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Refrigeration and Air Conditioning
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Second-Law Analysis to Improve the Energy Efficiency of Environmental Control Unit

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AB1

Presentation Outlines

- Motivation
- Objectives
- Thermodynamic Modeling
  - » 1st and 2nd law analysis
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- Experimental Methodology
- Results and Comparison
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Slide 2

AB1 Should I include an introduction section to talk about second law ?

Ammar Bahman, 6/26/2016

Motivation

- Environmental Control Units (ECUs) are used by the military for space cooling inside shelters in hot climate regions
- Need for identifying components with the potential to improve the efficiency of the ECU
- Lack of second-law analyses applied to ECUs

Objectives

- Develop a methodology, based on second-law analysis, to evaluate the irreversibilities within each component of an ECU
- Identify the potential in each component to contribute to the exergetic efficiency of the overall system in high temperature ambient conditions
- Comparisons of three units to provide a clear direction of how to increase the system exergetic efficiency of Environmental Control Units

Thermodynamic Modeling

1st law of thermodynamics

$$\sum_{i=0}^{n}\dot{Q}_i - \dot{W} + \sum_{in}\dot{m}\left(h + \frac{V^2}{2} + gz\right) - \sum_{out}\dot{m}\left(h + \frac{V^2}{2} + gz\right) = 0$$

2nd law of thermodynamics

$$\sum_{i=0}^{n}\frac{\dot{Q}_i}{T_i} + \sum_{in}\dot{m}s - \sum_{out}\dot{m}s + \dot{S}_{gen} = 0$$

Exergy destruction (irreversibility)

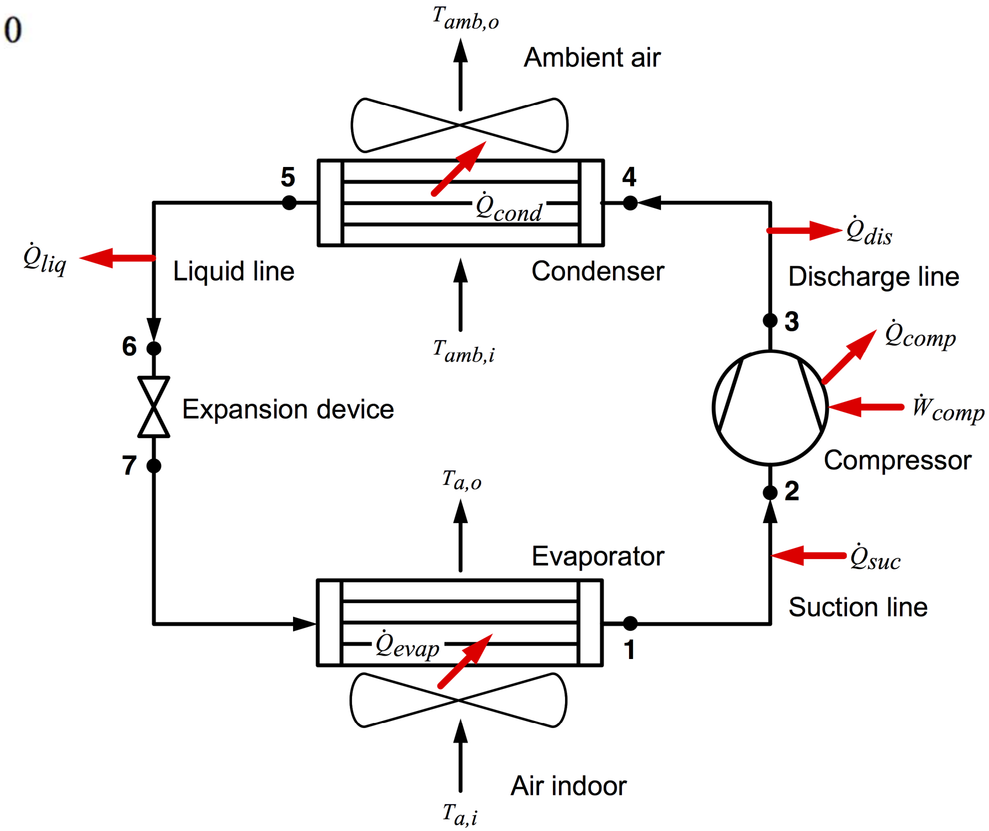
$$\dot{I} = T_0\dot{S}_{gen}$$

Exergy balance

$$\sum_{i=0}^{n}\left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i - \dot{W} + \sum_{in}\dot{m}\psi - \sum_{out}\dot{m}\psi - \dot{I} = 0$$

2nd law efficiency

$$\varepsilon = \frac{\text{exergy recovered}}{\text{exergy supplied}}$$



1st and 2nd law Analysis

$$\dot{Q}_{cond} = \dot{m}_r (h_5 - h_4)$$

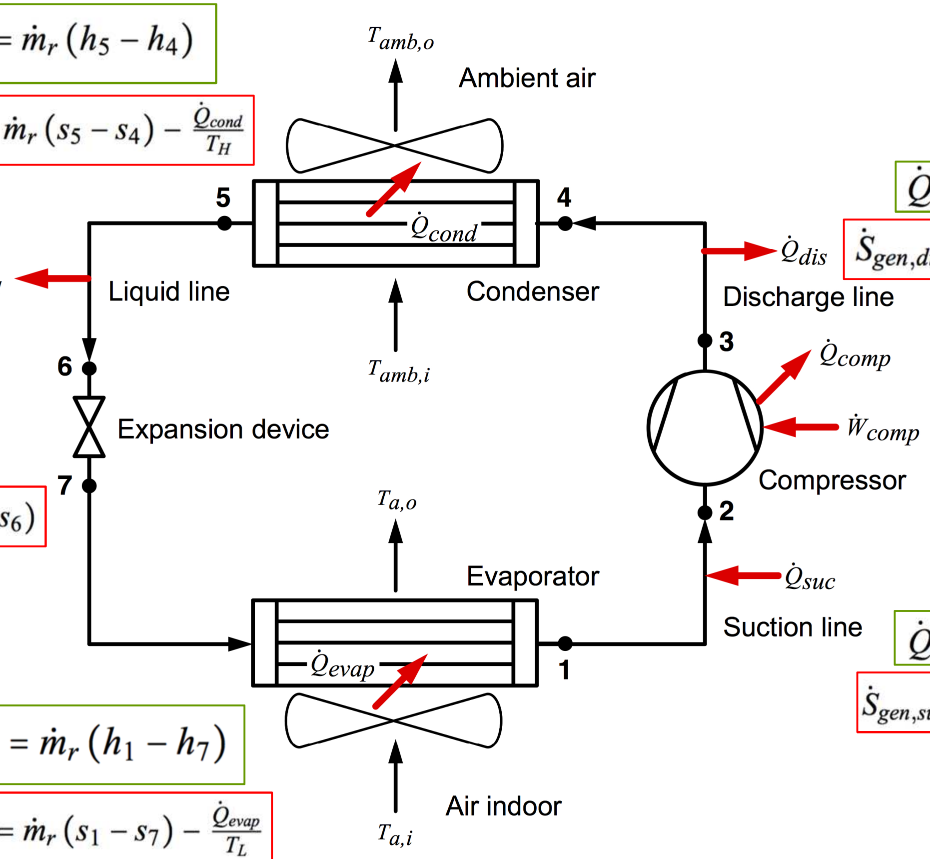
$$\dot{S}_{gen,cond} = \dot{m}_r (s_5 - s_4) - \frac{\dot{Q}_{cond}}{T_H}$$

$$\dot{Q}_{liq} = \dot{m}_r (h_6 - h_5)$$

$$\dot{S}_{gen,liq} = \dot{m}_r (s_6 - s_5) - \frac{\dot{Q}_{liq}}{T_0}$$

$$h_6 = h_7$$

$$\dot{S}_{gen,exv} = \dot{m}_r (s_7 - s_6)$$



$$\dot{Q}_{dis} = \dot{m}_r (h_4 - h_3)$$

$$\dot{S}_{gen,dis} = \dot{m}_r (s_4 - s_3) - \frac{\dot{Q}_{dis}}{T_0}$$

$$\dot{Q}_{comp} = \dot{m}_r (h_3 - h_2) + \dot{W}_{comp}$$

$$\dot{S}_{gen,comp} = \dot{m}_r (s_3 - s_2) - \frac{\dot{Q}_{loss}}{T_0}$$

$$\dot{Q}_{suc} = \dot{m}_r (h_2 - h_1)$$

$$\dot{S}_{gen,suc} = \dot{m}_r (s_2 - s_1) - \frac{\dot{Q}_{suc}}{T_0}$$

$$\dot{Q}_{evap} = \dot{m}_r (h_1 - h_7)$$

$$\dot{S}_{gen,evap} = \dot{m}_r (s_1 - s_7) - \frac{\dot{Q}_{evap}}{T_L}$$

Availability Analysis

$$\varepsilon_{cond} = \frac{\dot{m}_{cond,a}\Delta\psi_{cond,a}}{|\dot{m}_r \Delta\psi_{cond,r}|}$$

$$\Delta\psi_{cond,a} = h_{amb,o} - h_{amb,i} - T_0\left(s_{amb,o} - s_{amb,i}\right)$$
$$\Delta\psi_{cond,r} = h_5 - h_4 - T_0\left(s_5 - s_4\right)$$

$$\varepsilon_{liq} = \frac{\psi_{liq,o}}{\psi_{liq,i}}$$

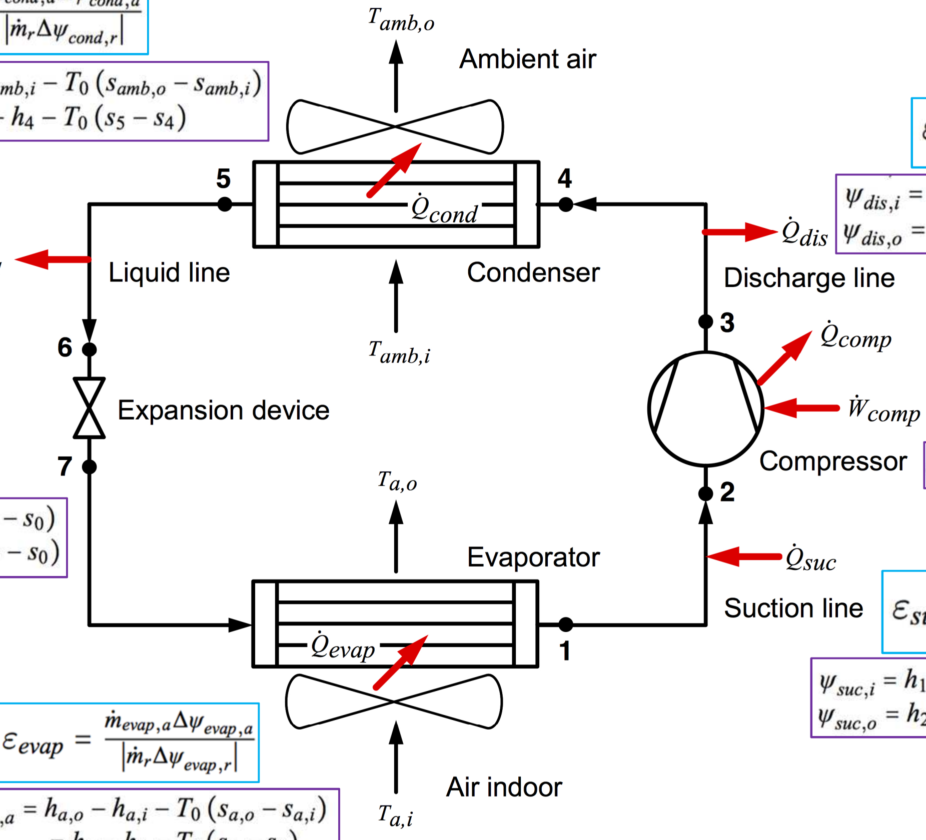
$$\psi_{liq,i} = h_5 - h_0 - T_0\left(s_5 - s_0\right)$$
$$\psi_{liq,o} = h_6 - h_0 - T_0\left(s_6 - s_0\right)$$

$$\varepsilon_{exv} = \frac{\psi_{exv,o}}{\psi_{exv,i}}$$

$$\psi_{exv,i} = h_6 - h_0 - T_0\left(s_6 - s_0\right)$$
$$\psi_{exv,o} = h_7 - h_0 - T_0\left(s_7 - s_0\right)$$

$$\varepsilon_{evap} = \frac{\dot{m}_{evap,a}\Delta\psi_{evap,a}}{|\dot{m}_r \Delta\psi_{evap,r}|}$$

$$\Delta\psi_{evap,a} = h_{a,o} - h_{a,i} - T_0\left(s_{a,o} - s_{a,i}\right)$$
$$\Delta\psi_{evap,r} = h_1 - h_7 - T_0\left(s_1 - s_7\right)$$



$$\varepsilon_{dis} = \frac{\psi_{dis,o}}{\psi_{dis,i}}$$

$$\psi_{dis,i} = h_3 - h_0 - T_0\left(s_3 - s_0\right)$$
$$\psi_{dis,o} = h_4 - h_0 - T_0\left(s_4 - s_0\right)$$

$$\varepsilon_{comp} = \frac{\dot{m}_r \Delta\psi_{comp}}{\dot{W}_{comp}}$$

$$\Delta\psi_{comp} = h_3 - h_2 - T_0\left(s_3 - s_2\right)$$

$$\varepsilon_{suc} = \frac{\psi_{suc,o}}{\psi_{suc,i}}$$

$$\psi_{suc,i} = h_1 - h_0 - T_0\left(s_1 - s_0\right)$$
$$\psi_{suc,o} = h_2 - h_0 - T_0\left(s_2 - s_0\right)$$

Component and Cycle Analysis

Exergy destruction ratio

$$E_d = \frac{\dot{I}_i}{\sum \dot{I}_i}$$

$$\dot{I} = T_0 \dot{S}_{gen}$$

$$\sum \dot{I}_i = T_0 \left(\dot{S}_{gen,comp} + \dot{S}_{gen,cond} + \dot{S}_{gen,exv} + \dot{S}_{gen,evap} + \dot{S}_{gen,suc} + \dot{S}_{gen,dis} + \dot{S}_{gen,liq} \right)$$

2nd law efficiency

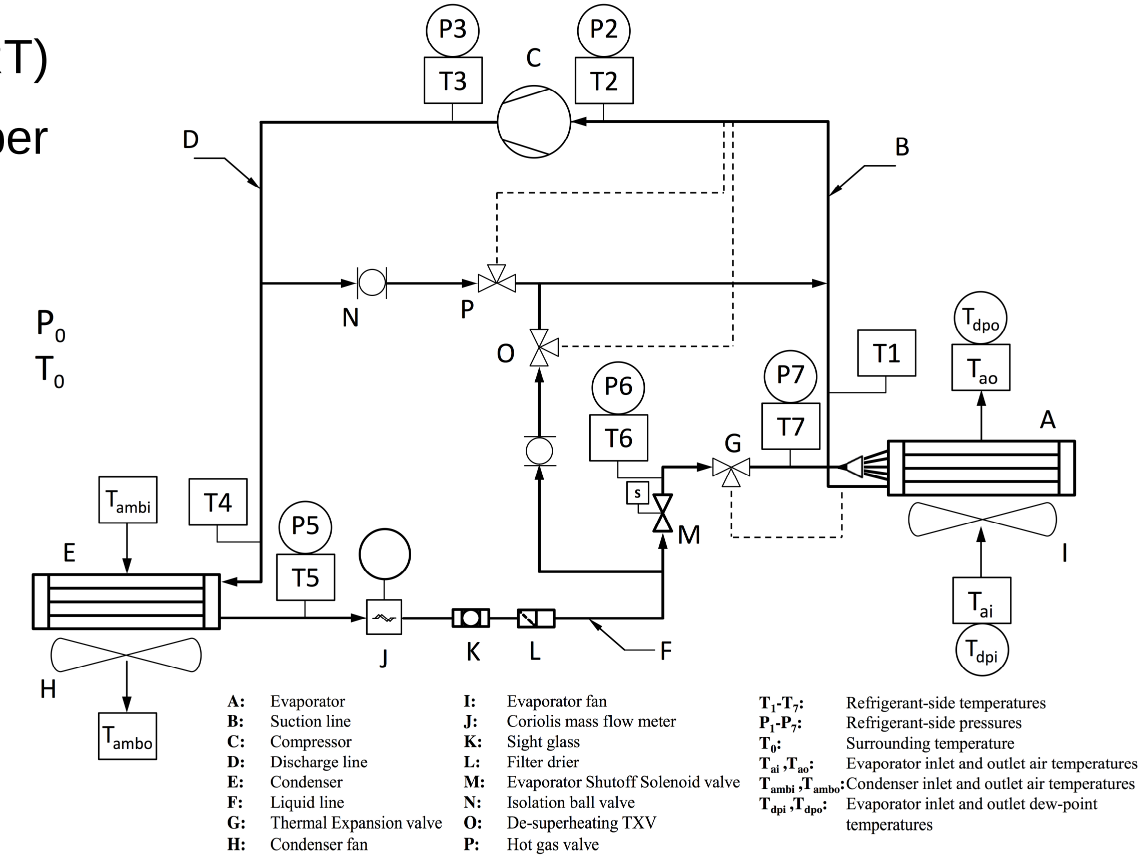
$$\varepsilon_c = \frac{\text{COP}_c}{\text{COP}_{rev}}$$

$$\text{COP}_c = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}}$$

$$\text{COP}_{rev} = \frac{T_L}{T_H - T_L}$$

Experimental Setup

- 3 ECUs (1.5 RT, 3 RT, and 5 RT)
- Tested in psychrometric chamber
- R407C and R410A
- Hermetic scroll compressor
- Aluminum micro-channel condenser
- Aluminum fin and copper tube evaporator (e-coated)
- Thermal expansion valve
- Hot-gas by-pass circuit
- Charged under condition:
  Outdoor: 95°F (db) / 75°F (wb)
  Indoor: 80°F (db) / 67°F (wb)



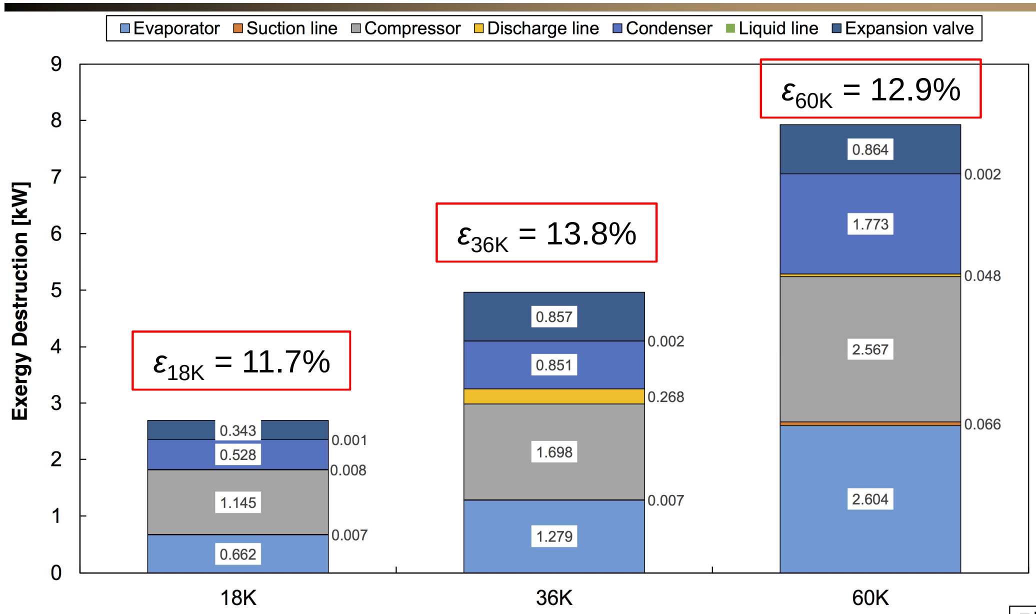
Physical parameter	Instrument	Range	Accuracy
Temperature	Stainless steel T-type	−250-350 °C	±0.5 °C
Pressure	Pressure transducer	0-1750, 0-3500, 0-7000 kPa	±0.08% FS
Air humidity	Hygrometer chilled mirror	−20-85 °C, 0-95%	±0.2 °C
Refrigerant flow rate	Coriolis flow meter	0-2720 kg/hr	±0.2%
Power consumption	Power transducer	0-45 kW	±0.25% FS

Experimental Method

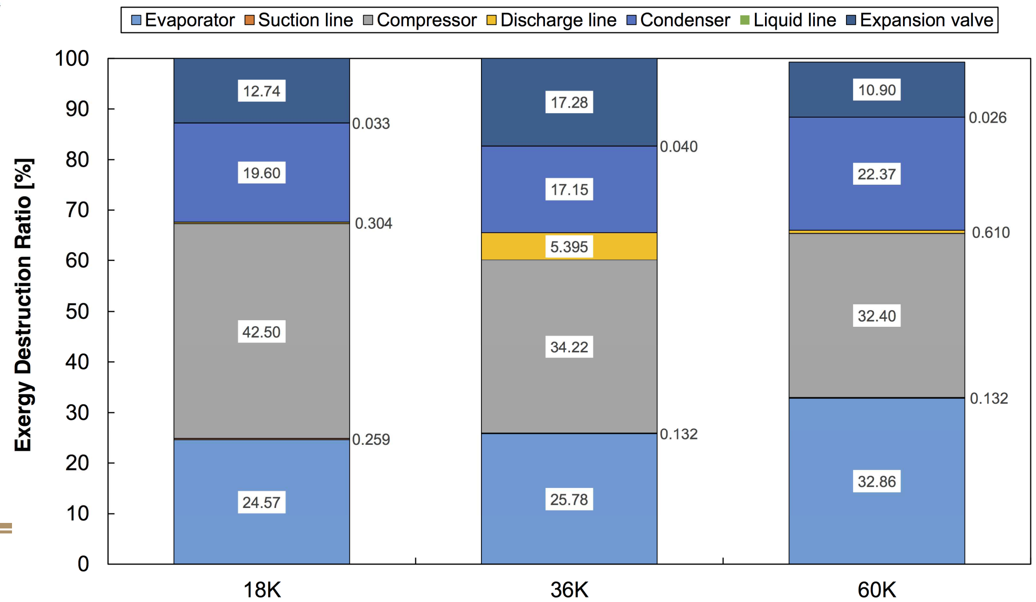
- Test conditions:
  Indoor: 90°F (db) / 85°F (wb)
  Outdoor: 125°F (db) / 75°F (wb)
- Steady-state, data measurements every two seconds for 15 minutes
- Air-side and refrigerant-side within 6% per ANSI/AHRI Standard 210/240
- Properties evaluated using Engineering Equation Solver (EES)

Unit	State	Pressure kPa	Temperature °C	Enthalpy kJ/kg	Entropy kJ/kg-K	Specific volume m^3/kg	Description
18K	1	655.8	16.59	420.4	1.785	0.037150	Evaporator outlet
	2	655.8	17.92	421.7	1.790	0.037430	Compressor inlet
	3	3108	111	486.2	1.857	0.009306	Compressor outlet
	4	3108	110	485.1	1.854	0.009252	Condenser inlet
	5	3095	60.57	295.6	1.307	0.001048	Condenser outlet
	6	3080	60.47	295.5	1.307	0.001047	Expansion valve inlet
	7	975	19.76	295.6	1.331	0.010040	Evaporator inlet
36K	1	1069	18.58	434.5	1.829	0.025910	Evaporator outlet
	2	1069	19.14	435.1	1.831	0.026010	Compressor inlet
	3	4363	110.1	492.6	1.875	0.007530	Compressor outlet
	4	4363	95.26	471.5	1.819	0.006708	Condenser inlet
	5	4316	58.67	302.3	1.326	0.001165	Condenser outlet
	6	4301	58.57	302.1	1.326	0.001165	Expansion valve inlet
	7	1308	16.4	302.4	1.355	0.008100	Evaporator inlet
60K	1	625.3	20.75	425.2	1.806	0.040160	Evaporator outlet
	2	625.3	25.75	430	1.822	0.041210	Compressor inlet
	3	3213	111.9	486.2	1.855	0.008957	Compressor outlet
	4	3213	110.2	484	1.849	0.008862	Condenser inlet
	5	3145	61.2	296.8	1.311	0.001052	Condenser outlet
	6	3130	61.1	296.6	1.31	0.001052	Expansion valve inlet
	7	1072	23.05	296.8	1.329	0.008100	Evaporator inlet

Results and Comparison



Unit	ε_{comp} %	ε_{evap} %	ε_{cond} %
18K	62.5	48.8	9.7
36K	70.5	50.0	7.5
60K	71.8	45.5	4.8



Conclusions

- Conducted 2nd-Law analyses of 3 military ECUs to identify the contribution of each component to the overall irreversibilities of the units.
- ECUs were experimentally investigated at high ambient condition and comparisons between the individual components were made to provide a clear direction of how to increase the exergetic efficiency
- The exergy destruction (or irreversibility) associated with each component in the tested ECUs follow the sequence:
  - » Compressor (32.4% to 42.5% of the total system irreversibility)
  - » Evaporator (24.6% to 32.9%)
  - » Condenser (19.6% to 22.4%)
- Compressor should be considered first in increasing the exergetic efficiency of all ECUs; whereas in 60K ECU, evaporator should also be considered.
- Second-law analysis helps identifying components with higher exergy destruction (or irreversibility)

THANK YOU