MENG541 Advanced Thermodynamics

Example: Exergy Analysis of Air-to-Water Heat Pump*

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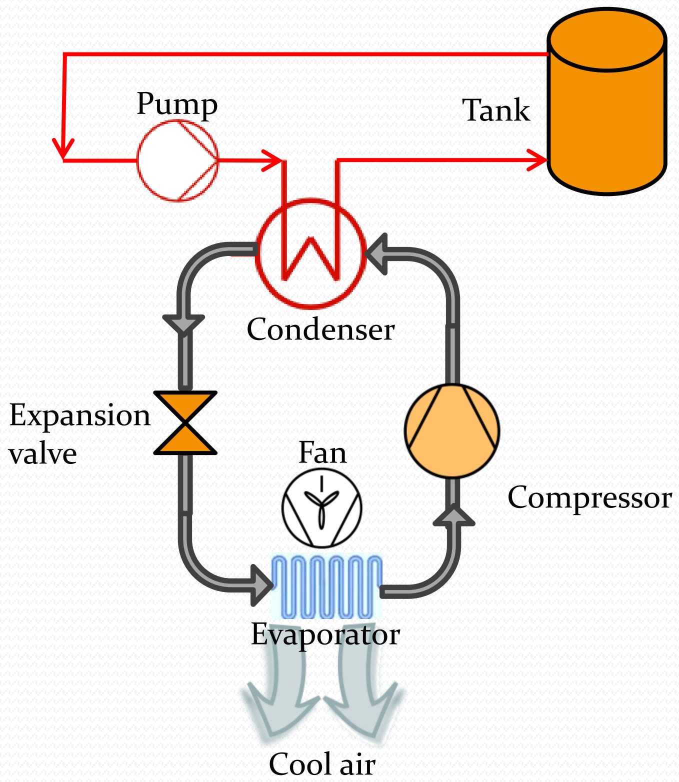
*Source: I. Dincer and M. Rosen, Exergy, Energy Environment and Sustainable Development. 2nd Ed., Elsevier

Example: Exergy analysis of an air-to-water heat pump

Schematic diagram:



System Description

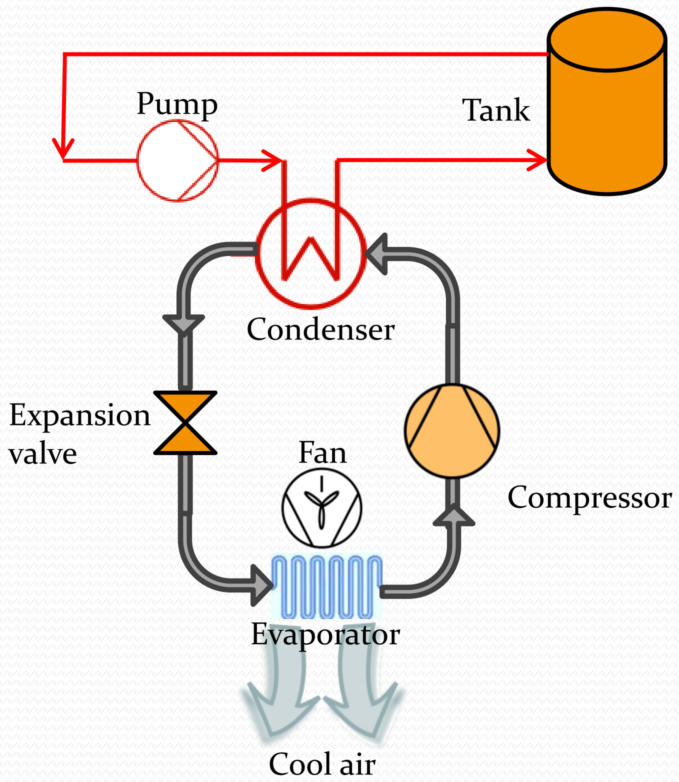
- The system consists of 2 separate circuits:

1. A heat pump circuit (refrigerant circuit)
2. A heat carriage circuit (water circuit)

- The refrigerant circuit consists of:
  - a compressor
  - a condenser
  - an expansion valve
  - an evaporator
- The water circuit consists of a storage tank and a pump.

Mass, Energy and Exergy Balances

Schematic diagram:



Equations:

For each component the following general equations can be used:

→A general mass balance can be written as follows:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

→Energy balance is given as:

$$\dot{E}_{in} = \dot{E}_{out}$$

→Exergy balance is expressed as:

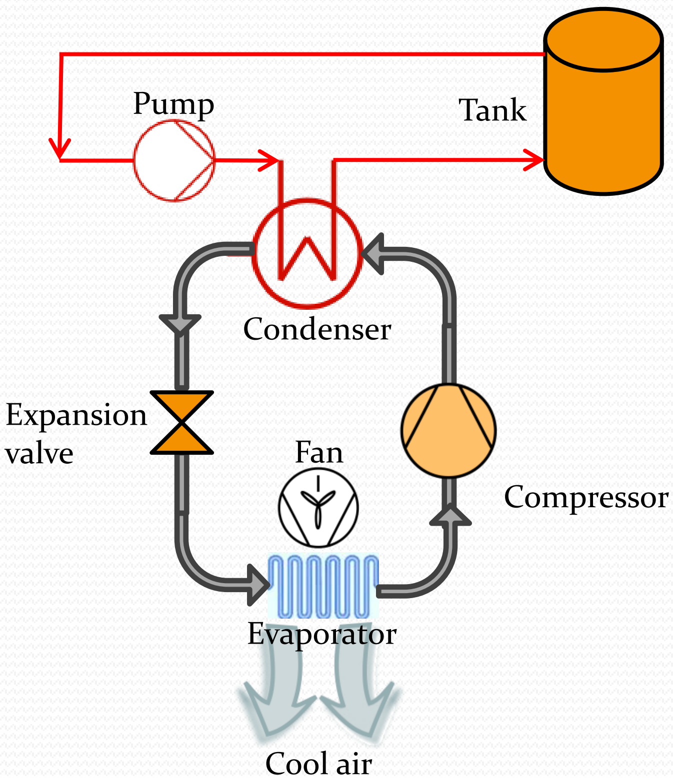
$$\dot{\Psi}_{in} - \dot{\Psi}_{out} = \dot{X}_{des}$$

Where $\dot{\Psi}$ is the rate of exergy of flowing stream

→The specific flow exergy of water:

$$\psi_{H_2O} = (h - h_0) - T_0(s - s_0)$$

Flow Exergy for Refrigerant and Air



→The specific flow exergy of refrigerant:

$$\psi_{ref} = (h - h_0) - T_0(s - s_0)$$

→The overall specific flow exergy of air can be expressed as follows*:

$$\psi_{air} = (C_{p,a} + \omega C_{p,v})T_0[(T/T_0) - 1 - \ln(T/T_0)] + (1 + 1.6078\omega)R_a T_0 \ln(P/P_0) + R_a T_0 \left\{ (1 + 1.6078\omega) \ln\left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega}\right) + 1.6078\omega \ln\frac{\omega}{\omega_0} \right\}$$

where ω is the specific humidity ratio ($=\dot{m}_v/\dot{m}_a$)

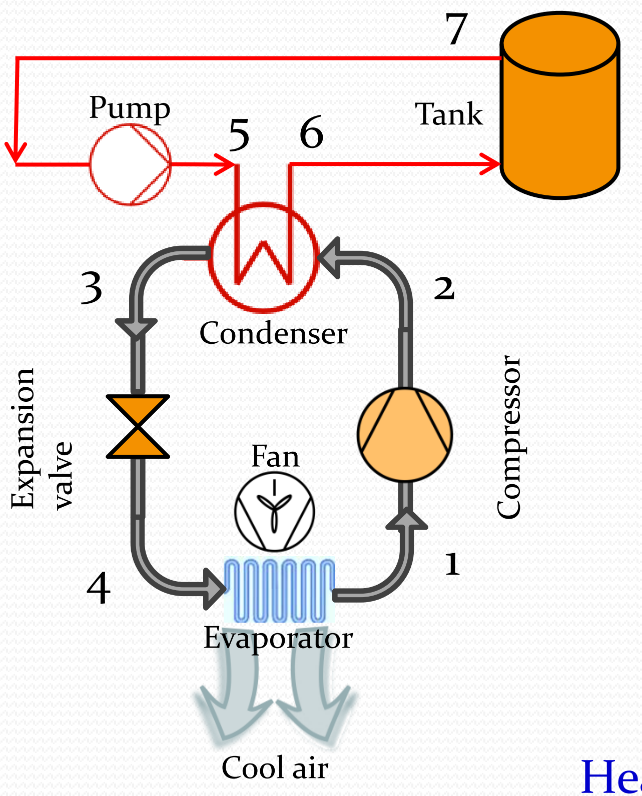
R_a is gas constant of air

*Source: Webfer et al. ASHRAE Trans. 85, 214-230 (1979)

Assumptions

- Steady flow process with negligible KE and PE
- Air behaves as an ideal gas
- Heat losses and pressure drops in pipes are negligible since they are short in length
- $\eta_{comp,mech} = 68\%$ and $\eta_{comp,elec} = 82\%$ based on actual data
- $\eta_{pump,mech} = 82\%$ and $\eta_{pump,elec} = 88\%$ based on actual data
- $\eta_{\text{fan},mech} = 40\%$ and $\eta_{\text{fan},elec} = 80\%$ based on actual data

Mass, Energy and Exergy Destruction of **Compressor**



$$\dot{m}_1 = \dot{m}_2 = \dot{m}_{ref}$$

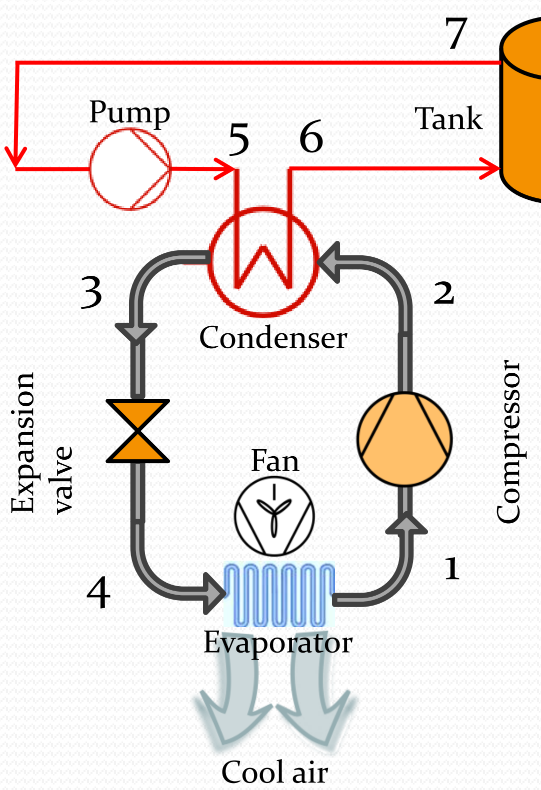
$$\dot{W}_{comp} = \dot{m}_{ref}\left(h_{2,act} - h_1\right)$$

$$\dot{X}_{des,comp} = \dot{W}_{comp} - (\dot{\Psi}_{out} - \dot{\Psi}_{in})$$

$$\dot{X}_{des,comp} = \dot{m}_{ref}\left(\psi_1 - \psi_{2,act}\right) + \dot{W}_{comp}$$

Heat interactions with the environment are neglected

Mass, Energy and Exergy Destruction of **Condenser**



$$\dot{m}_2 = \dot{m}_3 = \dot{m}_{ref}$$

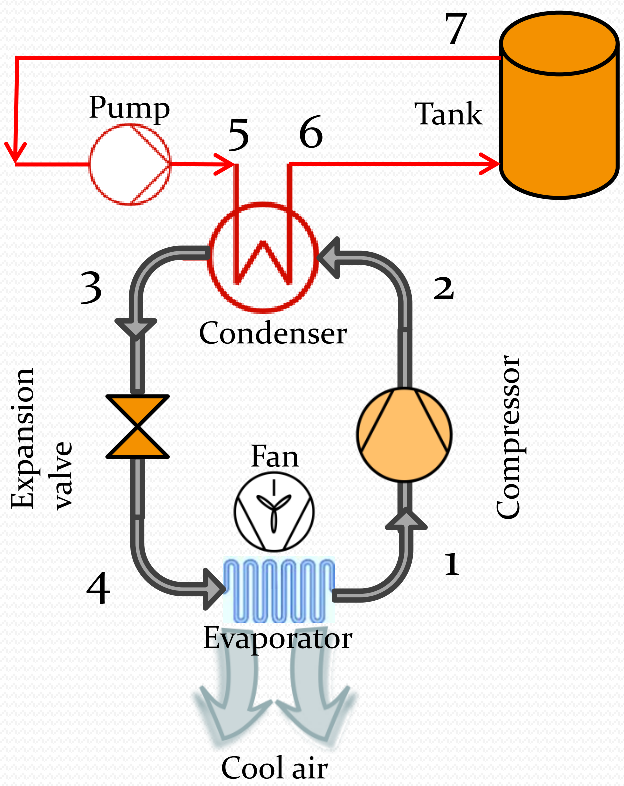
$$\dot{m}_5 = \dot{m}_6 = \dot{m}_{H_2O}$$

$$\dot{Q}_{cond} = \dot{m}_{ref}\left(h_{2,act} - h_3\right)$$

$$\dot{Q}_{cond} = \dot{m}_{H_2O} C_{p,H_2O}(T_6 - T_5)$$

$$\dot{X}_{des,cond} = \dot{m}_{ref}\left(\psi_{2,act} - \psi_3\right) + \dot{m}_{H_2O}(\psi_5 - \psi_6)$$

Mass, Energy and Exergy Destruction of **Expansion Valve**



$$\dot{m}_3 = \dot{m}_4 = \dot{m}_{ref}$$

$$h_3 = h_4$$

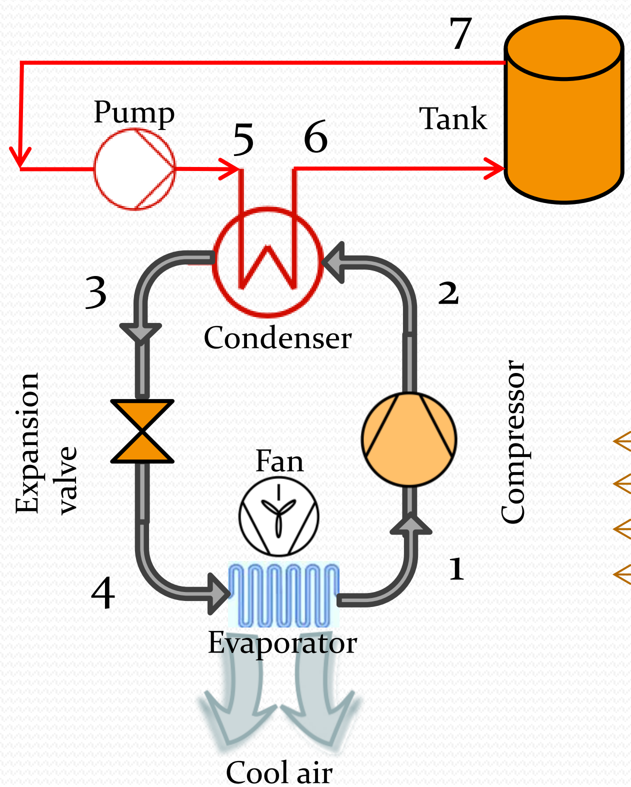
$$\dot{X}_{des,exp} = \dot{m}_{ref}(\psi_3 - \psi_4)$$

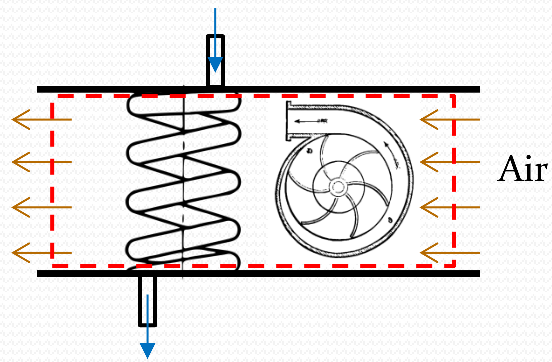
Mass, Energy and Exergy Destruction of **Evaporator**

$$\dot{m}_4 = \dot{m}_1 = \dot{m}_{ref}$$

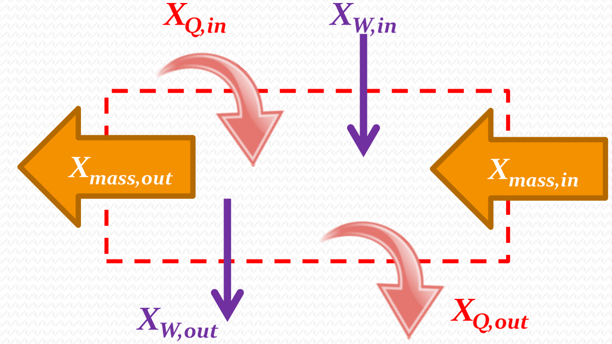
$$\dot{Q}_{evap} = \dot{m}_{ref}(h_1 - h_4)$$

$$\dot{Q}_{evap} = \dot{m}_{air}C_{p,air}(\Delta T_{air})$$





Exergy Balance:



$$\dot{X}_{des,evap} = \underbrace{\dot{m}_{ref}(\psi_4 - \psi_1) + \dot{m}_{air}(\Delta\psi_{air})}_{\dot{X}_{mass,in} - \dot{X}_{mass,out}} + \dot{W}_{fan}$$