{\text{m}^3}{\text{kg}}$$

State-2 (given $p_3 = p_2, s_2 = s_1$):

$$h_2 = 210.36 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given p_3, T_3):

$$h_3 = 69.67 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 69.67 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 210.36 - 183.19 = 27.17 \frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_H = h_2 - h_3 = 210.36 - 69.67 = 140.69 \dfrac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_C = h_1 - h_4 = 183.19 - 69.67 = 113.52 \dfrac{\text{kJ}}{\text{kg}}$

The mass flow rate of the refrigerant

$$\dot{m} = \frac{\dot{Q}_C}{q_C} = \frac{0.01667}{0.07665} = 0.217 \frac{\text{kg}}{\text{s}}$$

The power input to the compressor

$$\dot{W}_C = \dot{m} w_C = (0.217)(27.17) = 5.90 \text{ kW}$$

The refrigerating capacity

$$\dot{Q}_C = \dot{m} q_C = (0.217)(113.52) = 24.63 \text{ kW} = 7.00 \text{ ton}$$

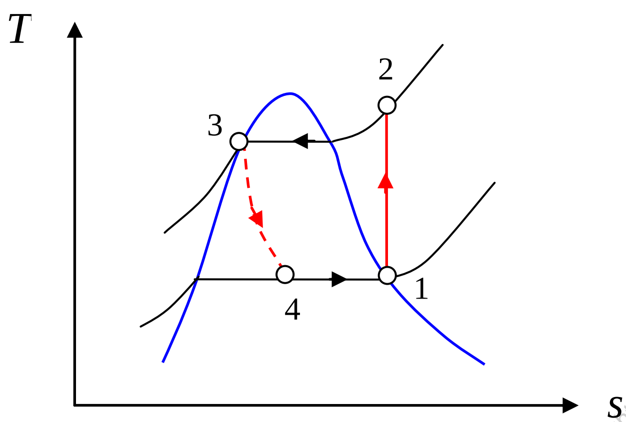
The COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{24.63}{5.90} = 4.17$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-16 [OCA] A refrigerator using R-134a as the working fluid operates on an ideal vapor compression refrigeration cycle between 0.15 MPa and 1 MPa. If the mass flow rate is 1 kg/s, determine (a) the net power necessary to run the system and (b) the COP_R. (c) What-if Scenario: What would the COP be if the expansion valve were replaced with an isentropic turbine?

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.15\text{MPa}} = 238.79\frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@0.15\text{MPa}} = 0.9382\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 278.41\frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@1\text{MPa}} = 106.61\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 106.61\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}(h_2 - h_1) = (1)(278.41 - 238.79) = 39.62\ \text{kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}(h_2 - h_3) = (1)(278.41 - 106.61) = 171.80\ \text{kW}$

Device-C (4-1): $\dot{Q}_C = \dot{m}(h_1 - h_4) = (1)(238.79 - 106.61) = 132.18\ \text{kW}$

Therefore, the COP can be obtained as

$$\mathrm{COP_R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{132.18}{39.62} = 3.34$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-17 [OCN] A vapor-compression refrigeration system, using ammonia as the working fluid, has evaporator and condenser pressures of 1 bar and 14 bar, respectively. The refrigerant passes through the evaporator with a negligible pressure drop. At the inlet and exit of the compressor, the temperatures are -12°C and 210°C, respectively. The heat transfer rate from the working fluid passing through the condenser is 15 kW, and liquid exits the condenser at 12 bar, 28°C. If the compressor operates adiabatically, determine (a) the compressor power input in kW and (b) the coefficient of performance. (c) What-if Scenario: What would the compressor power be if the condenser temperature rose to 250°C ?

SOLUTION

State-1 (given p_1, T_1):

$$h_1 = 1446.38 \frac{\text{kJ}}{\text{kg}}$$

State-2 (given p_2, T_2):

$$h_2 = 1929.37 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given p_3, T_3):

$$h_3 = 312.92 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 312.92 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 1929.37 - 1446.38 = 482.99 \frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_H = h_2 - h_3 = 1929.37 - 312.92 = 1616.45 \frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_C = h_1 - h_4 = 1446.38 - 312.92 = 1133.46 \frac{\text{kJ}}{\text{kg}}$

The mass flow through the condenser

$$\dot{m} = \frac{\dot{Q}_H}{q_H} = \frac{15}{1616.45} = 0.00925 \frac{\text{kg}}{\text{s}}$$

The compressor power input

$$\dot{W}_C = \dot{m} w_C = (0.00925)(482.99) = 4.47 \text{ kW}$$

Therefore, the COP can be obtained as

$$\mathrm{COP_R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{15}{4.47} = 3.36$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-18 [OCL] A vapor-compression refrigeration system, with a capacity of 15 tons, has superheated Refrigerant R-134a vapor entering the compressor at 15°C, 4 bar and exiting at 12 bar. The compression process can be taken as polytropic, with n = 1.01. At the condenser exit, the pressure is 11.6 bar and the temperature is 44°C. The condenser is water-cooled, with water entering at 20°C and leaving at 30°C with a negligible change in pressure. Heat transfer from the outside of the condenser can be neglected. Determine (a) the compressor power input in kW, (b) the coefficient of performance (COP_R) and (c) the irreversibility rate of the condenser, in kW, for T_0 = 20°C.

SOLUTION

State-1 (given p_1, T_1):

$$h_1 = 260.32 \frac{\text{kJ}}{\text{kg}}; \; v_1 = 0.05305 \frac{\text{m}^3}{\text{kg}}$$

State-2 (given p_2, n):

$$p_1 v_1^{\,n} = p_2 v_2^{\,n};$$

$$\Rightarrow v_2 = \left(\frac{p_1}{p_2} v_1^{\,n}\right)^{\frac{1}{n}} = \left[\left(\frac{4}{12}\right)(0.05305)^{1.01}\right]^{\frac{1}{1.01}} = 0.017877 \frac{\text{m}^3}{\text{kg}}$$

$$h_2 = 283.89 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given p_3, T_3):

$$h_3 = 113.64 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 113.64 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 283.89 - 260.32 = 23.57 \frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_H = h_2 - h_3 = 283.89 - 113.64 = 170.25 \frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_C = h_1 - h_4 = 260.32 - 113.64 = 146.68 \frac{\text{kJ}}{\text{kg}}$

The mass flow through the evaporator

$$\dot{m} = \frac{\dot{Q}_C}{q_C} = \frac{52.75}{146.68} = 0.360\frac{\text{kg}}{\text{s}}$$

The compressor power input

$$\dot{W}_C = \dot{m}w_C = (0.360)(23.57) = 8.49 \text{ kW}$$

Therefore, the COP can be obtained as

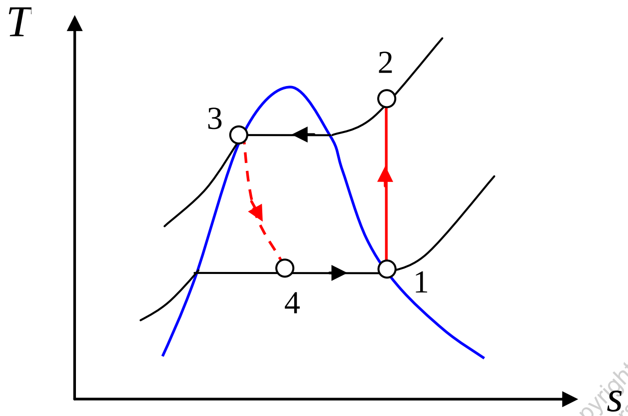
$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{52.75}{8.49} = 6.21$$

The rate of irreversibility

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-19 [OCE] An ideal vapor-compression refrigeration cycle, with ammonia as the working fluid, has an evaporator temperature of -25°C and a condenser pressure of 20 bar. Saturated vapor enters the compressor, and saturated liquid exits the condenser. The mass flow rate of the refrigerant is 3 kg/min. Determine (a) the coefficient of performance (COP_R) and (b) the refrigerating capacity, in tons. (c) What-if Scenario: What would the COP be if the evaporator temperature were -40°C?

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@-25°C} = 1411.20 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = s_{g@-25°C} = 5.6947 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 1821.04 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@200\text{bar}} = 418.24 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 418.24 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}(h_2 - h_1) = (0.05)(1821.04 - 1411.20) = 20.49 \text{ kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.05)(1821.04 - 418.24) = 70.14 \text{ kW}$

Device-C (4-1): $\dot{Q}_C = \dot{m}(h_1 - h_4) = (0.05)(1411.20 - 418.24) = 49.65 \text{ kW} = 14.12 \text{ ton}$

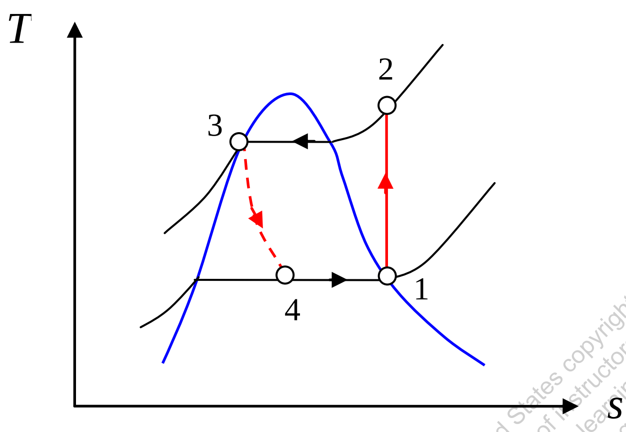
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{49.65}{20.49} = 2.42$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-20 [OCI] Consider a 500 kJ/min refrigeration system that operates on an ideal vapor-compression refrigeration cycle with refrigerant-134a as the working fluid. The refrigerant enters the compressor as saturated vapor at 150 kPa and is compressed to 800 kPa. (a) Show the cycle on a *T*-*s* diagram with respect to saturation lines, and determine (b) the quality of the refrigerant at the end of the throttling process, (c) the coefficient of performance (COP_R) and (d) the work input per unit mass of flow (w_{net}) to the compressor. (e) What-if Scenario: What would the answers be if R-12 were the working fluid?

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@150\text{kPa}} = 238.79 \frac{\text{kJ}}{\text{kg}}; \; s_1 = s_{g@150\text{kPa}} = 0.9382 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 273.62 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@800\text{kPa}} = 94.68 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 94.68\frac{\text{kJ}}{\text{kg}}$$

$$h_{f@150\text{kPa}} = 28.25\frac{\text{kJ}}{\text{kg}};\ h_{fg@150\text{kPa}} = 210.54\frac{\text{kJ}}{\text{kg}}$$

$$x_4 = \frac{h_4 - h_f}{h_{fg}} = \frac{94.68 - 28.25}{210.54} = 0.316$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 273.62 - 238.79 = 34.83\frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_H = h_2 - h_3 = 273.62 - 94.68 = 178.94\frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_C = h_1 - h_4 = 238.79 - 94.68 = 144.11\frac{\text{kJ}}{\text{kg}}$

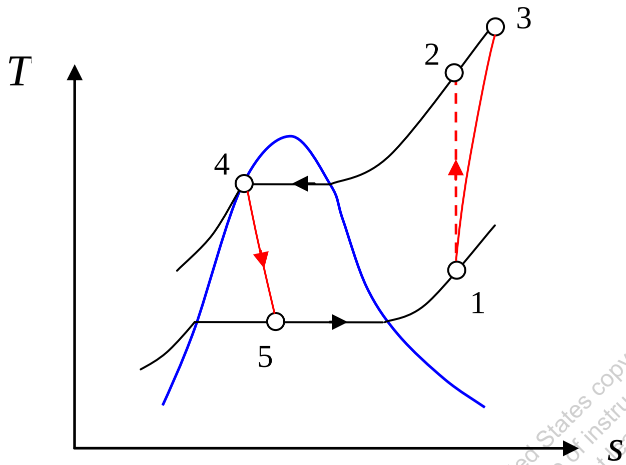
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{q_C}{w_C} = \frac{144.11}{34.83} = 4.14$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-21 [OCG] Refrigerant R-12 enters the compressor of a refrigerator as superheated vapor at 0.14 MPa, -20°C at a rate of 0.04 kg/s, and leaves at 0.7 MPa, 50°C. The refrigerant is cooled in the condenser to 24°C, 0.65 MPa and is throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components, (a) show the cycle on a *T*-*s* diagram with respect to saturation lines, determine (b) the rate of heat removal from the refrigerated space, (c) the power input to the compressor, (d) the isentropic efficiency of the compressor and (e) the COP of the refrigerator.

SOLUTION



State-1 (given p_1, T_1):

$$h_1 = 179.02 \frac{\text{kJ}}{\text{kg}}; \;\; s_1 = 0.7146 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 207.58 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, T_3$):

$$h_3 = 214.86 \frac{\text{kJ}}{\text{kg}}$$

$$\eta_C = \frac{h_2 - h_1}{h_3 - h_1} = \frac{207.58 - 179.02}{214.86 - 179.02} = 0.797 = 79.7\%$$

State-4 (given p_4, T_4):

$$h_4 = 58.75 \frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_1, h_5 = h_4$):

$$h_5 = h_4 = 58.75 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-3): $\dot{W}_C = \dot{m}(h_3 - h_1) = (0.04)(214.86 - 179.02) = 1.43 \text{ kW}$

Device-B (3-4): $\dot{Q}_H = \dot{m}(h_3 - h_4) = (0.04)(214.86 - 58.75) = 6.24 \text{ kW}$

Device-C (5-1): $\dot{Q}_C = \dot{m}(h_1 - h_5) = (0.04)(179.02 - 58.75) = 4.81 \text{ kW}$

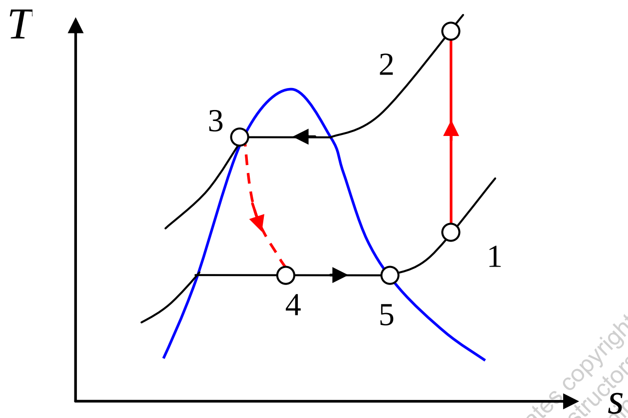
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{q_C}{w_C} = \frac{120.27}{35.84} = 3.36$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-22 [OCZ] Refrigerant R-12 enters the compressor of a refrigerator at 140 kPa, -10^{o}C at a rate of 0.3 m^3/min and leaves at 1 MPa. The compression process is isentropic. The refrigerant enters the throttling valve at 0.95 MPa, 30^{o}C and leaves the evaporator as saturated vapor at -18.5^{o}C. (a) Show the cycle on a *T-s* diagram with respect to saturation lines, determine (b) the power input to the compressor, (c) the rate of heat removal from the refrigerated space, (d) the pressure drop and rate of heat gain in the line between the evaporator and compressor.

SOLUTION



State-1 (given p_1, T_1):

$$h_1 = 185.00\frac{\text{kJ}}{\text{kg}};\ s_1 = 0.7371\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$v_1 = 0.12346\frac{\text{m}^3}{\text{kg}}$$

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{0.005}{0.12346} = 0.04\frac{\text{kg}}{\text{s}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 222.11\frac{\text{kJ}}{\text{kg}}$$

State-3 (given p_3, T_3):

$$h_3 = 64.75\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $T_4 = T_5, h_4 = h_3$):

$$h_4 = h_3 = 64.75 \frac{\text{kJ}}{\text{kg}}$$

State-5 (given T_5, x_5):

$$h_5 = h_{g@-18.5°\text{C}} = 179.41 \frac{\text{kJ}}{\text{kg}}$$

$$p_5 = p_{\text{sat}@-18.5°\text{C}} = 159.72 \text{ kPa}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}(h_2 - h_1) = (0.04)(222.11 - 185.00) = 1.48 \text{ kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.04)(222.11 - 64.75) = 6.29 \text{ kW}$

Device-C (4-1): $\dot{Q}_C = \dot{m}(h_1 - h_4) = (0.04)(185.00 - 64.75) = 4.81 \text{ kW}$

The pressure drop in the line between the evaporator and compressor

$\Delta p = p_5 - p_1 = 159.72 - 140.00 = 19.72 \text{ kPa}$

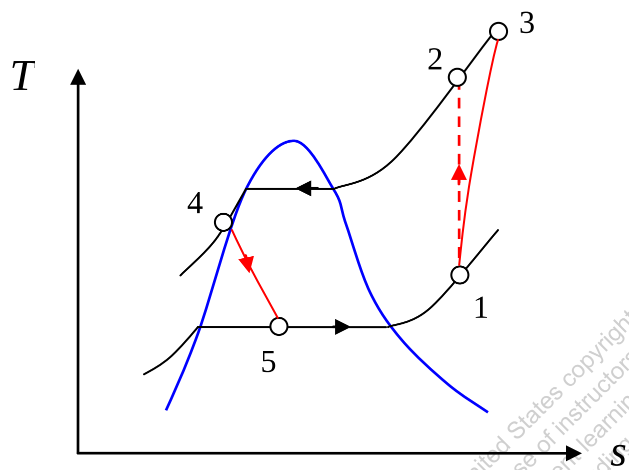
The rate of heat gain in the line between the evaporator and the compressor

$\dot{Q} = \dot{m}(h_1 - h_5) = (0.04)(185.00 - 179.41) = 0.22 \text{ kW}$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

xx10-1-23 [OCK] A vapor-compression refrigeration system for a household refrigerator has a refrigerating capacity of 1500 Btu/h and uses R-12 as the refrigerant. The refrigerant enters the evaporator at 21.422 lbf/in^2 and exits at 5^{o}F. The isentropic compressor efficiency is 70%. The refrigerant condenses at 122.95 lbf/in^2 and exits the condenser as subcooled at 90^{o}F. There are no significant pressure drops in the flows through the evaporator and condenser. Determine (a) the mass flow rate of refrigerant in lb/min, (b) the compressor power input in horsepower and (c) the coefficient of performance.

SOLUTION



State-1 (given $p_1 = p_5, T_1$):

$$h_1 = 181.8\frac{\text{kJ}}{\text{kg}};\ s_1 = 0.7217\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 213.5\frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, h_3 = h_1 + (h_2 - h_1)/(0.7)$):

$$h_3 = 227.1\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_3,\ T_4$):

$$h_4 = u_{f@T_4} + p_4 v_{f@T_4} = 66.84\frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5, h_5 = h_4$):

$$h_5 = 66.84 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-3): $w_C = h_3 - h_1 = 45.27 \frac{\text{kJ}}{\text{kg}}$

Device-B (3-4): $q_H = h_3 - h_4 = 160.3 \frac{\text{kJ}}{\text{kg}}$

Device-C (5-1): $q_C = h_1 - h_5 = 114.98 \frac{\text{kJ}}{\text{kg}}$

The mass flow through the evaporator

$$\dot{m} = \frac{\dot{Q}_C}{q_C} = \frac{0.440}{114.98} = 0.00383 \frac{\text{kg}}{\text{s}} = 0.5066 \frac{\text{lbm}}{\text{min}}$$

The compressor power input

$$\dot{W}_C = \dot{m} w_C = 0.1734 \text{ kW} = 0.2325 \text{ hp}$$

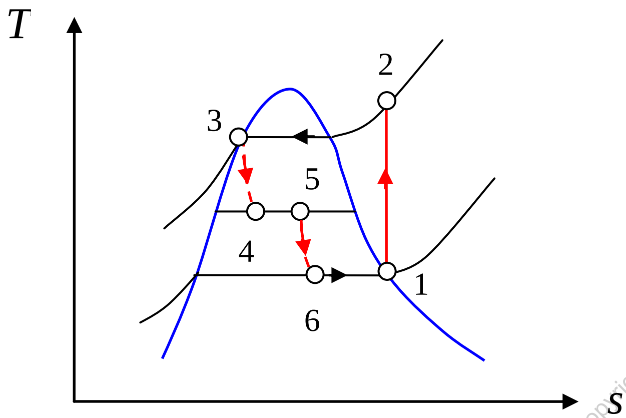
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{0.44}{0.1734} = 2.537$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-24 [OCQ] The refrigerator-freezer unit, shown in the schematic below, uses R-134a as the working fluid and operates on an ideal vapor-compression cycle. The temperatures in the condenser, refrigerator, and freezer are 25°C, 2°C, and -20°C, respectively. The mass flow rate of the refrigerant is 0.1 kg/s. If the refrigerant quality at the refrigerator exit is 0.4, determine the rate of heat removal from (a) the refrigerator and (b) freezer. Also, determine (c) the compressor power input and (d) the COP of the unit.

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@-20°C} = 237.10 \frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@-20°C} = 0.9404 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 270.42 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given T_3, x_3):

$$h_3 = h_{f@25°C} = 85.61 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $T_4 = T_5, h_4 = h_3$):

$$h_4 = h_3 = 85.61 \frac{\text{kJ}}{\text{kg}}$$

State-5 (given T_5, x_5):

$$h_{f@2°C} = 53.72\frac{\text{kJ}}{\text{kg}};\ h_{g@2°C} = 196.84\frac{\text{kJ}}{\text{kg}}$$

$$h_5 = h_{f@2°C} + x_5 h_{fg@2°C} = 53.72 + (0.4)(196.84) = 132.46\frac{\text{kJ}}{\text{kg}}$$

State-6 (given $T_6 = T_1, h_6 = h_5$):

$$h_6 = h_5 = 132.46\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}(h_2 - h_1) = (0.1)(270.42 - 237.10) = 3.33\ \text{kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.1)(270.42 - 85.61) = 18.48\ \text{kW}$

Device-C (4-5): $\dot{Q}_{C,\text{I}} = \dot{m}(h_5 - h_4) = (0.1)(132.46 - 85.61) = 4.69\ \text{kW}$

Device-D (6-1): $\dot{Q}_{C,\text{II}} = \dot{m}(h_1 - h_6) = (0.1)(237.10 - 132.46) = 10.46\ \text{kW}$

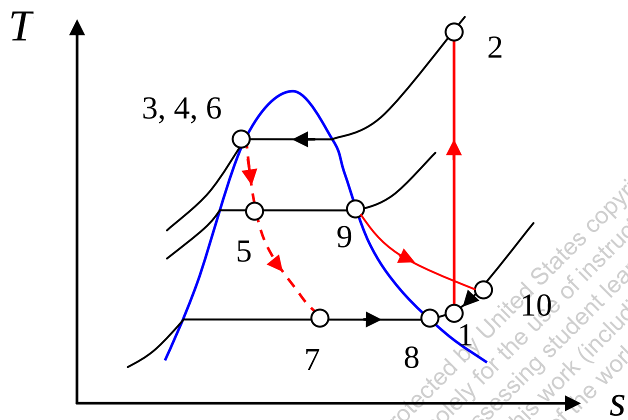
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{\dot{Q}_{C,\text{I}} + \dot{Q}_{C,\text{II}}}{\dot{W}_C} = \frac{4.69 + 10.46}{3.33} = 4.55$$

TEST Solution: Use PC vapor-compression cycle TESTcalc to verify this answer. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-25 [OCU] Refrigerant-134a is the working fluid in a vapor-compression refrigeration system with two evaporators. The system uses only one compressor. Saturated liquid leaves the condenser at 11 bar, one part of the liquid is throttled to 3 bar, the second part is throttled to the second evaporator at a temperature of -15°C. Vapor leaves the first evaporator as saturated vapor and is throttled to the pressure of the second evaporator. The refrigerating capacity in the first evaporator is 1 ton, in the second is 2 tons. All processes of the working fluid are internally reversible, except for the expansion through each valve. The compressor and valves operate adiabatically. Kinetic and potential energy effects are negligible. Determine (a) the mass flow rates through each evaporator, (b) the compressor power input, (c) the heat transfer from the refrigerant passing through the condenser. (d) What-if Scenario: What would the compressor power input be if the entire cooling capacity of the first evaporator were shifted to the second?

SOLUTION



Note: The states 3, 4 and 6 are the same, their differences is only in the mass rate, which can not be presented in diagram.

State-1 (given $p_1 = p_8$):

$$h_1 = \frac{\dot{m}_5}{\dot{m}_1} h_{10} + \frac{\dot{m}_7}{\dot{m}_8} h_8 = \left(\frac{0.0255}{0.0804}\right)(249.70) + \left(\frac{0.0549}{0.0804}\right)(240.22) = 243.23 \frac{\text{kJ}}{\text{kg}}$$

$$s_1 = 0.9476 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 283.58 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given p_3, x_3):

$$h_3 = h_{f\,@11\text{bar}} = 112.03 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_3, h_4 = h_3$):

$$h_4 = h_3 = 112.03 \frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5, h_5 = h_3$):

$$h_5 = 112.03 \frac{\text{kJ}}{\text{kg}}$$

State-6 (given $p_6 = p_3, h_6 = h_3$):

$$h_6 = h_3 = 112.03 \frac{\text{kJ}}{\text{kg}}$$

State-7 (given $T_7, h_7 = h_3$):

$$h_7 = h_3 = 112.03 \frac{\text{kJ}}{\text{kg}}$$

State-8 (given $T_8 = T_7, x_8$):

$$h_8 = h_{g@-15^\circ\text{C}} = 240.22 \frac{\text{kJ}}{\text{kg}}$$

State-9 (given $T_9 = T_5, x_9$):

$$h_9 = h_{g@3\text{bar}} = 249.70 \frac{\text{kJ}}{\text{kg}}$$

State-10 (given $p_{10} = p_8, h_{10} = h_9$):

$$h_{10} = h_9 = 249.70 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_C = h_2 - h_1 = 283.58 - 243.23 = 40.35 \frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_H = h_2 - h_3 = 283.58 - 112.03 = 171.55 \frac{\text{kJ}}{\text{kg}}$

Device-C (5-9): $q_{C,\text{I}} = h_9 - h_5 = 249.70 - 112.03 = 137.67 \frac{\text{kJ}}{\text{kg}}$

Device-D (7-8): $q_{C,\text{II}} = h_8 - h_7 = 240.22 - 112.03 = 128.19 \frac{\text{kJ}}{\text{kg}}$

The mass flow through the first evaporator

$$\dot{m}_5 = \frac{\dot{Q}_{C,\mathrm{I}}}{q_{C,\mathrm{I}}} = \frac{3.517}{137.67} = 0.0255\frac{\mathrm{kg}}{\mathrm{s}} = 1.53\frac{\mathrm{kg}}{\mathrm{min}}$$

The mass flow through the second evaporator

$$\dot{m}_7 = \frac{\dot{Q}_{C,\mathrm{II}}}{q_{C,\mathrm{II}}} = \frac{7.034}{128.19} = 0.0549\frac{\mathrm{kg}}{\mathrm{s}} = 3.29\frac{\mathrm{kg}}{\mathrm{min}}$$

The total mass flow

$$\dot{m}_1 = \dot{m}_5 + \dot{m}_7 = 0.0255 + 0.0549 = 0.0804\frac{\mathrm{kg}}{\mathrm{s}}$$

The compressor power input

$$\dot{W}_C = \dot{m}_1 w_C = (0.0804)(40.35) = 3.24\ \mathrm{kW}$$

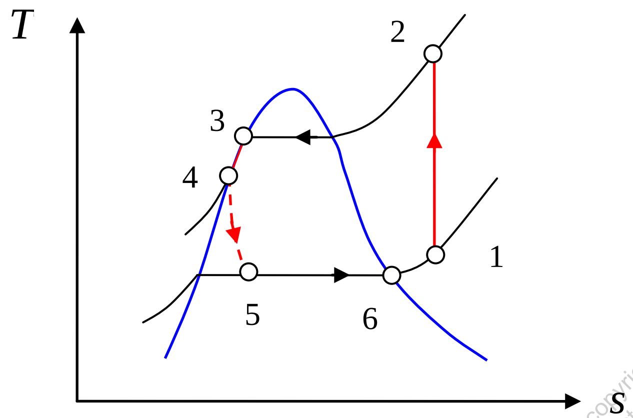
The heat transfer in the condenser

$$\dot{Q}_H = \dot{m}_1 q_H = (0.0804)(171.55) = 13.79\ \mathrm{kW}$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-26 [OCX] An ideal vapor-compression cycle uses R-134a as a working fluid and operates between the pressures of 0.1 MPa and 1.5 MPa. The refrigerant leaves the condenser at 30°C and the heat exchanger at 10°C. The refrigerant is then throttled to the evaporator pressure. Refrigerant leaves the evaporator as saturated vapor and goes to the heat exchanger. The mass flow rate is 1 kg/s. Determine (a) the rate of heat removal from the refrigerated space per unit of the mass flow and (b) the COP. (c) What-if Scenario: What would the answers be if the heat exchanger were removed?

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = 260.96\frac{\text{kJ}}{\text{kg}};\ s_1 = 1.0525\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 327.47\frac{\text{kJ}}{\text{kg}}$$

State-3 (given p_3, T_3):

$$h_3 = 93.42\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_2, T_4$):

$$h_4 = 65.46\frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_1, h_5 = h_4$):

$$h_5 = h_4 = 65.46\frac{\text{kJ}}{\text{kg}}$$

State-6 (given $p_6 = p_1, x_6$):

$$h_6 = h_{g@0.1\text{MPa}} = 233.00\,\frac{\text{kJ}}{\text{kg}}$$

An energy balance is performed on the heat exchanger

$$h_3 - h_4 = h_1 - h_6;$$

$$\Rightarrow h_1 = h_6 + h_3 - h_4;$$

$$\Rightarrow h_1 = 233.00 + 93.42 - 65.46 = 260.96\,\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}\left(h_2 - h_1\right) = (1)(327.47 - 260.96) = 66.51\ \text{kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}\left(h_2 - h_3\right) = (1)(327.47 - 93.42) = 234.05\ \text{kW}$

Device-C (5-6): $\dot{Q}_C = \dot{m}\left(h_6 - h_5\right) = (1)(233.00 - 65.46) = 167.54\ \text{kW}$

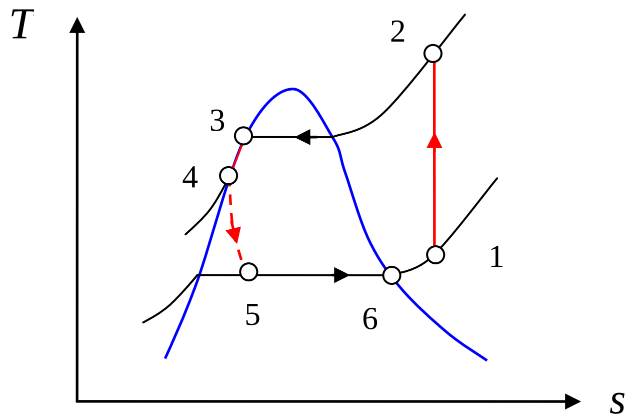
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{167.54}{66.51} = 2.52$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-27 [OCC] Repeat problem 10-1-26 [OCX] with R-12 as the working fluid.

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = 193.17\frac{\text{kJ}}{\text{kg}};\ s_1 = 0.7904\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 249.52\frac{\text{kJ}}{\text{kg}}$$

State-3 (given p_3, T_3):

$$h_3 = 65.17\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_2, T_4$):

$$h_4 = 46.16\frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_1, h_5 = h_4$):

$$h_5 = h_4 = 46.16\frac{\text{kJ}}{\text{kg}}$$

State-6 (given $p_6 = p_1, x_6$):

$$h_6 = h_{g@0.1\text{MPa}} = 174.16\frac{\text{kJ}}{\text{kg}}$$

An energy balance is performed on the heat exchanger

$$h_3 - h_4 = h_1 - h_6;$$
$$\Rightarrow h_1 = h_6 + h_3 - h_4;$$
$$\Rightarrow h_1 = 174.16 + 65.17 - 46.16 = 193.17 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_C = \dot{m}\left(h_2 - h_1\right) = \left(1\right)\left(249.52 - 193.17\right) = 56.35 \text{ kW}$

Device-B (2-3): $\dot{Q}_H = \dot{m}\left(h_2 - h_3\right) = \left(1\right)\left(249.52 - 65.17\right) = 184.35 \text{ kW}$

Device-C (5-6): $\dot{Q}_C = \dot{m}\left(h_6 - h_5\right) = \left(1\right)\left(174.16 - 46.16\right) = 128.00 \text{ kW}$

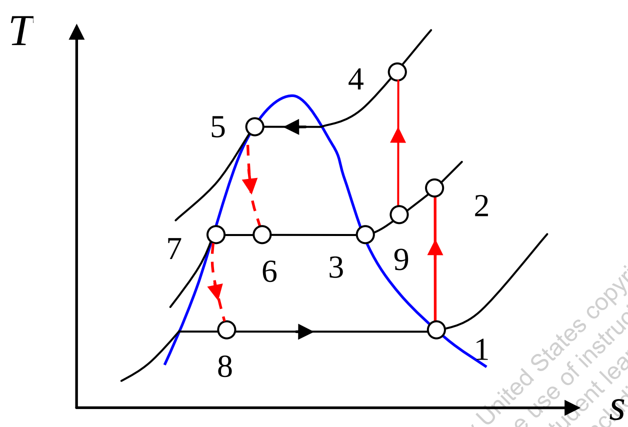
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{128.00}{56.35} = 2.27$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-28 [OCV] Consider a two-stage R-12 refrigeration system operating between 0.15 MPa and 1 MPa. The refrigerant leaves the condenser as saturated liquid and is throttled to a flash chamber operating at 0.4 MPa. The vapor from the flash chamber is mixed with the refrigerant leaving the low-pressure compressor and the mixture is compressed by the high-pressure compressor to the condenser pressure. The liquid in the flash chamber is throttled to the evaporator pressure where the cooling load is handled through evaporation. Assuming the refrigerant leaves the evaporator as saturated vapor and both compressors are isentropic, determine (a) the fraction of refrigerant that evaporates in the flash chamber, (b) the cooling load and (c) the COP. (d) What-if Scenario: What would the COP be if the intermediate pressure were changed to 0.8 MPa?

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.15\text{MPa}} = 178.67\frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@0.15\text{MPa}} = 0.7088\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 195.63\frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{g@0.4\text{MPa}} = 190.96\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4, s_4 = s_9$):

$$h_4 = 211.50\frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_4, x_5$):

$$h_5 = h_{f\,@1\mathrm{MPa}} = 76.26\,\frac{\mathrm{kJ}}{\mathrm{kg}}$$

State-6 (given $p_6 = p_2, h_6 = h_5$):

$$h_6 = h_5 = 76.26\,\frac{\mathrm{kJ}}{\mathrm{kg}}$$

State-7 (given $p_7 = p_6, x_7$):

$$h_7 = h_{f\,@0.4\mathrm{MPa}} = 43.63\,\frac{\mathrm{kJ}}{\mathrm{kg}}$$

State-8 (given $p_8 = p_1, h_8 = h_7$):

$$h_8 = h_7 = 43.63\,\frac{\mathrm{kJ}}{\mathrm{kg}}$$

State-9 (given $p_9 = p_2$):

$$\dot{m}_9 h_9 = \dot{m}_2 h_2 + \dot{m}_3 h_3;$$

$$\Rightarrow h_9 = \frac{\dot{m}_2}{\dot{m}_9} h_2 + \frac{\dot{m}_3}{\dot{m}_9} h_3;$$

$$\Rightarrow h_9 = (1 - x_8) h_2 + x_6 h_3;$$

$$\Rightarrow h_9 = (1 - 0.221)(195.63) + (0.221)(190.96) = 194.60\,\frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$s_9 = 0.7052\,\frac{\mathrm{kJ}}{\mathrm{kg}\cdot\mathrm{K}}$$

Through an energy balance, it is seen that the fraction of refrigerant that evaporates in the flash chamber is the quality of state-6.

$$\dot{m}_6 = \dot{m}_3 + \dot{m}_7$$

$$\dot{m}_6 h_6 = \dot{m}_3 h_3 + \dot{m}_7 h_7;$$

$$\Rightarrow h_6 = \frac{\dot{m}_3}{\dot{m}_6} h_3 + \frac{\dot{m}_7}{\dot{m}_6} h_7;$$

$$\Rightarrow h_6 = x_6 h_3 + (1 - x_6) h_7;$$

$$\Rightarrow r = x_6 = \frac{h_6 - h_7}{h_3 - h_7} = \frac{76.26 - 43.63}{190.96 - 43.63} = 0.221$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_{C,\mathrm{I}} = (1 - r)(h_2 - h_1) = (1 - 0.221)(195.63 - 178.67) = 13.21\,\frac{\mathrm{kJ}}{\mathrm{kg}}$

Device-B (9-4): $w_{C,\text{II}} = h_4 - h_9 = 211.50 - 194.60 = 16.90 \dfrac{\text{kJ}}{\text{kg}}$

Device-C (4-5): $q_H = h_4 - h_5 = 211.50 - 76.26 = 135.24 \dfrac{\text{kJ}}{\text{kg}}$

Device-D (8-1):

$$q_C = (1-r)(h_1 - h_8);$$

$$q_C = (1-0.221)(178.67 - 43.63) = 105.20 \frac{\text{kJ}}{\text{kg}} = 29.91 \frac{\text{ton}}{\text{kg}}$$

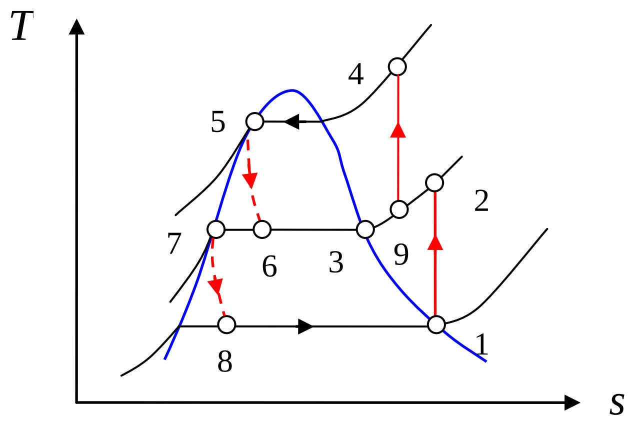
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{q_C}{w_C} = \frac{q_c}{w_{C,\text{I}} + w_{C,\text{II}}} = \frac{105.20}{13.21+16.90} = 3.49$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-29 [OCT] Repeat problem 10-1-28 [OCV] with R-134a as the working fluid.

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.15\text{MPa}} = 238.79 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = s_{g@0.15\text{MPa}} = 0.9382 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 258.89 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{g@0.4\text{MPa}} = 254.56 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4, s_4 = s_9$):

$$h_4 = 277.33 \frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_4, x_5$):

$$h_5 = h_{f@1\text{MPa}} = 106.61 \frac{\text{kJ}}{\text{kg}}$$

State-6 (given $p_6 = p_2, h_6 = h_5$):

$$h_6 = h_5 = 106.61 \frac{\text{kJ}}{\text{kg}}$$

State-7 (given $p_7 = p_6, x_7$):

$$h_7 = h_{f@0.4\text{MPa}} = 62.99\frac{\text{kJ}}{\text{kg}}$$

State-8 (given $p_8 = p_1, h_8 = h_7$):

$$h_8 = h_7 = 62.99\frac{\text{kJ}}{\text{kg}}$$

State-9 (given $p_9 = p_2$):

$$\dot{m}_9 h_9 = \dot{m}_2 h_2 + \dot{m}_3 h_3;$$

$$\Rightarrow h_9 = \frac{\dot{m}_2}{\dot{m}_9}h_2 + \frac{\dot{m}_3}{\dot{m}_9}h_3;$$

$$\Rightarrow h_9 = (1-x_8)h_2 + x_6 h_3;$$

$$\Rightarrow h_9 = (1-0.228)(258.89)+(0.228)(254.56) = 257.90\frac{\text{kJ}}{\text{kg}}$$

$$s_9 = 0.9348\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

Through an energy balance, it is seen that the fraction of refrigerant that evaporates in the flash chamber is the quality of state-6.

$$\dot{m}_6 = \dot{m}_3 + \dot{m}_7$$

$$\dot{m}_6 h_6 = \dot{m}_3 h_3 + \dot{m}_7 h_7;$$

$$\Rightarrow h_6 = \frac{\dot{m}_3}{\dot{m}_6}h_3 + \frac{\dot{m}_7}{\dot{m}_6}h_7;$$

$$\Rightarrow h_6 = x_6 h_3 + (1-x_6)h_7;$$

$$\Rightarrow r = x_6 = \frac{h_6 - h_7}{h_3 - h_7} = \frac{106.61-62.99}{254.56-62.99} = 0.228$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_{C,\text{I}} = (1-r)(h_2-h_1) = (1-0.228)(258.89-238.79) = 15.52\frac{\text{kJ}}{\text{kg}}$

Device-B (9-4): $w_{C,\text{II}} = h_4 - h_9 = 277.33-257.90 = 19.43\frac{\text{kJ}}{\text{kg}}$

Device-C (4-5): $q_H = h_4 - h_5 = 277.33-106.61 = 170.72\frac{\text{kJ}}{\text{kg}}$

Device-D (8-1):

$$q_C = (1-r)(h_1-h_8);$$

$$q_C = (1-0.228)(238.79-62.99) = 135.72\frac{\text{kJ}}{\text{kg}} = 38.59\frac{\text{ton}}{\text{kg}}$$

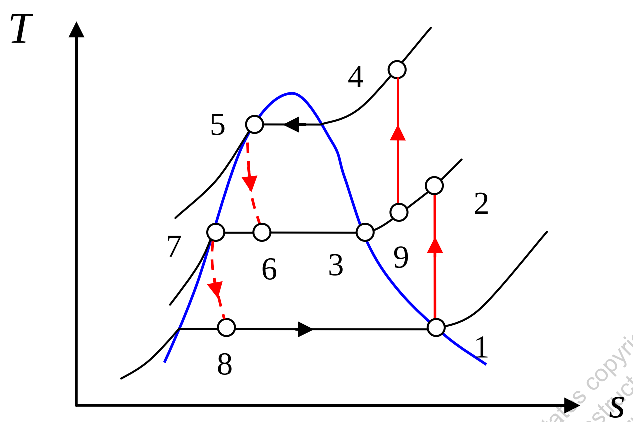
Therefore, the COP can be obtained as

$$\mathrm{COP}_{\mathrm{R}} = \frac{q_C}{w_C} = \frac{q_c}{w_{C,\mathrm{I}} + w_{C,\mathrm{II}}} = \frac{135.72}{15.52 + 19.43} = 3.88$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-30 [OCY] Consider an ideal two-stage refrigeration system (see Fig. 10-1-38) that uses R-12 as the working fluid. Saturated liquid leaves the condenser at 40°C and is throttled to -20°C. The liquid and vapor at this temperature are separated, and the liquid is throttled to the evaporator temperature at -70°C. Vapor leaving the evaporator is compressed to the saturation pressure corresponding to -20°C, after which it is mixed with the vapor leaving the flash chamber. Determine (a) the coefficient of performance (COP_R) of the system. (b) What-if Scenario: What would the COP be if the flash chamber were removed with the entire flow directed to the second expansion valve?

SOLUTION



State-1 (given $T_1 = T_8, x_1$):

$$h_1 = h_{g@-70°C} = 155.64 \frac{kJ}{kg}; \; s_1 = s_{g@-70°C} = 0.7749 \frac{kJ}{kg \cdot K}$$

State-2 (given $p_2 = p_6, s_2 = s_1$):

$$h_2 = 196.62 \frac{kJ}{kg}$$

State-3 (given $T_3 = T_6, x_3$):

$$h_3 = h_{g@-20°C} = 178.74 \frac{kJ}{kg}$$

State-4 (given $p_4 = p_5, s_4 = s_9$):

$$h_4 = 226.14 \frac{kJ}{kg}$$

State-5 (given T_5, x_5):

$$h_5 = h_{f@40°C} = 74.59 \frac{kJ}{kg}$$

State-6 (given $T_6, h_6 = h_5$):

$$h_6 = h_5 = 74.59\,\frac{\text{kJ}}{\text{kg}}$$

State-7 (given $T_7 = T_6, x_7$):

$$h_7 = h_{f\,@-20°\text{C}} = 17.82\,\frac{\text{kJ}}{\text{kg}}$$

State-8 (given $T_8, h_8 = h_7$):

$$h_8 = h_7 = 17.82\,\frac{\text{kJ}}{\text{kg}}$$

State-9 (given $p_9 = p_6$):

$$\dot{m}_9 h_9 = \dot{m}_2 h_2 + \dot{m}_3 h_3;$$

$$\Rightarrow h_9 = \frac{\dot{m}_2}{\dot{m}_9} h_2 + \frac{\dot{m}_3}{\dot{m}_9} h_3;$$

$$\Rightarrow h_9 = \left(1 - x_8\right) h_2 + x_6 h_3;$$

$$\Rightarrow h_9 = \left(1 - 0.353\right)\left(196.62\right) + \left(0.353\right)\left(178.74\right) = 190.31\,\frac{\text{kJ}}{\text{kg}}$$

$$s_9 = 0.7523\,\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

Through an energy balance, it is seen that the fraction of refrigerant that evaporates in the flash chamber is the quality of state-6.

$$\dot{m}_6 = \dot{m}_3 + \dot{m}_7$$

$$\dot{m}_6 h_6 = \dot{m}_3 h_3 + \dot{m}_7 h_7;$$

$$\Rightarrow h_6 = \frac{\dot{m}_3}{\dot{m}_6} h_3 + \frac{\dot{m}_7}{\dot{m}_6} h_7;$$

$$\Rightarrow h_6 = x_6 h_3 + \left(1 - x_6\right) h_7;$$

$$\Rightarrow r = x_6 = \frac{h_6 - h_7}{h_3 - h_7} = \frac{74.59 - 17.82}{178.74 - 17.82} = 0.353$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_{C,\text{I}} = \left(1 - r\right)\left(h_2 - h_1\right) = \left(1 - 0.353\right)\left(196.62 - 155.64\right) = 26.51\,\frac{\text{kJ}}{\text{kg}}$

Device-B (9-4): $w_{C,\text{II}} = h_4 - h_9 = 226.14 - 190.31 = 35.83\,\frac{\text{kJ}}{\text{kg}}$

Device-C (4-5): $q_H = h_4 - h_5 = 226.14 - 74.59 = 151.55 \dfrac{\text{kJ}}{\text{kg}}$

Device-D (8-1): $q_C = (1-r)(h_1 - h_8) = (1-0.353)(155.64 - 17.82) = 89.17 \dfrac{\text{kJ}}{\text{kg}}$

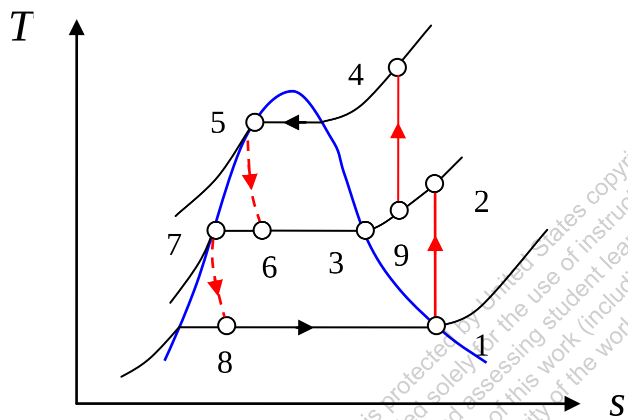
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{q_C}{w_C} = \frac{q_c}{w_{C,\text{I}} + w_{C,\text{II}}} = \frac{89.17}{26.51 + 35.83} = 1.43$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-31 [OCF] Consider a two-stage compression refrigeration system operating between the pressure limits of 1.2 MPa and 0.08 MPa. The working fluid is R-12. The refrigerant leaves the condenser as saturated liquid with a mass flow rate of 1 kg/s and is throttled to a flash chamber operating at 0.4 MPa. Part of the refrigerant evaporates during this flashing process, and this vapor is mixed with the refrigerant leaving the low-pressure compressor. The mixture is then compressed to the condenser pressure by the high-pressure compressor. The liquid in the flash chamber is throttled to the evaporator pressure, and it cools the refrigerated space as it vaporizes in the evaporator. Assuming the refrigerant leaves the evaporator as saturated vapor and both compressors are isentropic, determine (a) the fraction of the refrigerant that evaporates as it is throttled to the flash chamber, (b) the amount of heat removed from the refrigerated space, (c) the net compressor work and (d) the coefficient of performance. (e) What-if Scenario: What would the answers be if R-134a were used instead?

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.08\text{MPa}} = 171.81\frac{\text{kJ}}{\text{kg}};\; s_1 = s_{g@0.08\text{MPa}} = 0.7221\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 199.52\frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{g@0.4\text{MPa}} = 190.96\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4, s_4 = s_9$):

$$h_4 = 217.91\frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_4, x_5$):

$$h_5 = h_{f\,@1.2\text{MPa}} = 83.43\frac{\text{kJ}}{\text{kg}}$$

State-6 (given $p_6 = p_2, h_6 = h_5$):

$$h_6 = h_5 = 83.43\frac{\text{kJ}}{\text{kg}}$$

State-7 (given $p_7 = p_6, x_7$):

$$h_7 = h_{f\,@0.4\text{MPa}} = 43.63\frac{\text{kJ}}{\text{kg}}$$

State-8 (given $p_8 = p_1, h_8 = h_7$):

$$h_8 = h_7 = 43.63\frac{\text{kJ}}{\text{kg}}$$

State-9 (given $p_9 = p_2$):

$$\dot{m}_9 h_9 = \dot{m}_2 h_2 + \dot{m}_3 h_3;$$

$$\Rightarrow h_9 = \frac{\dot{m}_2}{\dot{m}_9}h_2 + \frac{\dot{m}_3}{\dot{m}_9}h_3;$$

$$\Rightarrow h_9 = \left(1 - x_8\right)h_2 + x_6 h_3;$$

$$\Rightarrow h_9 = \left(1 - 0.270\right)\left(199.52\right) + \left(0.270\right)\left(190.96\right) = 197.21\frac{\text{kJ}}{\text{kg}}$$

$$s_9 = 0.7142\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

Through an energy balance, it is seen that the fraction of refrigerant that evaporates in the flash chamber is the quality of state-6.

$$\dot{m}_6 = \dot{m}_3 + \dot{m}_7$$

$$\dot{m}_6 h_6 = \dot{m}_3 h_3 + \dot{m}_7 h_7;$$

$$\Rightarrow h_6 = \frac{\dot{m}_3}{\dot{m}_6}h_3 + \frac{\dot{m}_7}{\dot{m}_6}h_7;$$

$$\Rightarrow h_6 = x_6 h_3 + \left(1 - x_6\right)h_7;$$

$$\Rightarrow r = x_6 = \frac{h_6 - h_7}{h_3 - h_7} = \frac{83.43 - 43.63}{190.96 - 43.63} = 0.270$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_{C,\text{I}} = \dot{m}(1-r)(h_2 - h_1) = (1)(1-0.270)(199.52-171.81) = 20.23 \text{ kW}$

Device-B (9-4): $\dot{W}_{C,\text{II}} = \dot{m}(h_4 - h_9) = (1)(217.91-197.21) = 20.70 \text{ kW}$

Device-C (4-5): $\dot{Q}_H = \dot{m}(h_4 - h_5) = (1)(217.91-83.43) = 134.48 \text{ kW}$

Device-D (8-1): $\dot{Q}_C = \dot{m}(1-r)(h_1 - h_8) = (1)(1-0.270)(171.81-43.63) = 93.57 \text{ kW}$

The net compressor power

$$\dot{W}_C = \dot{W}_{C,\text{I}} + \dot{W}_{C,\text{II}} = 20.23 + 20.70 = 40.93 \text{ kW}$$

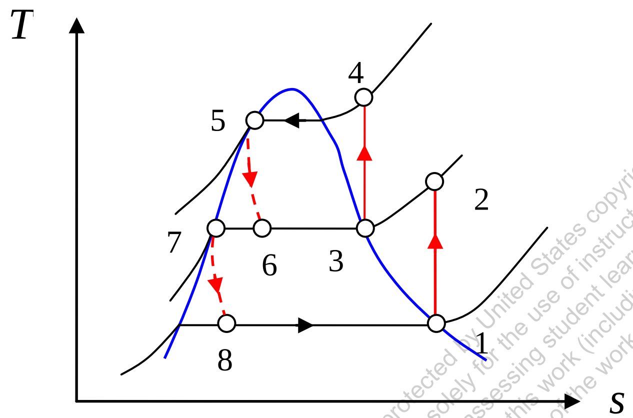
Therefore, the COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{93.57}{40.93} = 2.29$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-32 [OCD] A two-stage compression refrigeration system operates between the pressure limits of 1 MPa and 0.12 MPa. The refrigerant, R-134a, leaves the condenser as saturated liquid and is throttled to a flash chamber operating at 0.7 MPa. The refrigerant leaving the low-pressure compressor at 0.7 MPa is also routed to the flash chamber. The vapor in the flash chamber is then compressed to the condenser pressure by the high-pressure compressor, and the liquid is throttled to the evaporator pressure. Assuming the refrigerant leaves the evaporator as saturated vapor and both the compressors are isentropic, determine (a) the fraction of the refrigerant that evaporates as it is throttled to the flash chamber, (b) the rate of heat removed from the refrigerated space for a mass flow rate of 1 kg/s through the condenser and (c) the coefficient of performance. (d) What-if Scenario: Do a parametric study of how the COP changes with the flash chamber pressure as it increases from 0.5 MPa to 0.9 MPa.

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.12\text{MPa}} = 235.55 \frac{\text{kJ}}{\text{kg}}; \; s_1 = s_{g@0.12\text{MPa}} = 0.9427 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 272.18 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{g@0.7\text{MPa}} = 264.38 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4, s_4 = s_3$):

$$h_4 = 271.75 \frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_4, x_5$):

$$h_5 = h_{f\,@1\mathrm{MPa}} = 106.61\frac{\mathrm{kJ}}{\mathrm{kg}}$$

State-6 (given $p_6 = p_2, h_6 = h_5$):

$$h_6 = h_5 = 106.61\frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$h_{f\,@0.7\mathrm{MPa}} = 87.99\frac{\mathrm{kJ}}{\mathrm{kg}};\ h_{fg\,@0.7\mathrm{MPa}} = 176.39\frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$x_6 = \frac{h_6 - h_f}{h_{fg}} = \frac{106.61 - 87.99}{176.39} = 0.106$$

State-7 (given $p_7 = p_6, x_7$):

$$h_7 = h_{f\,@0.7\mathrm{MPa}} = 87.99\frac{\mathrm{kJ}}{\mathrm{kg}}$$

State-8 (given $p_8 = p_1, h_8 = h_7$):

$$h_8 = h_7 = 87.99\frac{\mathrm{kJ}}{\mathrm{kg}}$$

An energy balance is carried out on the flash chamber to find the fraction of refrigerant that is used in the high pressure cycle

$$\dot{m} = \dot{m}_6 + \dot{m}_2$$

$$\dot{m}_6 h_6 + m_2 h_2 = \dot{m}_3 h_3 + \dot{m}_7 h_7;$$

$$\Rightarrow \dot{m}_6 h_6 + m_2 h_2 = \dot{m}_6 h_3 + \dot{m}_2 h_7;$$

$$\Rightarrow \dot{m}_6\left(h_6 - h_3\right) = \dot{m}_2\left(h_7 - h_2\right);$$

$$\Rightarrow \dot{m}_6\left(h_6 - h_3\right) = \left(\dot{m} - \dot{m}_6\right)\left(h_7 - h_2\right);$$

$$\Rightarrow \dot{m}_6\left(h_6 - h_3\right) = \dot{m}\left(h_7 - h_2\right) - \dot{m}_6\left(h_7 - h_2\right);$$

$$\Rightarrow \dot{m}_6\left(h_6 - h_3 + h_7 - h_2\right) = \dot{m}\left(h_7 - h_2\right);$$

$$\Rightarrow r = \frac{\dot{m}_6}{\dot{m}} = \frac{h_7 - h_2}{h_6 - h_3 + h_7 - h_2} = \frac{87.99 - 272.18}{106.61 - 264.38 + 87.99 - 272.18} = 0.539$$

Therefore, the amount of refrigerant evaporated during the throttling to the flash chamber pressure is the fraction of refrigerant in the high pressure cycle multiplied by the quality at state-6.

$$rx_6 = (0.539)(0.106) = 0.057$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $\dot{W}_{C,\mathrm{I}} = \dot{m}(1-r)(h_2 - h_1) = (1)(1-0.539)(272.18-235.55) = 16.89\ \mathrm{kW}$

Device-B (3-4): $\dot{W}_{C,\mathrm{II}} = \dot{m}r(h_4 - h_3) = (1)(0.539)(271.75-264.38) = 3.95\ \mathrm{kW}$

Device-C (4-5): $\dot{Q}_H = \dot{m}r(h_4 - h_5) = (1)(0.539)(271.75-106.61) = 89.01\ \mathrm{kW}$

Device-D (8-1): $\dot{Q}_C = \dot{m}(1-r)(h_1 - h_8) = (1)(1-0.539)(235.55-87.99) = 68.03\ \mathrm{kW}$

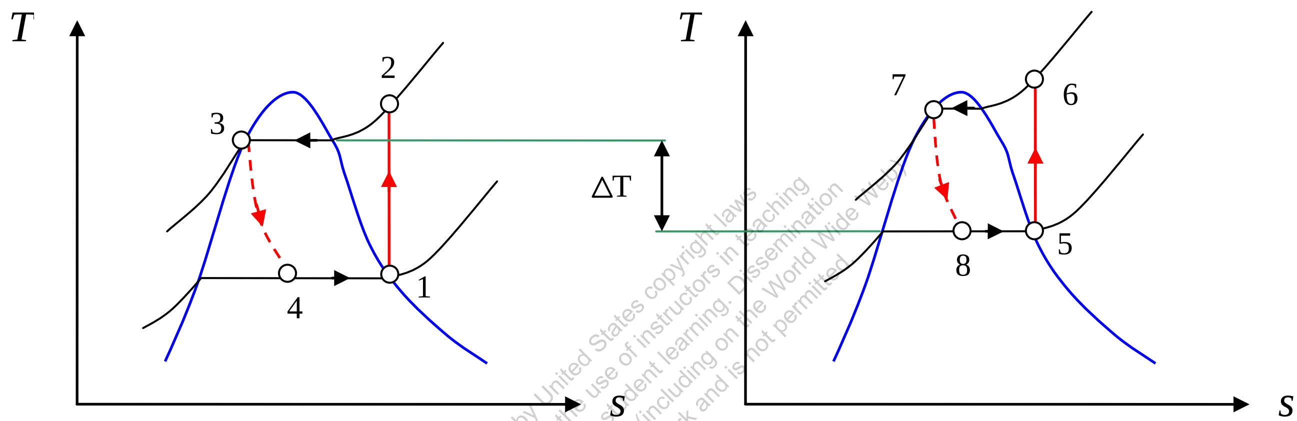
Therefore, the COP can be obtained as

$$\mathrm{COP_R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{\dot{Q}_C}{\dot{W}_{C,\mathrm{I}} + \dot{W}_{C,\mathrm{II}}} = \frac{68.03}{16.89+3.95} = 3.26$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-33 [OCM] Consider a two-stage cascade refrigeration system operating between the pressure limits of 2 MPa and 0.05 MPa. Each stage operates on an ideal vapor-compression refrigeration cycle with R-134a as the working fluid. Heat rejection from the lower cycle to the upper cycle takes place in an adiabatic counterflow heat exchanger where both streams enter at 0.5 MPa. If the mass flow rate of the refrigerant through the upper cycle is 0.25 kg/s, determine (a) the mass flow rate of the refrigerant through the lower cycle, (b) the rate of heat removal from the refrigerated space, (c) the power input to the compressor in the lower cycle and (d) the coefficient of performance (COP_R) of this cascade refrigerator. What-if Scenario: What would the COP be if the heat exchanger pressure were (e) 0.4 MPa or (f) 0.7 MPa?

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.05\text{MPa}} = 224.06 \frac{\text{kJ}}{\text{kg}}; \; s_1 = s_{g@0.05\text{MPa}} = 0.9640 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 271.28 \frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@0.5\text{MPa}} = 72.42 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 72.42 \frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_2, x_5$):

$$h_5 = h_{g@0.5\text{MPa}} = 258.45\,\frac{\text{kJ}}{\text{kg}};\ \ s_5 = s_{g@0.5\text{MPa}} = 0.9207\,\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-6 (given $p_6, s_6 = s_5$):

$$h_6 = 286.95\,\frac{\text{kJ}}{\text{kg}}$$

State-7 (given $p_7 = p_6, x_7$):

$$h_7 = h_{f@2\text{MPa}} = 151.34\,\frac{\text{kJ}}{\text{kg}}$$

State-8 (given $p_8 = p_5, h_8 = h_7$):

$$h_8 = h_7 = 151.34\,\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_{C,\text{I}} = h_2 - h_1 = 271.28 - 224.06 = 47.22\,\frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_{H,\text{I}} = h_2 - h_3 = 271.28 - 72.42 = 198.86\,\frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_{C,\text{I}} = h_1 - h_4 = 224.06 - 72.42 = 151.64\,\frac{\text{kJ}}{\text{kg}}$

Device-D (5-6): $w_{C,\text{II}} = h_6 - h_5 = 286.95 - 258.45 = 28.50\,\frac{\text{kJ}}{\text{kg}}$

Device-E (6-7): $q_{H,\text{II}} = h_6 - h_7 = 286.95 - 151.34 = 135.61\,\frac{\text{kJ}}{\text{kg}}$

Device-F (8-5): $q_{C,\text{II}} = h_5 - h_8 = 258.45 - 151.34 = 107.11\,\frac{\text{kJ}}{\text{kg}}$

An energy balance on the counterflow heat exchanger provides the mass flow in the lower cycle.

$$\dot{m}_1 q_{H,\text{I}} = \dot{m}_5 q_{C,\text{II}};$$

$$\Rightarrow \dot{m}_1 = \dot{m}_5 \frac{q_{C,\text{II}}}{q_{H,\text{I}}} = (0.25)\left(\frac{107.11}{198.86}\right) = 0.135\,\frac{\text{kg}}{\text{s}}$$

The rate of heat removal from the refrigerated space

$$\dot{Q}_{C,\text{I}} = \dot{m}_1 q_{C,\text{I}} = (0.135)(151.64) = 20.47\ \text{kW}$$

The power input to the compressor in the lower cycle

$$\dot{W}_{C,\mathrm{I}} = \dot{m}_1 w_{C,\mathrm{I}} = (0.135)(47.22) = 6.37\ \mathrm{kW}$$

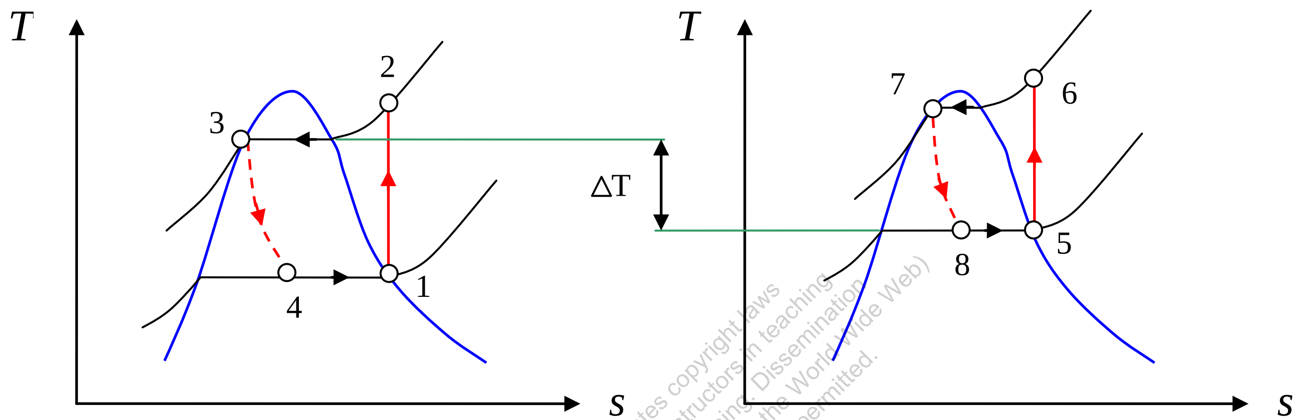
The COP can be obtained as

$$\mathrm{COP_R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{\dot{Q}_{C,\mathrm{I}}}{\dot{W}_{C,\mathrm{I}} + \dot{W}_{C,\mathrm{II}}} = \frac{20.47}{6.37 + (0.25)(28.50)} = 1.52$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-34 [OCJ] Consider a two-stage cascade refrigeration system operating between -80°C and 80°C. Each stage operates on an ideal vapor-compression refrigeration cycle. Upper cycle use R-12 as working fluid, lower cycle use R-13. In the lower cycle refrigerant condenses at 0°C, in the upper cycle refrigerant evaporates at -5°C. If the mass flow rate in the lower cycle is 1 kg/s, determine (a) the mass flow rate through the upper cycle, (b) the amount of heat removed from the refrigerated space and (c) COP. (d) What-if Scenario: What would the COP be if we consider a one-stage ideal vapor-compression system between -80°C and 80°C with R-13 as the working fluid?

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@-80°C} = 110.56\frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@-80°C} = 0.5925\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 161.17\frac{\text{kJ}}{\text{kg}}$$

State-3 (given T_3, x_3):

$$h_3 = h_{f@0°C} = 43.81\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 43.81\frac{\text{kJ}}{\text{kg}}$$

State-5 (given T_5, x_5):

$$h_5 = h_{g@-5°C} = 185.37\frac{\text{kJ}}{\text{kg}};\ s_5 = s_{g@-5°C} = 0.6991\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-6 (given $T_6, s_6 = s_5$):

$$h_6 = 220.84 \frac{\text{kJ}}{\text{kg}}$$

$$p_6 = 1881.24 \text{ kPa}$$

State-7 (given $p_7 = p_6, x_7$):

$$h_7 = h_{f\,@1881.24\text{kPa}} = 107.01 \frac{\text{kJ}}{\text{kg}}$$

State-8 (given $p_8 = p_5, h_8 = h_7$):

$$h_8 = h_7 = 107.01 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_{C,\text{I}} = h_2 - h_1 = 161.17 - 110.56 = 50.61 \frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_{H,\text{I}} = h_2 - h_3 = 161.17 - 43.81 = 117.36 \frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_{C,\text{I}} = h_1 - h_4 = 110.56 - 43.81 = 66.75 \frac{\text{kJ}}{\text{kg}}$

Device-D (5-6): $w_{C,\text{II}} = h_6 - h_5 = 220.84 - 185.37 = 35.47 \frac{\text{kJ}}{\text{kg}}$

Device-E (6-7): $q_{H,\text{II}} = h_6 - h_7 = 220.84 - 107.01 = 113.83 \frac{\text{kJ}}{\text{kg}}$

Device-F (8-5): $q_{C,\text{II}} = h_5 - h_8 = 185.37 - 107.01 = 78.36 \frac{\text{kJ}}{\text{kg}}$

An energy balance on the counterflow heat exchanger provides the mass flow in the upper cycle.

$$\dot{m}_1 q_{H,\text{I}} = \dot{m}_5 q_{C,\text{II}};$$

$$\Rightarrow \dot{m}_5 = \dot{m}_1 \frac{q_{H,\text{I}}}{q_{C,\text{II}}} = (1)\left(\frac{117.36}{78.36}\right) = 1.50 \frac{\text{kg}}{\text{s}}$$

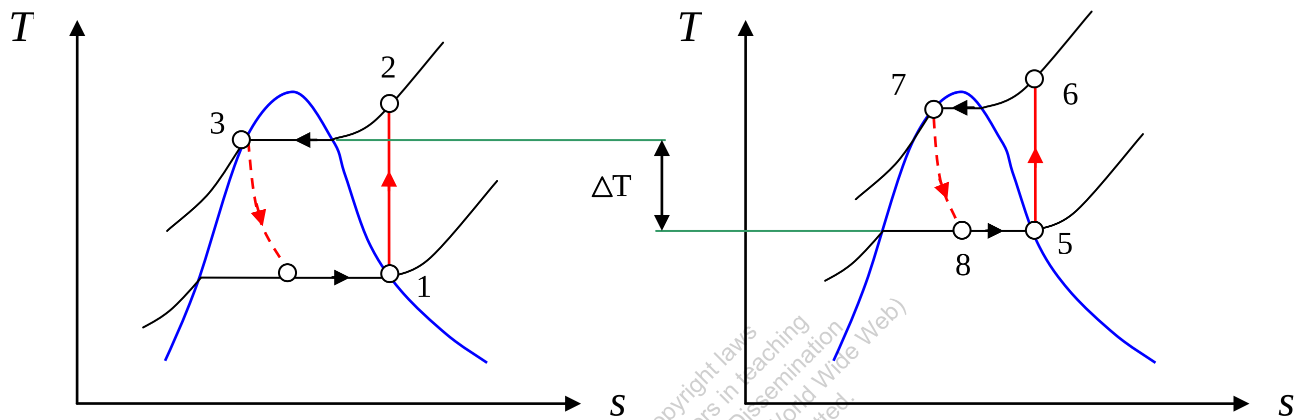
The COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{\dot{Q}_{C,\text{I}}}{\dot{W}_{C,\text{I}} + \dot{W}_{C,\text{II}}} = \frac{(1)(66.75)}{(1)(50.61) + (1.50)(35.47)} = 0.64$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-35 [OVO] Consider a two-stage cascade refrigeration system operating between 0.1 MPa and 1 MPa. Each stage operates on the ideal cycle with R-134a as the working fluid. Heat rejection from the lower to the upper cycle occurs at 0.4 MPa. If the mass flow rate in the upper cycle is 0.1 kg/s, determine (a) the mass flow rate through the lower cycle and (b) the COP. (c) What-if Scenario: What would the COP be if the intermediate pressure were changed to 0.6 MPa?

SOLUTION



State-1 (given p_1, x_1):

$$h_1 = h_{g@0.1\text{MPa}} = 233.00\frac{\text{kJ}}{\text{kg}};\ s_1 = s_{g@0.1\text{MPa}} = 0.9465\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2, s_2 = s_1$):

$$h_2 = 261.30\frac{\text{kJ}}{\text{kg}}$$

State-3 (given $p_3 = p_2, x_3$):

$$h_3 = h_{f@0.4\text{MPa}} = 62.99\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 62.99\frac{\text{kJ}}{\text{kg}}$$

State-5 (given $p_5 = p_2, x_5$):

$$h_5 = h_{g@0.4\text{MPa}} = 254.56\frac{\text{kJ}}{\text{kg}};\ s_5 = s_{g@0.4\text{MPa}} = 0.9232\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-6 (given $p_6, s_6 = s_5$):

$$h_6 = 273.65\,\frac{\text{kJ}}{\text{kg}}$$

State-7 (given $p_7 = p_6, x_7$):

$$h_7 = h_{f\,@1\text{MPa}} = 106.61\,\frac{\text{kJ}}{\text{kg}}$$

State-8 (given $p_8 = p_5, h_8 = h_7$):

$$h_8 = h_7 = 106.61\,\frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_{C,\text{I}} = h_2 - h_1 = 261.30 - 233.00 = 28.30\,\frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_{H,\text{I}} = h_2 - h_3 = 261.30 - 62.99 = 198.31\,\frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_{C,\text{I}} = h_1 - h_4 = 233.00 - 62.99 = 170.01\,\frac{\text{kJ}}{\text{kg}}$

Device-D (5-6): $w_{C,\text{II}} = h_6 - h_5 = 273.65 - 254.56 = 19.09\,\frac{\text{kJ}}{\text{kg}}$

Device-E (6-7): $q_{H,\text{II}} = h_6 - h_7 = 273.65 - 106.61 = 167.04\,\frac{\text{kJ}}{\text{kg}}$

Device-F (8-5): $q_{C,\text{II}} = h_5 - h_8 = 254.56 - 106.61 = 147.95\,\frac{\text{kJ}}{\text{kg}}$

An energy balance on the counterflow heat exchanger provides the mass flow in the lower cycle.

$$\dot{m}_1 q_{H,\text{I}} = \dot{m}_5 q_{C,\text{II}};$$

$$\Rightarrow \dot{m}_1 = \dot{m}_5 \frac{q_{C,\text{II}}}{q_{H,\text{I}}} = (0.1)\left(\frac{147.95}{198.31}\right) = 0.075\,\frac{\text{kg}}{\text{s}}$$

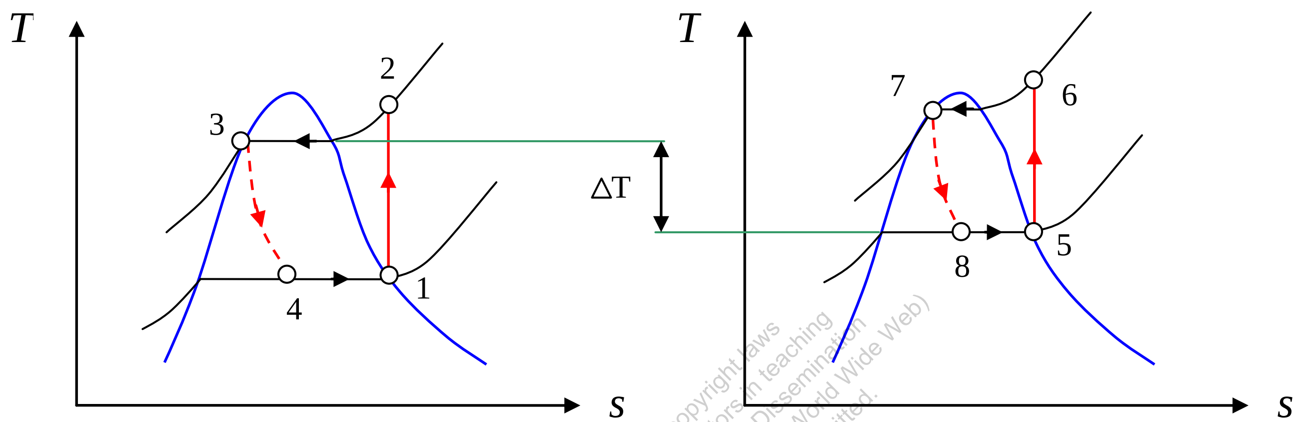
The COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{\dot{Q}_{C,\text{I}}}{\dot{W}_{C,\text{I}} + \dot{W}_{C,\text{II}}} = \frac{(0.075)(170.01)}{(0.075)(28.30) + (0.1)(19.09)} = 3.16$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).

10-1-36 [OCW] Consider a two-stage cascade refrigeration system operating between -60°C and 50°C. Each stage operates on an ideal vapor-compression refrigeration cycle. The upper cycle uses R-134a as working fluid, lower cycle uses R-22. In the lower cycle refrigerant condenses at 10°C, in the upper cycle refrigerant evaporates at 0°C. If the mass flow rate in the upper cycle is 0.5 kg/s, determine (a) the mass flow rate through the lower cycle, (b) the rate of cooling in tons, (c) the coefficient of performance (COP_R) and (d) the compressor power input in kW.

SOLUTION



State-1 (given T_1, x_1):

$$h_1 = h_{g@-60°C} = 223.70\frac{\text{kJ}}{\text{kg}};\; s_1 = s_{g@-60°C} = 1.0540\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-2 (given $p_2 = p_3, s_2 = s_1$):

$$h_2 = 297.40\frac{\text{kJ}}{\text{kg}}$$

State-3 (given T_3, x_3):

$$h_3 = h_{f@10°C} = 56.46\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, h_4 = h_3$):

$$h_4 = h_3 = 56.46\frac{\text{kJ}}{\text{kg}}$$

State-5 (given T_5, x_5):

$$h_5 = h_{g@0°C} = 249.38\frac{\text{kJ}}{\text{kg}};\; s_5 = s_{g@0°C} = 0.9271\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

State-6 (given $T_6, s_6 = s_5$):

$$h_6 = 278.32 \frac{\text{kJ}}{\text{kg}}$$

$$p_6 = 1178.34 \text{ kPa}$$

State-7 (given $p_7 = p_6, x_7$):

$$h_7 = h_{f\,@1178.34\text{kPa}} = 116.04 \frac{\text{kJ}}{\text{kg}}$$

State-8 (given $p_8 = p_5, h_8 = h_7$):

$$h_8 = h_7 = 116.04 \frac{\text{kJ}}{\text{kg}}$$

A steady-state energy analysis is carried out for each device as follows.

Device-A (1-2): $w_{C,\text{I}} = h_2 - h_1 = 297.40 - 223.70 = 73.70 \frac{\text{kJ}}{\text{kg}}$

Device-B (2-3): $q_{H,\text{I}} = h_2 - h_3 = 297.40 - 56.46 = 240.94 \frac{\text{kJ}}{\text{kg}}$

Device-C (4-1): $q_{C,\text{I}} = h_1 - h_4 = 223.70 - 56.46 = 167.24 \frac{\text{kJ}}{\text{kg}}$

Device-D (5-6): $w_{C,\text{II}} = h_6 - h_5 = 278.32 - 249.38 = 28.94 \frac{\text{kJ}}{\text{kg}}$

Device-E (6-7): $q_{H,\text{II}} = h_6 - h_7 = 278.32 - 116.04 = 162.28 \frac{\text{kJ}}{\text{kg}}$

Device-F (8-5): $q_{C,\text{II}} = h_5 - h_8 = 249.38 - 116.04 = 133.34 \frac{\text{kJ}}{\text{kg}}$

An energy balance on the counterflow heat exchanger provides the mass flow in the lower cycle.

$$\dot{m}_1 q_{H,\text{I}} = \dot{m}_5 q_{C,\text{II}};$$

$$\Rightarrow \dot{m}_1 = \dot{m}_5 \frac{q_{C,\text{II}}}{q_{H,\text{I}}} = (0.5)\left(\frac{133.34}{240.94}\right) = 0.277 \frac{\text{kg}}{\text{s}}$$

The rate of heat removal from the refrigerated space

$$\dot{Q}_{C,\text{I}} = \dot{m}_1 q_{C,\text{I}} = (0.277)(167.24) = 46.33 \text{ kW} = 13.17 \text{ ton}$$

The power input to the compressors

$$\dot{W}_C = \dot{W}_{C,\text{I}} + \dot{W}_{C,\text{II}} = \dot{m}_1 w_{C,\text{I}} + \dot{m}_5 w_{C,\text{II}} = (0.277)(73.70) + (0.5)(28.94) = 34.88 \text{ kW}$$

The COP can be obtained as

$$\text{COP}_\text{R} = \frac{\dot{Q}_C}{\dot{W}_C} = \frac{46.33}{34.88} = 1.33$$

TEST Solution and What-if Scenario: Use PC vapor-compression cycle TESTcalc to verify this answer and explore the what-if scenario. TEST-code for this problem can be found in thermofluids.net (the professional site of TEST).