Analysis and Diagnosis of a Refrigeration/Heat Pump System

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Tuesday Session, Recording 2

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Role of refrigeration and heat pump systems in the industry

Refrigeration and Heat pumps are found throughout multiple industries, they are often used to offset costs and increase the efficiency of a process [1]. Coupled with a waste heat producing process, the energy can be extracted and used elsewhere by way of a heat pump; this offsets the overall cost, as a lower amount of energy is required to reach the desired temperature. Further these systems can be used to maintain processes that require a constant temperature, without the need for a boiler or heating element, which are less efficient, often more expensive and less precise. A vapour-compression refrigeration cycle is also the most widely used form of refrigeration and so is the main choice where cooling is required for industrial processes. Further industrial refrigeration unrelated to processes, such as the heating and cooling of buildings, food storage and transport and medical supply preservation overwhelmingly make use of the refrigeration cycle to maintain a range of temperatures lower than ambient conditions.

Calculation

Table 1: Collected data. Sourced from Tuesday Lab Session, Recording 2, 21/09/2021.

Parameters	Measured values (only use one data set from any one of the runs)	Units
Following experimental data is for R134a		
Press. compressor inlet (P1)	190 (291.13 abs)	kPa
Press. compressor outlet (P2)	729 (830.13 abs)	kPa
Press. before exp. valve (P3)	721 (822.13 abs)	kPa
Press. after exp. valve (P4)	196 (297.13 abs)	kPa
Temp. after evap. (T1)	3.77	°C
Temp. before condenser (T2)	64	°C
Temp. after condenser (T3)	30.7	°C
Temp. after exp. Valve (T4)	0.31	°C
Refrigerant flow rate (m_{dot_ref})	0.58	kg/min
Following experimental data is for Water that is getting chilled or heated		

Temp. into condenser (T_{c1})	24	°C
Temp. out of condenser (T_{c2})	39	°C
Temp. into evaporator (T_{e1})	34	°C
Temp. out of evaporator (T_{e2})	22	°C
Condenser water flow rate (m_{dot_c})	0.77	kg/min
Evaporator water flow rate (m_{dot_e})	0.75	kg/min
Compressor supply electrical power	400.1	W

Results

Evaporator Calculations

Water

Specific Heat Capacity = 4.18 kg/kj/k (from table A-3)

Mass Flow Rate = 0.0125 kg/s

Change in Temp = 34 - 22 = 12 Degrees

Power = Q_dot = M_dot * c * deltaT

Power = 0.627 kW (Removed from water)

Refrigerant 134a

IN

T = 0.31 C

Pressure = 297 KPa (Abs)

Fluid is below Sat Temperature (0.32 @ 297 KPa, from Linear Extrapolation, Tbl A-11)

Enthalpy = 52.26 (From Table A-11, hf, using Linear Extrapolation)

Enthalpy would equal H at Condenser Out in ideal situations

OUT

T = 3.77 C

Pressure = 291 KPa (Abs)

Fluid is Superheated

Enthalpy = 253.94 (From Table A-13, P = 0.28 MPa, using Linear Extrapolation)

Heat Transfer

DeltaH = 253.94 - 52.26 = 201.68

Mass Flow of 134a = 0.01 kg/s

Power = Q_dot = M_dot * DeltaH

Power = 2.02 kW (Gained from Evaporator)

Condenser Calculations

Water

Specific Heat Capacity = 4.18 kg/kj/k (from table A-3)

Mass Flow Rate = 0.013 kg/s

Change in Temp = 39 - 24 = 15 Degrees

Power = Q_dot = M_dot * c * deltaT

Power = 0.82 kW (Gained from Condenser)

Refrigerant 134a

IN

T = 64 C

Pressure = 830 KPa (Abs)

Fluid is Superheated

Enthalpy = 301.8 (From Table A-13, P = 0.8 MPa, using Linear Extrapolation)

OUT

T = 30.7 C

Pressure = 822 KPa (Abs)

Fluid is below Saturation Temperature

Enthalpy = 94.6 (From Table A-11, hf, using Linear Extrapolation)

Heat Transfer

DeltaH = 301.8 - 94.6 = 207.2

Mass Flow of 134a = 0.01 kg/s

Power = Q_dot = M_dot * DeltaH

Power = 2.07 kW (Removed from Refrigerant)

Work on Refrigerant by Compressor

In

T = 3.77 C

P = 291.13 KPa

Enthalpy = 253.94 (See Above: "Evaporator Refrigerant Out")

Out

T = 64 C

P = 830.13 KPa

Enthalpy = 301.8 (See Above: "Condenser Refrigerant In")

Work Done

DeltaH = 301.8 - 253.94 = 47.86

Mass Flow of 134a = 0.01 kg/s

Work per Second = Power = DeltaH * M_dot

Work per Second = 0.48 kW

Coefficient of Performance

Work input and Evaporator

COP = Heat Lost / Work Input
Heat Lost = 2.02 kW (Transferred to Refrigerant in Evaporator)
Work Input = 0.48 kW (From Enthalpy values across the Compressor)

COP = 4.21

Motor to Chilled Water

Heat Lost = 0.627 kW (From Chilled Water)
Work input = 0.4 kW (Electrical energy used by compressor)

COP = 1.57

Table 2: Results. Based on Values in **Table 1**; Calculations shown in the results section.

Parameters	Values	Units
Rate of heat transfer to evaporator from the chilled water	0.627	kW
Rate of heat transfer from condenser to the cooling water	0.784	kW
Rate of heat transfer to refrigerant in “Evaporator” using enthalpy values	2.02	kW
Rate of heat transfer from refrigerant in “Condenser” using enthalpy values	2.07	kW
Work input from the compressor to the refrigerant using enthalpy values	0.48	kW
COP from enthalpy changes across work input and evaporator	4.21	N/A
COP from motor electrical power input as work and rate of heat transfer to the chilled water	1.57	N/A

P-h diagram

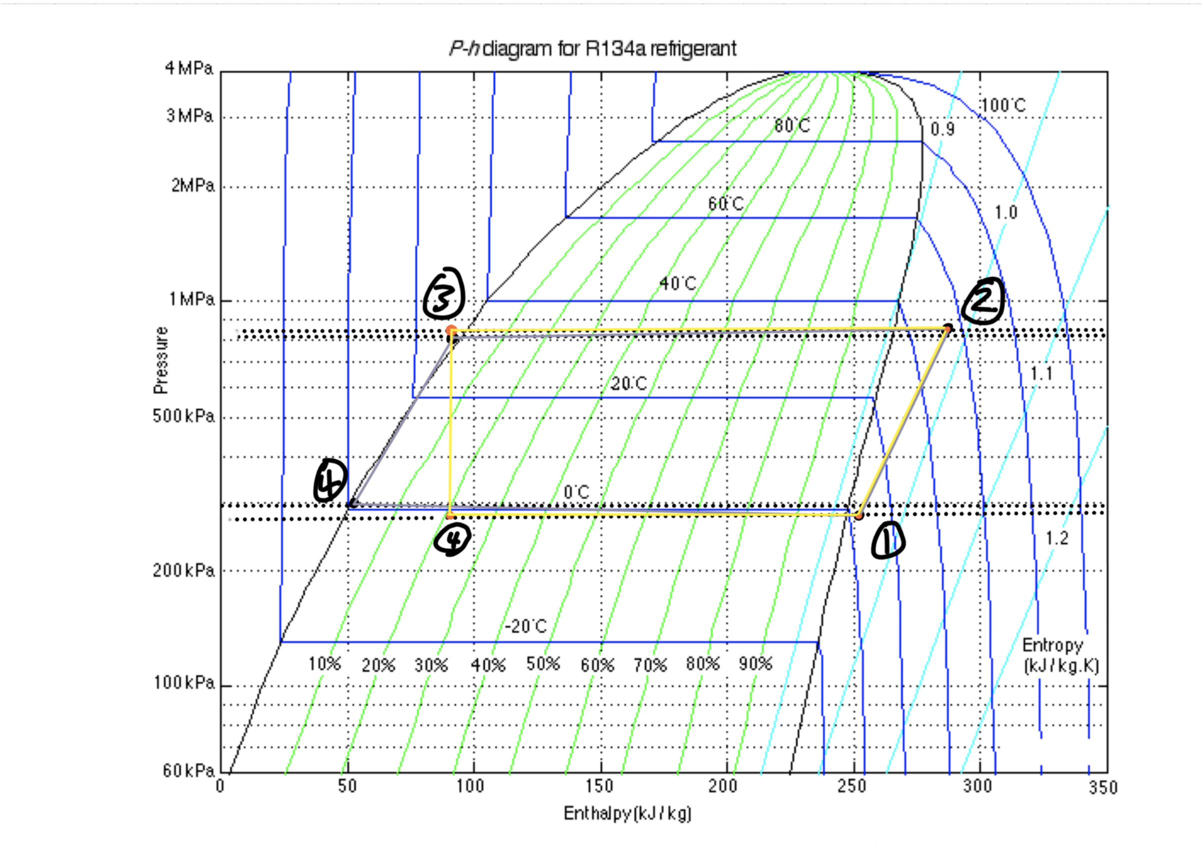

Figure 1: P-g Diagram. Yellow is Ideal; Purple is derived from results; Points are labeled respectively and constant pressure lines indicated in dotted black.

Evaluation of results

It's from the results that there exists a disparity between the experimental setup and an ideal refrigeration cycle. The most prevalent difference is the lack of energy balance within the closed system; this is of course due to the system not being entirely closed. Even with proper insulation the system absorbs and releases energy from its environment. Considering heat transfer at the evaporator and condenser: the overall energy transferred directly to or from the working fluid, is a relatively small margin of the overall energy transferred. The refrigerant in the condenser and evaporator transfer 2.07 and 2.02 kilowatts respectively, and the water in the condenser and evaporator transfers 0.627 and 0.784 kilowatts respectively. This indicates a difference of 1.44 kilowatts for the evaporator and 1.24 for the condenser, lost or gained by the surroundings. Other significant losses would occur as the water is moving between components via piping, through a combination of friction losses and temperature losses. These losses lead to the variance between the Enthalpy at Point 3 and Point 4 which in ideal conditions should be the same. With all these losses taken into account the system would demonstrate energy balance in accordance with the first law of thermodynamics.

The system aims to facilitate a transfer of heat from one isolated system to another; leading to a reduction in temperature at the evaporator Side and an increase at the condenser side. This is done through a vapor-condensation cycle, this cycle involves the input of work through a compressor and takes advantage of the latent heat a fluid can absorb without temperature change when said fluid is saturated. This occurs during both energy transfer stages, both these processes are ideally isobaric and transfer large amounts of energy with fairly moderate changes in temperature. This keeps the refrigerant on the cusp of a phase change, and so will readily change state and in doing so transfer energy, when put in contact with a warmer or colder fluid/medium. The Compressor and Thermal Expansion valve are thus needed to maintain these conditions, ensuring the working fluid is kept at the ideal temperature and pressure for condensation or evaporation. The collective result is the continuous movement of heat between two mediums at the expense of input energy.

Diagnosis and fault determination

Assume you are a maintenance engineer responsible for operation of a large cold storage facility and during a routine inspection of the refrigeration system you observed that the system performance is abnormal. It is your responsibility to examine the abnormal performance and provide your diagnosis of possible fault of such performance.

Scenario 1

The average cold storage temperature over the previous two weeks is 5°C above the long term historical normal average.

- Insulation damage near the evaporator or in the pipes leading to it. Could allow the cold refrigerant to have absorbed more external energy from the environment and heated up. Resulting in a lower cooling efficiency.
- Filter wear out could have allowed particulates into the compressor and damaged it, this could slow the flow rate and reduce the efficiency of the overall system.
- Refrigerant accumulator is running low on fluid and is circulating vapor or air which can't absorb enough heat in the evaporator due to the lack of a phase change.

Scenario 2

The refrigerant temperature at the condenser outlet is 2°C above the saturation temperature at the condenser outlet pressure. And you know that the system was recently recharged with refrigerant.

- Compressor is adding too much energy to the refrigerant, due to damage or malfunction. Leading to a surplus of heat energy entering the condenser which can not be drawn out fast enough to trigger condensation.
- The fluid or medium absorbing energy from the condenser is approaching the temperature of the refrigerant and as such cannot absorb enough of the condenser's energy. This could be due to an unusually hot external environment or a faulty heat sink.
- Damage within the condenser is limiting the time the refrigerant is spending in close proximity with the heat absorbing fluid/medium.

References

[1] U.S. Department of Energy, “Industrial Heat Pumps for Steam and Fuel Savings Energy Efficiency and Renewable Energy.” [Online]. Available: https://www.energy.gov/sites/prod/files/2014/05/f15/heatpump.pdf.

[2] ÇengelY. A., J. M. Cimbala, and R. H. Turner, *Fundamentals of thermal-fluid sciences*. New York: Mcgraw-Hill Higher Education, 2012.

[3] D. A. Date, “Refrigeration Lab Information,” *Instructure.com*. https://rmit.instructure.com/courses/89178/pages/pra01-refrigeration-lab-activity-page?module_item_id=3369727 (accessed Oct. 06, 2021).