CAE 464/517 HVAC Systems Design

Spring 2023

April 25, 2023

Vapor compression cycles

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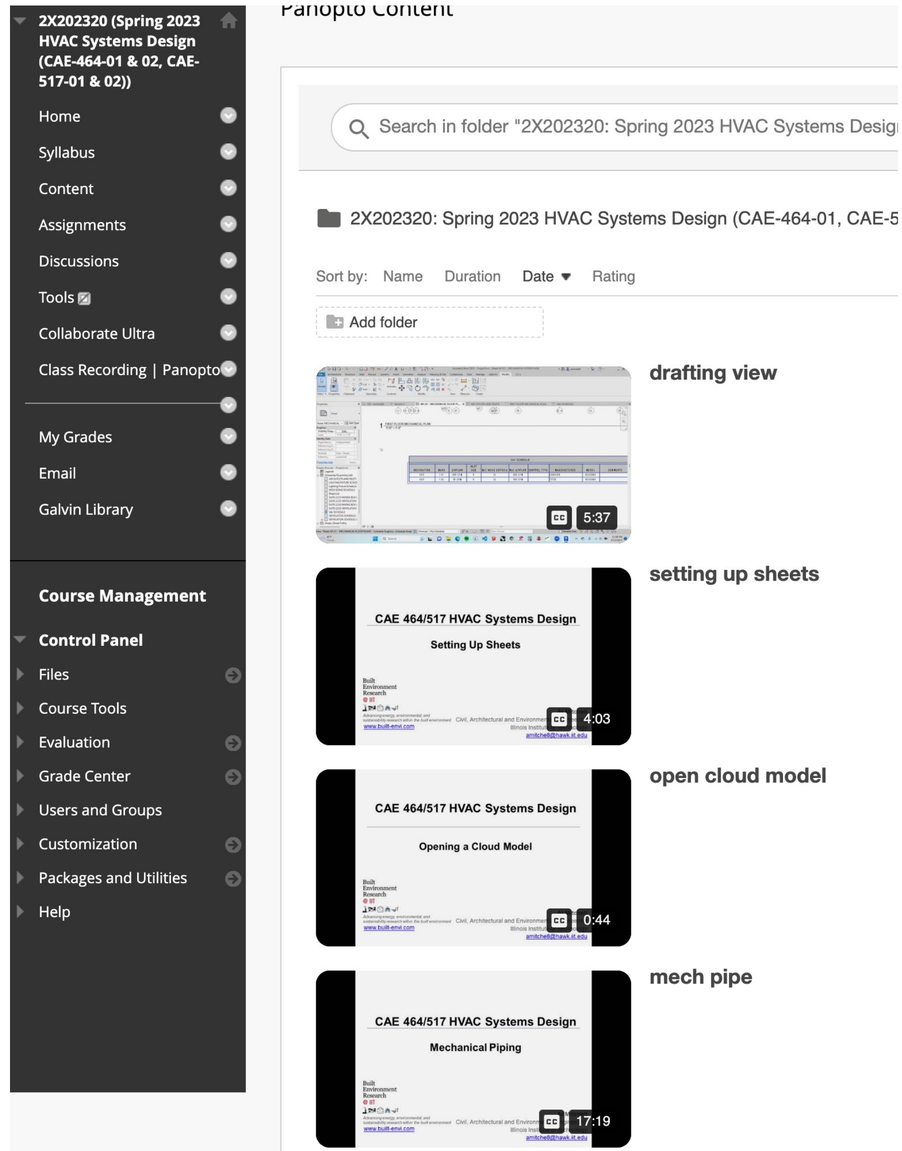
ANNOUNCEMENTS

Announcements

- Please do not forget about submitting the final presentation time change survey (everyone should agree with the change)
- Project Part 3 is due tonight (no extension)
- We will have a building tour Thursday (Stuart and Kaplan) – additional instructions will be provided for writing a summary visit report (those who needs extra credit)
- Sample final report submissions are provided in Blackboard

Announcements

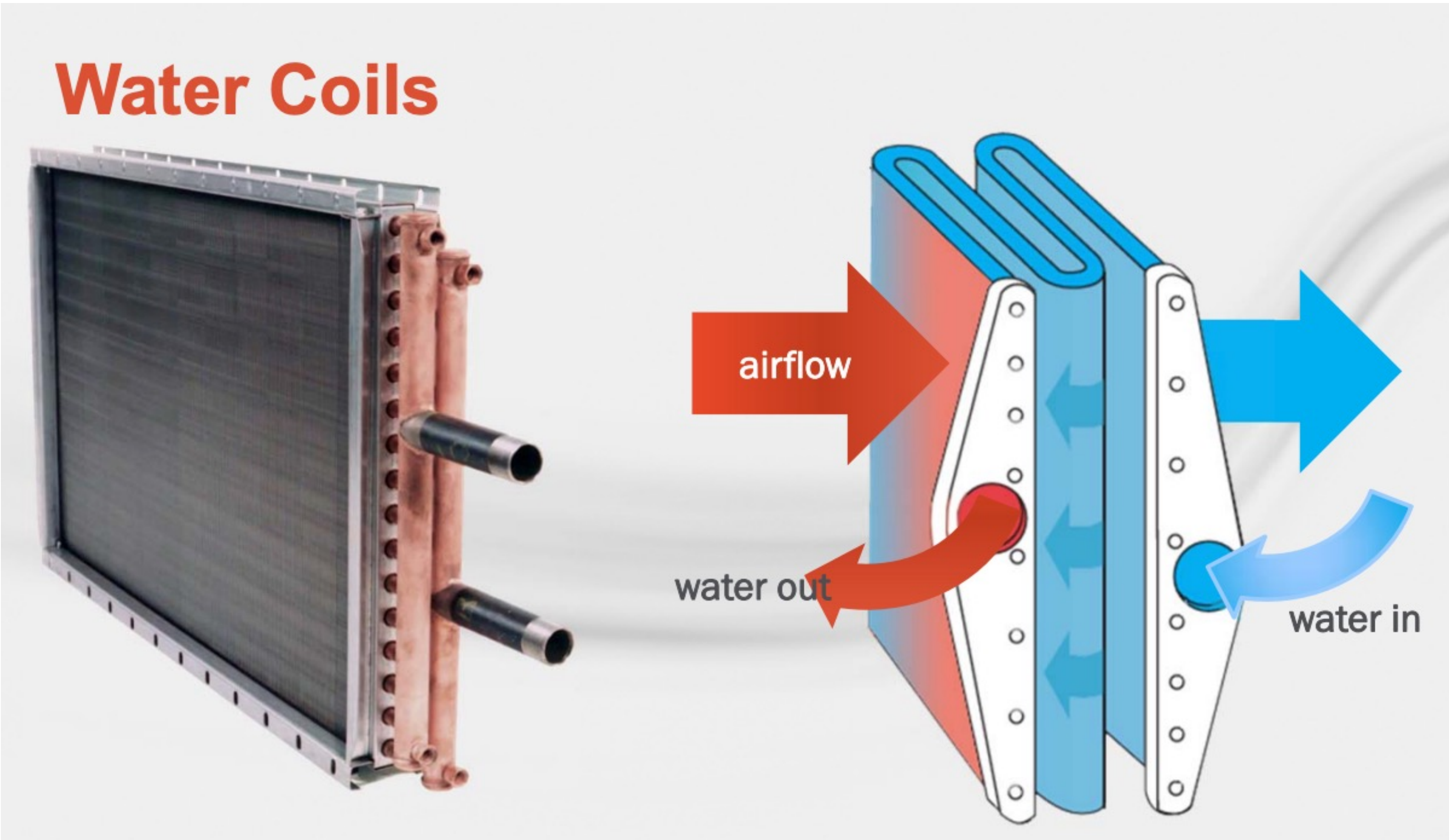
- A few additional Revit training videos are uploaded



RECAP

Recap

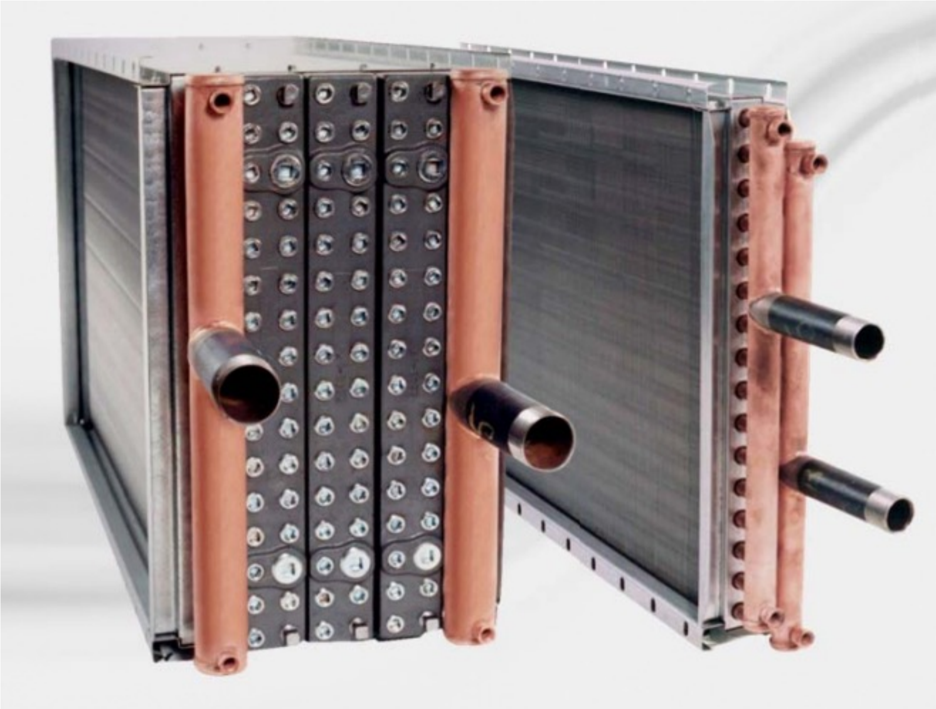
- Example of coils



https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/education-training/continuing-education-gbci-aia-pdh/HVAC-Coil-Selection-and-Optimization/APP-CMC054-EN_course%20material.pdf

Recap

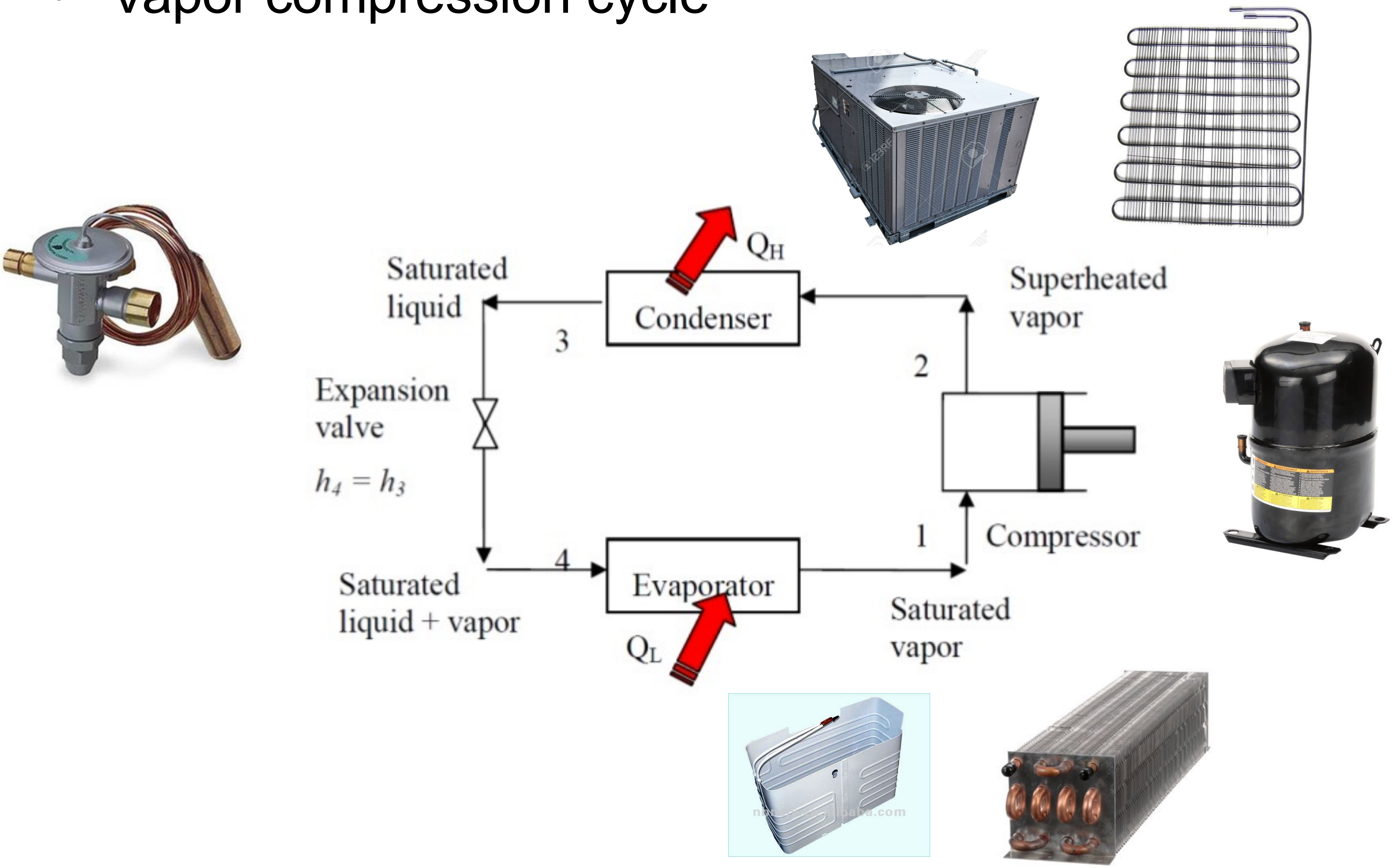
- What are important variables?
  - ❑ Coil face area
  - ❑ Number of rows of tubes
  - ❑ Tube diameter
  - ❑ Number of fins
  - ❑ Fin surface design
  - ❑ Coil circuiting
  - ❑ Turbulators



https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/education-training/continuing-education-gbci-aia-pdh/HVAC-Coil-Selection-and-Optimization/APP-CMC054-EN_course%20material.pdf

Recap

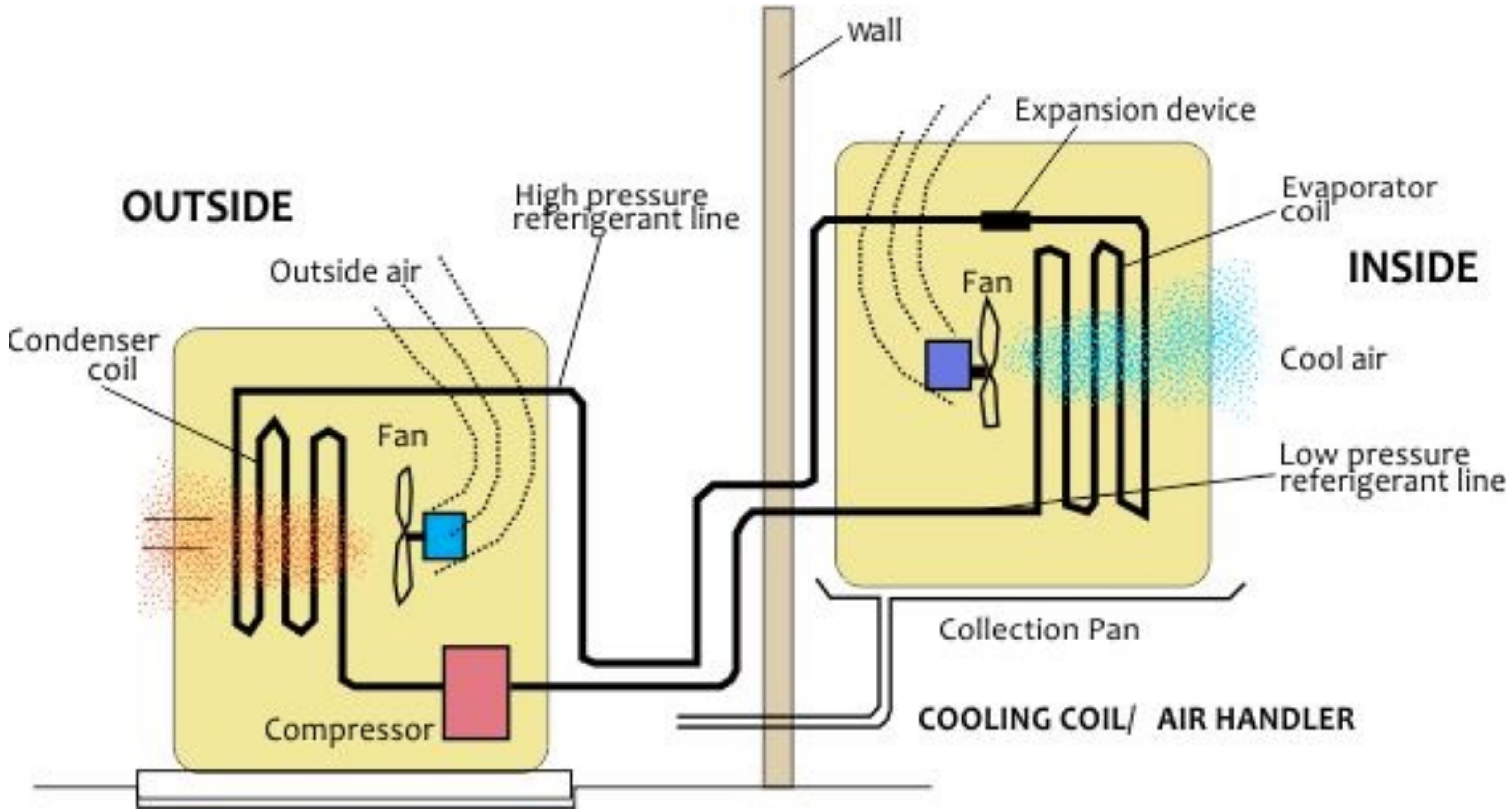
- Vapor compression cycle



https://www.slideshare.net/ilovemylifesomuch/simple-vapour-compression-refrigeration-system http://valveproducts.net/expansion-valve/guides-to-choose-a-expansion-valve, https://www.indiamart.com/proddetail/refrigerator-condenser-16049771448.html
https://www.webstaurantstore.com/taylor-057011-58-compressor/HP05701158.html?utm_source=Google&utm_medium=cpc&utm_campaign=GoogleShopping&gclid=EAIaIQobChMIttzNpoGl4QIVgx-tBh0KVAIFEAQYAiABEgIS4_D_BwE
https://www.123rf.com/photo_41197404_commercial-cooling-hvac-air-conditioner-condenser-evaporator-fan-ac-unit-for-building-climate-contro.html

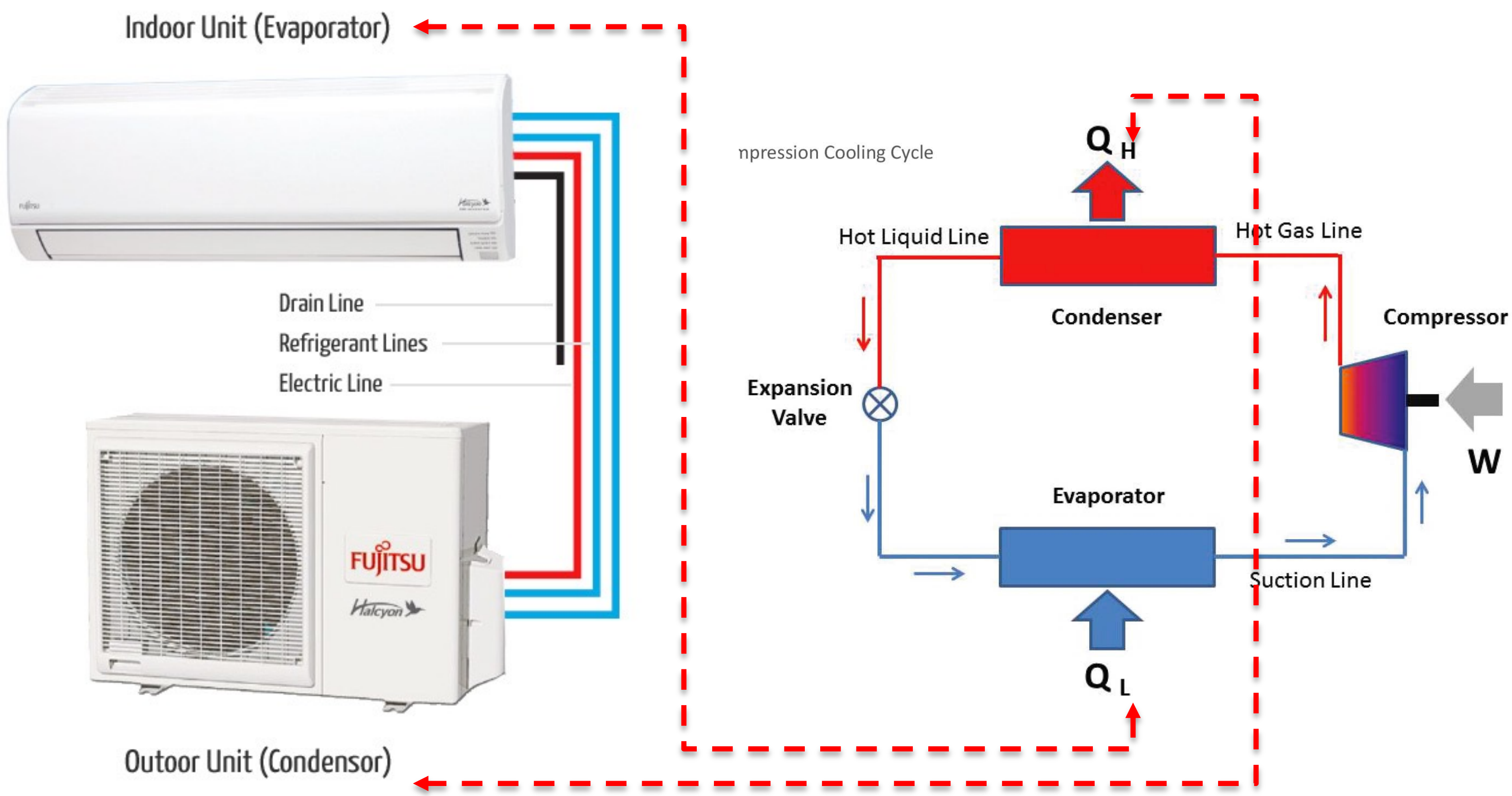
Recap

- Vapor compression cycle



http://www.nzeb.in/knowledge-centre/hvac-2/cooling-equipment/

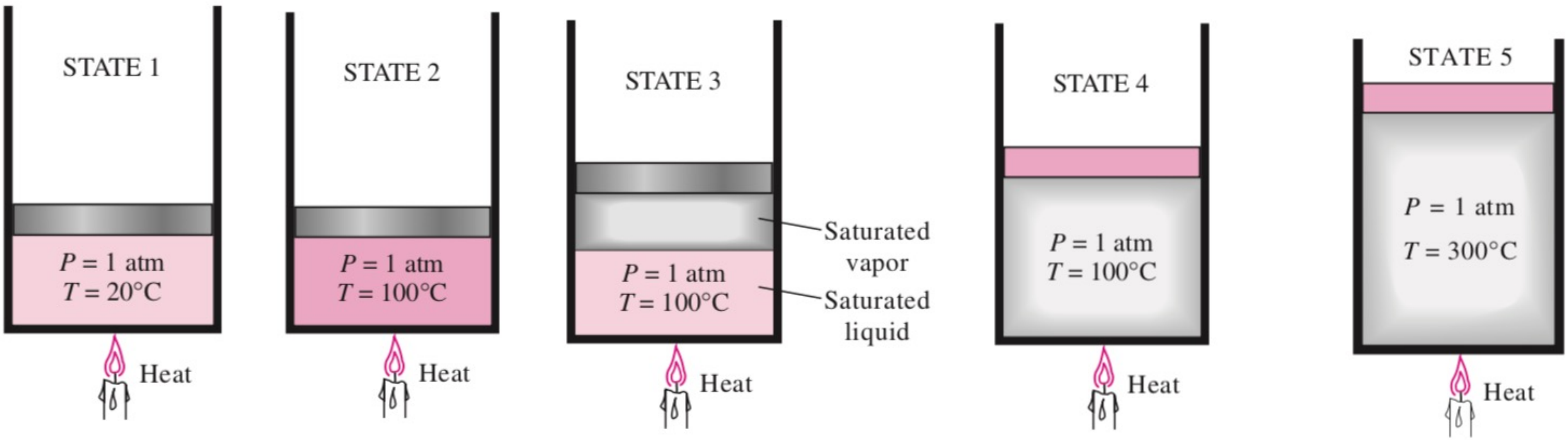
Recap



https://insulation.org/io/articles/understanding-thermal-systems-industrial-refrigeration-systems/ http://www.fujitsugeneral.com/us/residential/what-is-a-mini-split.html

Recap

- Let's assume heating up under a constant pressure



Subcooled Or Compressed liquid

Saturated liquid

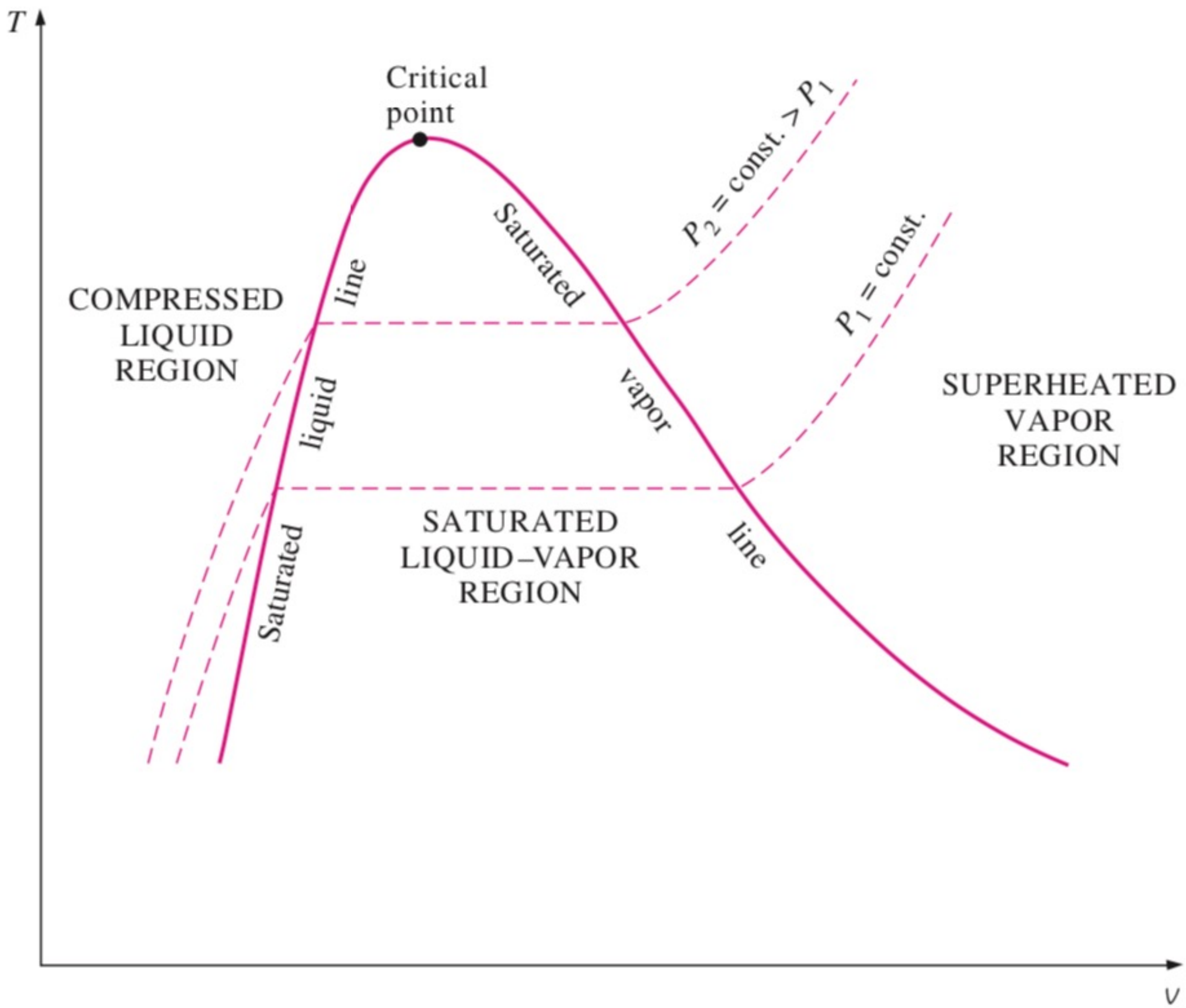
Saturated liquid + Saturated vapor

Saturated vapor

Superheated

Recap

- We can put all these lines and form a saturation dome



Recap

The Built Environment Research Group

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HOME PEOPLE PROJECTS PUBLICATIONS PRESENTATIONS FACILITIES COURSES BLOG

CAE 208/MMAE 320: Thermodynamics (Fall 2022)

CAE 208/MMAE 320 covers basic principles of thermodynamics applied to engineering systems using pure substances and mixtures as working fluids as well as covering direct application of the laws of thermodynamics to analysis of closed and open systems, mass and energy flow.

Course Syllabus

- Syllabus

Lecture Notes

- Lecture 01: Course overview and introduction
- Lecture 02: Basic concepts of thermodynamics (I)
- Lecture 03: Basic concepts of thermodynamics (II)
- Lecture 04: Basic concepts of thermodynamics (III)
- Lecture 05: Energy and energy analysis (I)
- Lecture 06: Energy and energy analysis (II)
- Lecture 07: Energy and energy analysis (III)
- Lecture 08: No Class
- Lecture 09: Properties of pure substances (I)
- Lecture 10: Properties of pure substances (II)
- Lecture 11: Properties of pure substances (III)
- Lecture 12: Properties of pure substances (IV)
- Lecture 13: Energy analysis of closed systems (I)
- Lecture 14: Energy analysis of closed systems (II)

http://built-envi.com/courses/cae-208-thermodynamics-fall-2022/

VAPOR COMPRESSION CYCLE COP

Vapor Compression COP

- We used the thermodynamic properties before

1.8 **2017 ASHRAE Handbook—Fundamentals**

Table 3 Thermodynamic Properties of Water at Saturation (*Continued*)

Temp., °F t	Absolute Pressure p_{ws}, psia	Specific Volume, ft³/lb$_w$ Sat. Solid v_i/v_f	Evap. v_{ig}/v_{fg}	Sat. Vapor v_g	Specific Enthalpy, Btu/lb$_w$ Sat. Solid h_i/h_f	Evap. h_{ig}/h_{fg}	Sat. Vapor h_g	Specific Entropy, Btu/lb$_w$·°F Sat. Solid s_i/s_f	Evap. s_{ig}/s_{fg}	Sat. Vapor s_g	Temp., °F t
–12	0.009700	0.01741	27490	27490	–164.46	1220.32	1055.86	–0.3365	2.7259	2.3895	–12
–11	0.010249	0.01741	26073	26073	–164.00	1220.30	1056.30	–0.3355	2.7198	2.3844	–11
–10	0.010827	0.01741	24736	24736	–163.54	1220.28	1056.74	–0.3344	2.7137	2.3793	–10
–9	0.011435	0.01741	23473	23473	–163.08	1220.26	1057.18	–0.3334	2.7077	2.3743	–9
–8	0.012075	0.01741	22279	22279	–162.62	1220.24	1057.63	–0.3324	2.7016	2.3692	–8
–7	0.012747	0.01742	21151	21152	–162.15	1220.22	1058.07	–0.3314	2.6956	2.3642	–7
–6	0.013453	0.01742	20086	20086	–161.69	1220.20	1058.51	–0.3303	2.6896	2.3593	–6
–5	0.014194	0.01742	19078	19078	–161.23	1220.17	1058.95	–0.3293	2.6837	2.3543	–5
–4	0.014974	0.01742	18125	18125	–160.76	1220.15	1059.39	–0.3283	2.6777	2.3494	–4
–3	0.015792	0.01742	17223	17223	–160.29	1220.12	1059.83	–0.3273	2.6718	2.3445	–3
–2	0.016651	0.01742	16370	16370	–159.83	1220.10	1060.27	–0.3263	2.6659	2.3396	–2
–1	0.017553	0.01742	15563	15563	–159.36	1220.07	1060.71	–0.3252	2.6600	2.3348	–1
0	0.018499	0.01743	14799	14799	–158.89	1220.04	1061.15	–0.3242	2.6542	2.3300	0
1	0.019492	0.01743	14076	14076	–158.42	1220.01	1061.59	–0.3232	2.6483	2.3251	1
2	0.020533	0.01743	13391	13391	–157.95	1219.98	1062.03	–0.3222	2.6425	2.3204	2
3	0.021625	0.01743	12742	12742	–157.48	1219.95	1062.47	–0.3212	2.6368	2.3156	3
4	0.022770	0.01743	12127	12127	–157.00	1219.92	1062.91	–0.3201	2.6310	2.3109	4
5	0.023971	0.01743	11545	11545	–156.53	1219.88	1063.35	–0.3191	2.6253	2.3062	5
6	0.025229	0.01743	10992	10992	–156.05	1219.85	1063.79	–0.3181	2.6196	2.3015	6
7	0.026547	0.01744	10469	10469	–155.58	1219.81	1064.23	–0.3171	2.6139	2.2968	7
8	0.027929	0.01744	9972	9972	–155.10	1219.77	1064.67	–0.3160	2.6082	2.2921	8
9	0.029375	0.01744	9501	9501	–154.62	1219.74	1065.11	–0.3150	2.6025	2.2875	9
10	0.030890	0.01744	9055	9055	–154.15	1219.70	1065.55	–0.3140	2.5969	2.2829	10
11	0.032476	0.01744	8631	8631	–153.67	1219.66	1065.99	–0.3130	2.5913	2.2783	11
12	0.034136	0.01744	8228	8228	–153.18	1219.61	1066.43	–0.3120	2.5857	2.2738	12
13	0.035874	0.01744	7846	7846	–152.70	1219.57	1066.87	–0.3109	2.5802	2.2692	13
14	0.037692	0.01745	7484	7484	–152.22	1219.53	1067.31	–0.3099	2.5746	2.2647	14
15	0.039593	0.01745	7139	7139	–151.74	1219.48	1067.75	–0.3089	2.5691	2.2602	15
16	0.041582	0.01745	6812	6812	–151.25	1219.44	1068.19	–0.3079	2.5636	2.2557	16
17	0.043662	0.01745	6501	6501	–150.77	1219.39	1068.63	–0.3069	2.5581	2.2513	17
18	0.045837	0.01745	6205	6205	–150.28	1219.34	1069.06	–0.3058	2.5527	2.2468	18
19	0.048109	0.01745	5925	5925	–149.79	1219.29	1069.50	–0.3048	2.5473	2.2424	19

Vapor Compression COP

- We used the thermodynamic properties before

Thermophysical Properties of Refrigerants **30.43**

Refrigerant 718 (Water/Steam) Properties of Saturated Liquid and Saturated Vapor

Temp.,* °F	Pressure, psia	Density, lb/ft³ Liquid	Volume, ft³/lb Vapor	Enthalpy, Btu/lb Liquid	Enthalpy, Btu/lb Vapor	Entropy, Btu/lb·°F Liquid	Entropy, Btu/lb·°F Vapor	Specific Heat c_p, Btu/lb·°F Liquid	Specific Heat c_p, Btu/lb·°F Vapor	c_p/c_v Vapor	Vel. of Sound, ft/s Liquid	Vel. of Sound, ft/s Vapor	Viscosity, lb_m/ft·h Liquid	Viscosity, lb_m/ft·h Vapor	Thermal Cond., Btu/h·ft·°F Liquid	Thermal Cond., Btu/h·ft·°F Vapor	Surface Tension, dyne/cm	Temp.,* °F
32.02[a]	0.089	62.42	3299.7	0.00	1075.92	0.0000	2.1882	1.0086	0.4504	1.3285	4601	1342	4.333	0.0223	0.3244	0.00987	75.65	32.02
40	0.122	62.42	2443.3	8.04	1079.42	0.0162	2.1604	1.0055	0.4514	1.3282	4670	1352	3.738	0.0226	0.3293	0.01001	75.02	40
50	0.178	62.41	1702.8	18.08	1083.79	0.0361	2.1271	1.0028	0.4528	1.3278	4748	1365	3.159	0.0229	0.3353	0.01019	74.22	50
60	0.256	62.36	1206.0	28.10	1088.15	0.0556	2.0954	1.0010	0.4543	1.3275	4815	1378	2.712	0.0232	0.3413	0.01038	73.40	60
70	0.363	62.30	867.11	38.10	1092.50	0.0746	2.0653	0.9999	0.4558	1.3273	4874	1391	2.359	0.0236	0.3471	0.01058	72.57	70
80	0.507	62.21	632.38	48.10	1096.83	0.0933	2.0366	0.9993	0.4574	1.3272	4924	1403	2.074	0.0240	0.3527	0.01079	71.71	80
90	0.699	62.11	467.40	58.09	1101.15	0.1117	2.0093	0.9990	0.4591	1.3271	4967	1416	1.841	0.0244	0.3579	0.01101	70.84	90
100	0.951	61.99	349.84	68.08	1105.44	0.1297	1.9832	0.9989	0.4609	1.3272	5003	1428	1.648	0.0248	0.3628	0.01124	69.96	100
110	1.277	61.86	264.97	78.07	1109.71	0.1474	1.9583	0.9991	0.4628	1.3273	5033	1440	1.486	0.0252	0.3672	0.01148	69.05	110
120	1.695	61.71	202.95	88.06	1113.95	0.1648	1.9346	0.9993	0.4648	1.3276	5056	1452	1.348	0.0256	0.3713	0.01172	68.13	120
130	2.226	61.55	157.09	98.06	1118.17	0.1819	1.9118	0.9997	0.4671	1.3280	5075	1463	1.230	0.0260	0.3750	0.01198	67.19	130
140	2.893	61.38	122.82	108.06	1122.35	0.1987	1.8901	1.0003	0.4696	1.3285	5088	1475	1.128	0.0265	0.3783	0.01225	66.24	140
150	3.723	61.19	96.930	118.07	1126.49	0.2152	1.8693	1.0009	0.4723	1.3291	5097	1486	1.040	0.0269	0.3813	0.01253	65.27	150
160	4.747	61.00	77.184	128.08	1130.59	0.2315	1.8493	1.0016	0.4753	1.3299	5101	1497	0.962	0.0273	0.3839	0.01282	64.28	160
170	6.000	60.79	61.980	138.11	1134.65	0.2476	1.8302	1.0025	0.4787	1.3309	5101	1508	0.894	0.0278	0.3862	0.01312	63.28	170
180	7.520	60.58	50.169	148.14	1138.65	0.2634	1.8118	1.0035	0.4824	1.3320	5098	1518	0.834	0.0282	0.3881	0.01343	62.26	180
190	9.350	60.35	40.916	158.19	1142.60	0.2789	1.7942	1.0046	0.4865	1.3333	5090	1528	0.780	0.0287	0.3898	0.01375	61.23	190
200	11.538	60.12	33.609	168.24	1146.48	0.2943	1.7772	1.0059	0.4911	1.3348	5080	1538	0.732	0.0291	0.3912	0.01409	60.19	200
210	14.136	59.88	27.794	178.31	1150.30	0.3094	1.7609	1.0073	0.4961	1.3366	5066	1547	0.690	0.0296	0.3924	0.01444	59.13	210
211.95[b]	14.696	59.83	26.802	180.28	1151.04	0.3124	1.7578	1.0076	0.4971	1.3369	5063	1549	0.682	0.0297	0.3926	0.01451	58.92	211.95
220	17.201	59.63	23.133	188.40	1154.05	0.3244	1.7451	1.0088	0.5016	1.3386	5049	1557	0.651	0.0300	0.3934	0.01480	58.05	220
230	20.795	59.37	19.371	198.51	1157.72	0.3391	1.7299	1.0106	0.5077	1.3408	5029	1565	0.616	0.0305	0.3941	0.01517	56.96	230
240	24.986	59.10	16.314	208.63	1161.31	0.3537	1.7153	1.0125	0.5145	1.3434	5007	1574	0.585	0.0310	0.3947	0.01556	55.86	240
250	29.844	58.82	13.815	218.78	1164.81	0.3680	1.7011	1.0147	0.5218	1.3464	4981	1582	0.556	0.0314	0.3951	0.01596	54.74	250
260	35.447	58.53	11.759	228.95	1168.21	0.3823	1.6874	1.0170	0.5299	1.3496	4953	1590	0.530	0.0319	0.3953	0.01638	53.62	260
270	41.878	58.24	10.058	239.14	1171.52	0.3963	1.6741	1.0196	0.5387	1.3533	4923	1597	0.506	0.0324	0.3953	0.01680	52.47	270
280	49.222	57.94	8.6431	249.37	1174.71	0.4102	1.6612	1.0224	0.5483	1.3574	4890	1604	0.484	0.0328	0.3952	0.01725	51.32	280
290	57.574	57.63	7.4600	259.62	1177.79	0.4239	1.6487	1.0254	0.5586	1.3620	4855	1611	0.464	0.0333	0.3949	0.01770	50.16	290
300	67.029	57.31	6.4658	269.91	1180.75	0.4375	1.6365	1.0287	0.5698	1.3671	4817	1617	0.445	0.0338	0.3944	0.01817	48.98	300

Vapor Compression COP

- Where do find them?

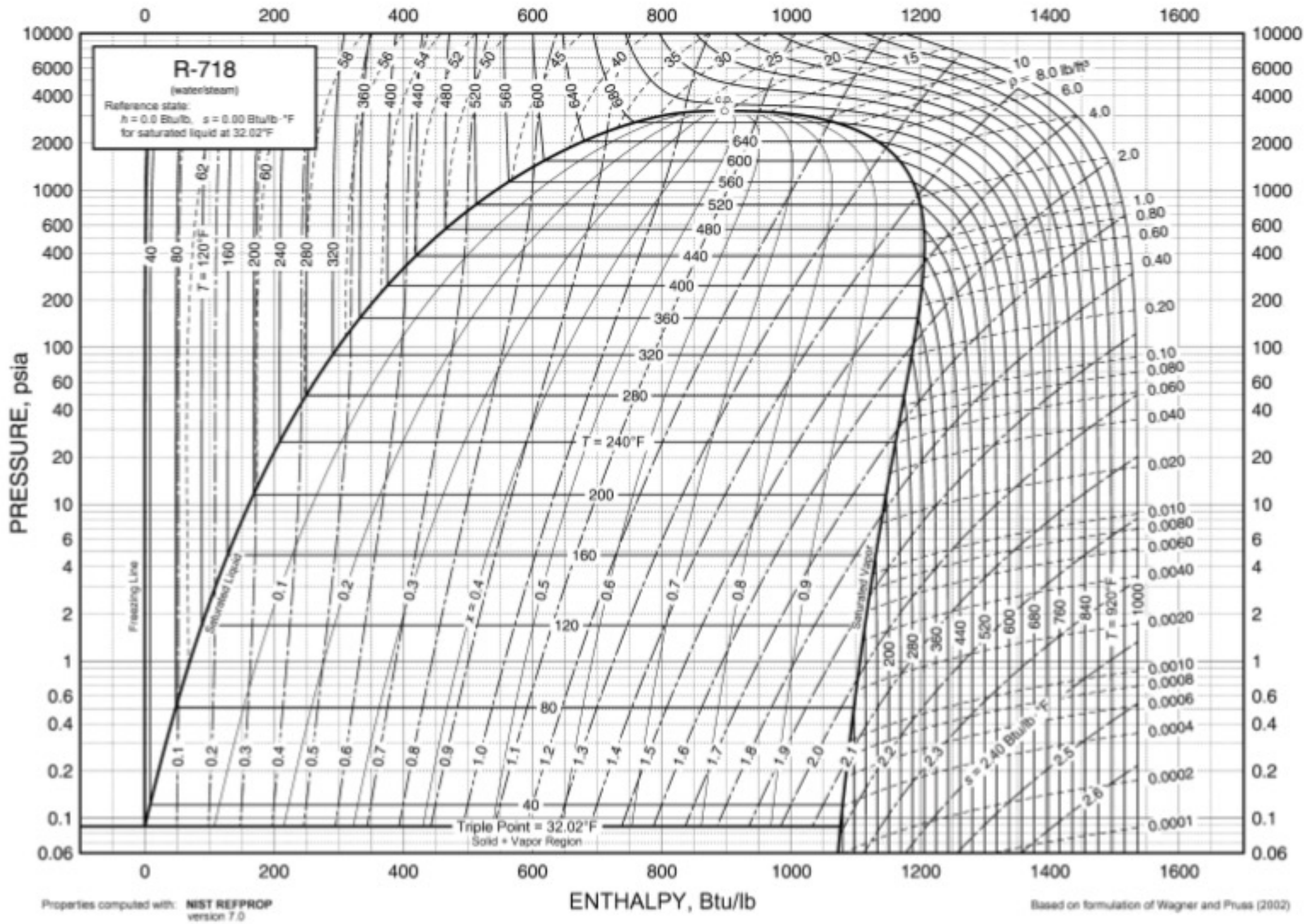
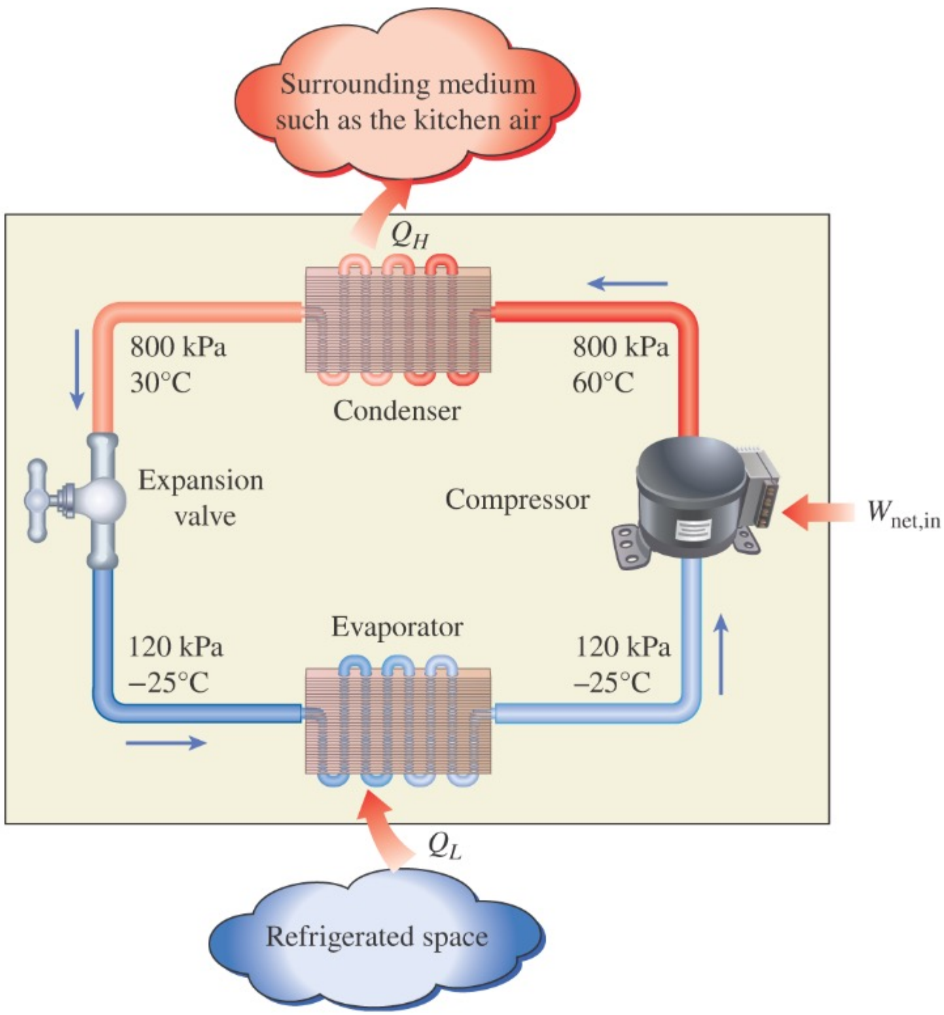


Fig. 20 Pressure-Enthalpy Diagram for Refrigerant 718 (Water/Steam)

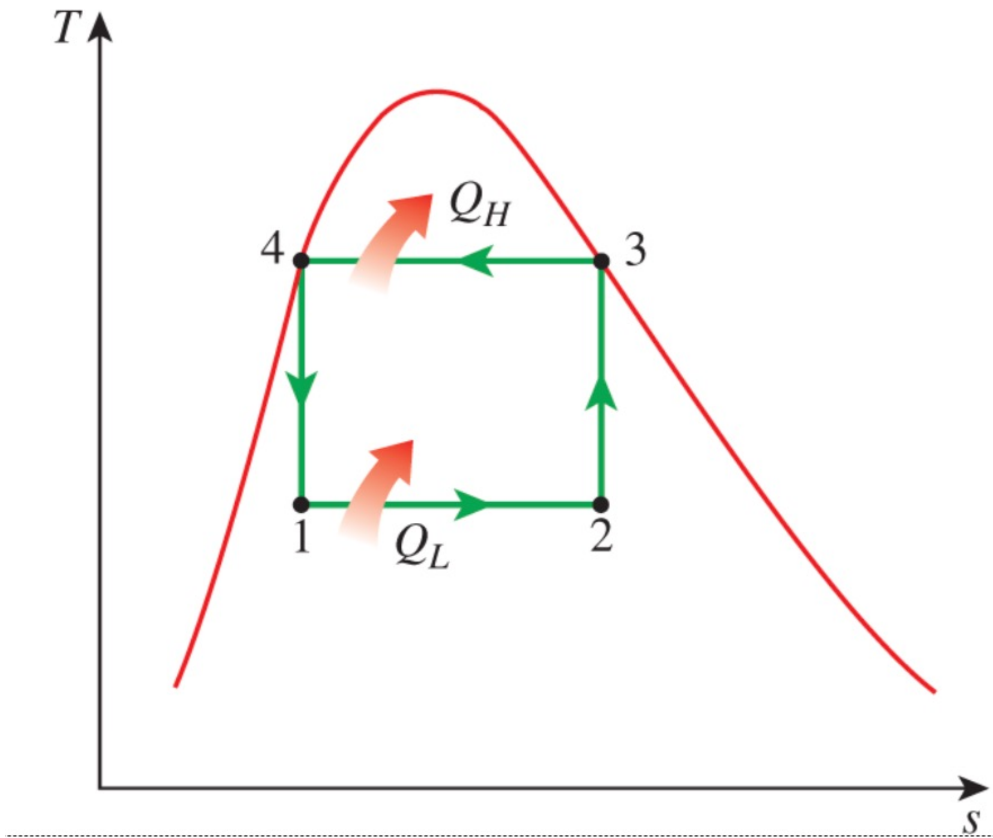
Vapor Compression COP

- The most frequently used refrigeration cycle is the vapor-compression refrigeration cycle



Vapor Compression COP

- The T-s diagram for the Carnot cycle is:



Vapor Compression COP

- The efficiency of a refrigerator is expressed in terms of the coefficient of performance (COP)
- The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space

$$COP_R = \frac{Desired\ output}{Required\ input} = \frac{Q_L}{W_{net,in}}$$

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

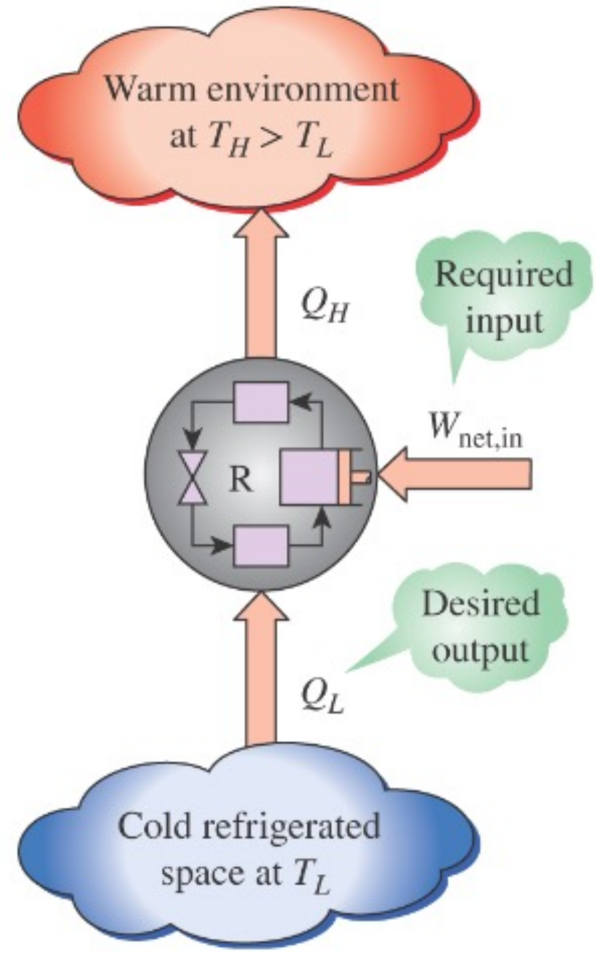
Vapor Compression COP

- ***Heat Pumps:*** The objective of a heat pump is to supply heat Q_H into the warmer space

$$COP_{HP} = \frac{Desired\ output}{Require\ input} = \frac{Q_H}{W_{net,in}}$$

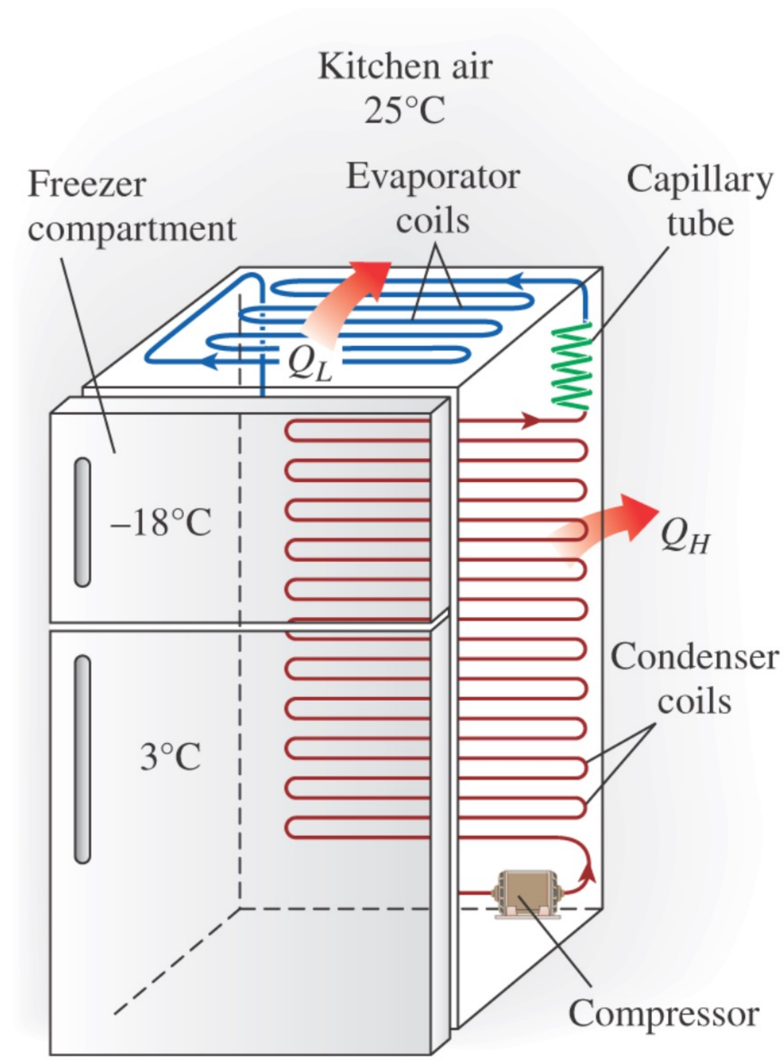
$$COP_{HP} = \frac{Desired\ output}{Require\ input} = \frac{Q_H}{Q_H - Q_L}$$

$$COP_{HP} = COP_R + 1$$



Vapor Compression COP

- An ordinary refrigerator, has all the four main components:

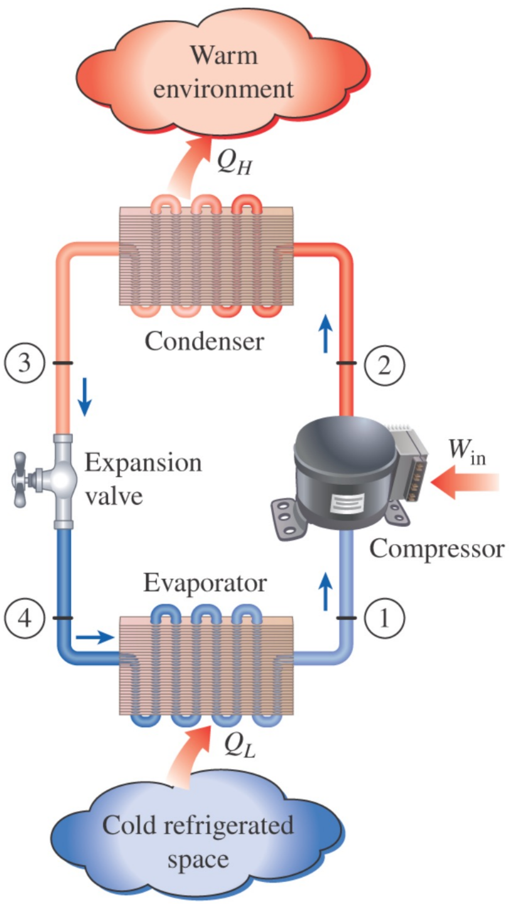


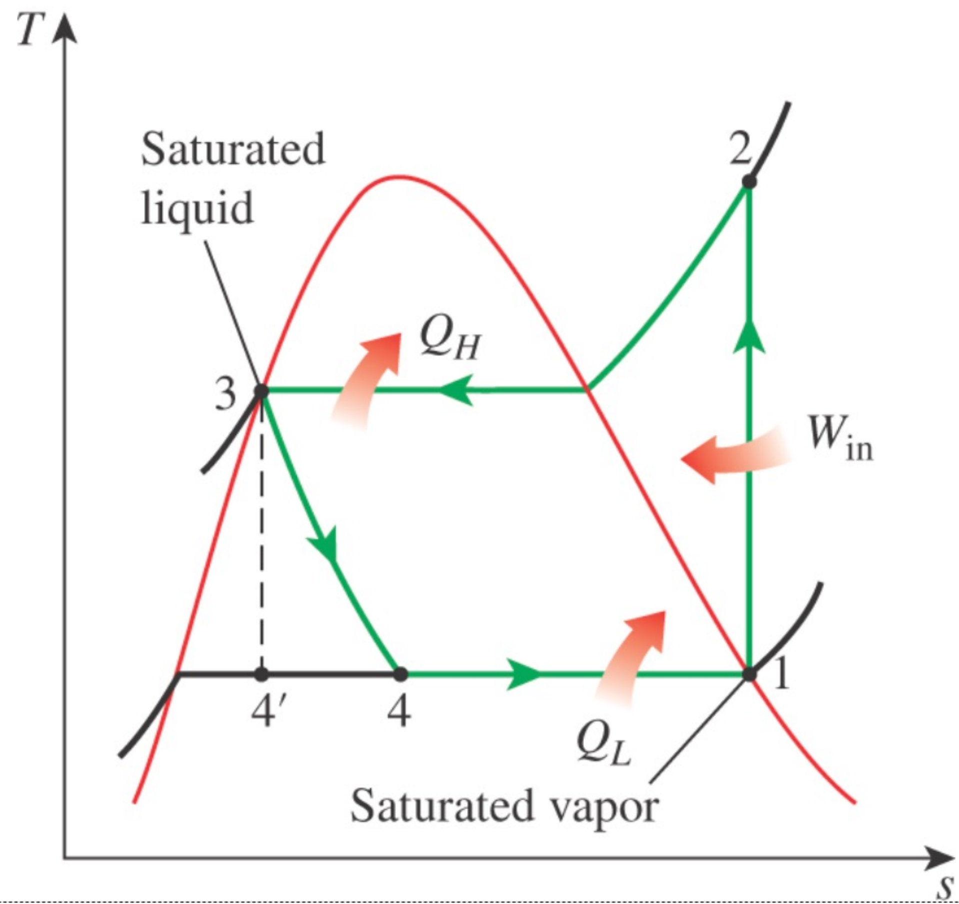
Vapor Compression COP

- In practice, there are several issues that limit the use of Carnot vapor compression cycle:
  - ❑ 1-2: Isentropic compression in a compressor
  - ❑ 2-3: Constant pressure heat rejection in a condenser
  - ❑ 3-4: Throttling in an expansion valve
  - ❑ 4-1: Constant pressure heat absorption in an evaporator

Vapor Compression COP

- In practice, there are several issues that limit the use of Carnot vapor compression cycle:

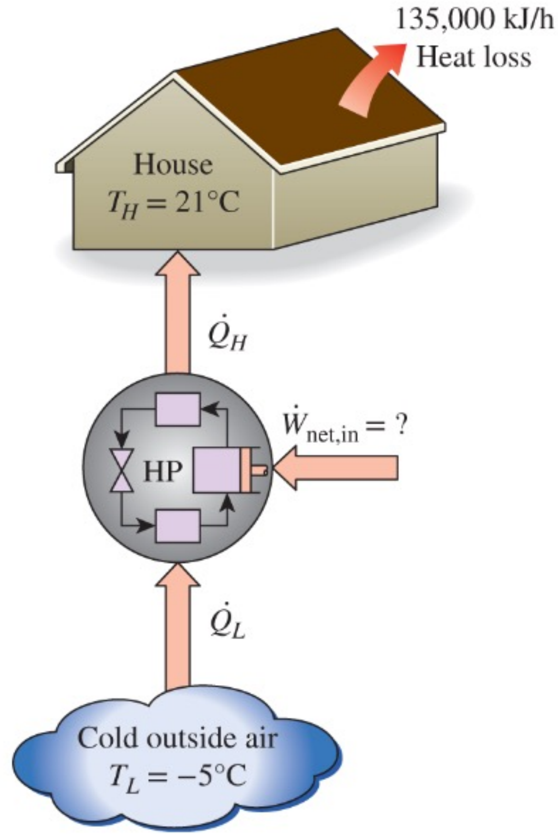




CLASS ACTIVITY

Class Activity

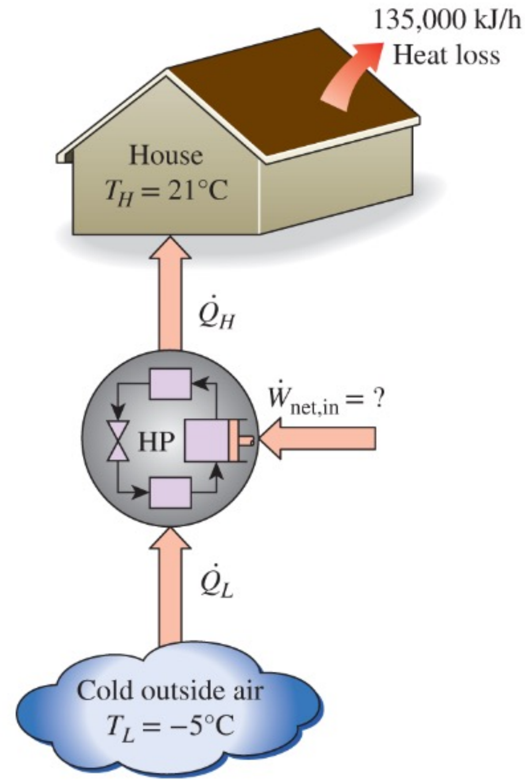
- A heat pump is to be used during the winter. The house is to be maintained at 21 °C at all times. The house is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to -5 °C. Determine the minimum power required to drive this heat pump.



Class Activity

- Solution:

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - \frac{-5 + 273}{21 + 273}} = 11.3$$



$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{37.5\ kW}{11.3} = 3.32\ kW$$

PROJECT