EVERYDAY EXAMPLES OF ENGINEERING CONCEPTS

T8: Refrigeration & heat pumps

This is an extract from 'Real Life Examples in Thermodynamics: Lesson plans and solutions' edited by Eann A. Patterson, first published in 2010 (ISBN: 978-0-9842142-1-1*) and contains suggested exemplars within lesson plans for Sophomore Thermodynamics Courses. They were prepared as part of the NSF-supported project (#0431756) entitled: "Enhancing Diversity in the Undergraduate Mechanical Engineering Population through Curriculum Change".*

INTRODUCTION

(from *'Real Life Examples in Thermodynamics: Lesson plans and solutions'*)

These notes are designed to enhance the teaching of a sophomore level course in thermodynamics, increase the accessibility of the principles, and raise the appeal of the subject to students from diverse backgrounds. The notes have been prepared as skeletal lesson plans using the principle of the 5Es: Engage, Explore, Explain, Elaborate and Evaluate. The 5E outline is not original and was developed by the Biological Sciences Curriculum Study[1] in the 1980s from work by Atkin & Karplus[2] in 1962. Today this approach is considered to form part of the constructivist learning theory[3].

These notes are intended to be used by instructors and are written in a style that addresses the instructor, however this is not intended to exclude students who should find the notes and examples interesting, stimulating and hopefully illuminating, particularly when their instructor is not utilizing them. In the interest of brevity and clarity of presentation, standard derivations, common tables/charts, and definitions are not included since these are readily available in textbooks which these notes are not intended to replace but rather to supplement and enhance. Similarly, it is anticipated that these lesson plans can be used to generate lectures/lessons that supplement those covering the fundamentals of each topic.

This is the third in a series of such notes. The others are entitled 'Real Life Examples in Mechanics of Solids' (ISBN: 978-0-615-20394-2), 'Real Life Examples in Dynamics'(ISBN: 978-0-9842142-0-4).

Acknowledgements

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[1] Engleman, Laura (ed.), *The BSCS Story: A History of the Biological Sciences Curriculum Study*. Colorado Springs: BSCS, 2001.
[2] Atkin, J. M. and Karplus, R. (1962). Discovery or invention? *Science Teacher* 29(5): 45.
[3] e.g. Trowbridge, L.W., and Bybee, R.W., *Becoming a secondary school science teacher*. Merrill Pub. Co. Inc., 1990.

THERMODYNAMIC APPLICATIONS

8. Topic**: Refrigeration and heat pumps**

Engage:

Acquire (purchase[4] or borrow) a portable refrigerator, prepare yourself a picnic meal and pack it into the refrigerator. Take the refrigerator to class, open it and start to eat your picnic – the more elaborate the better; include items that obviously need to be refrigerated, e.g. fruit juice, yoghourt …

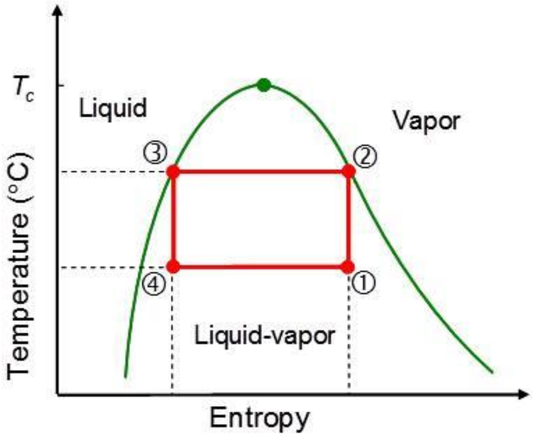
Explore:

Remind the students of the Clausius statement of the second law of thermodynamics: '*It is impossible for any system to operate in a thermodynamic cycle and produce no effect other than the transfer by heat from a cooler to a hotter body'*. Point out that a refrigerator transfers heat from its cold box to the warmer room, i.e. '*the transfer by heat from a cooler to a hotter body'* hence there has to be another 'effect'.

Ask students what impact a refrigerator has on a room. Someone will mention the noise and you can talk about the compressor doing work, i.e. the 'effect' required by the Clausius statement.

Explain:

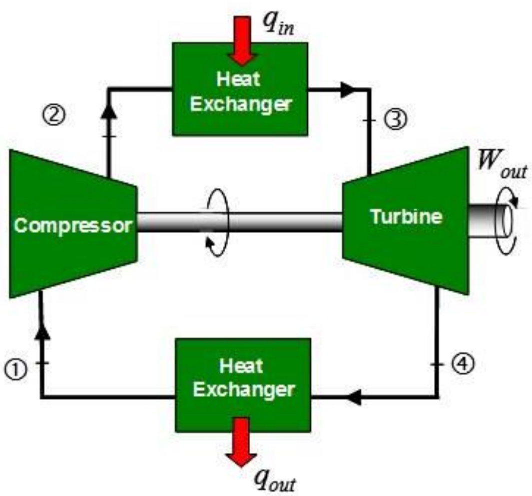
Remind them about the Carnot cycle, the most efficient cycle operating between two temperatures. It consists of two isotherms and two adiabats (processes involving no heat transfer, only work) as shown in the diagram.



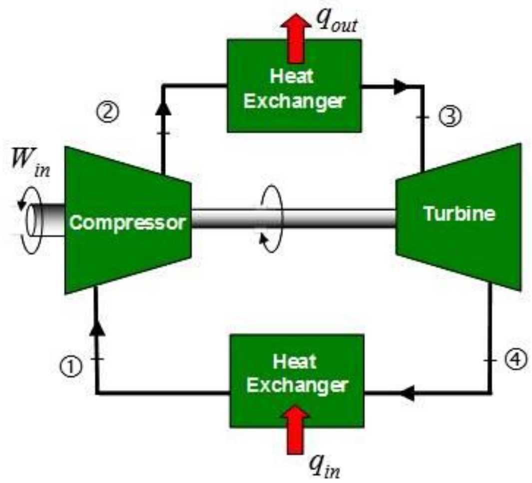
Discuss the fact that the power cycles in the previous two chapters (lessons) go around this ideal cycle clockwise where as for a refrigeration cycle it is necessary to go around anti-clockwise.

[4] At the time of writing you could purchase a Personal Mini Fridge Cooler via www.amazon.com for about $40.

In example 7.2 the Brayton gas turbine cycle was introduced. This cycle can be reversed to produce a refrigerator, i.e.

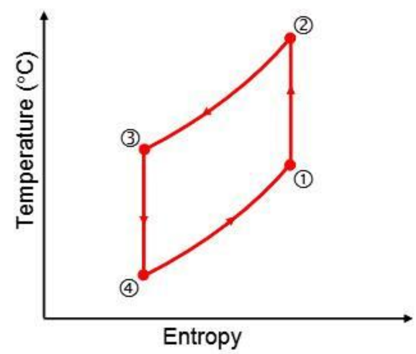


Brayton Power Cycle



Brayton Refrigeration Cycle

And is represented on a T-s diagram as shown. This assumes isentropic compression from ① to ② and expansion from ③ to ④. For a Brayton gas power cycle the arrows would be reversed on the T-s diagram, i.e., the cycle would run clockwise.



Elaborate:

A Brayton refrigeration cycle operates using gas as a refrigerant just as the power cycle uses gas as the working fluid. This approach is fine in certain applications such as aircraft cabin cooling or the liquefaction of air. However, in domestic refrigerators it is more usual for the refrigerant to change phase as heat is transferred from the cold zone. Thus, one heat exchanger is known as an evaporator and one as a condenser; in addition the expansion achieved by the turbine is performed by an expansion valve.

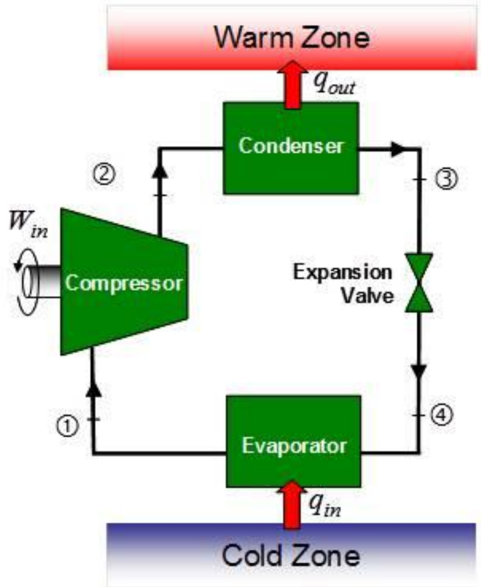
So consider a refrigerator sitting in a room at 20°C if the food compartment is to be maintained at 4°C, using CF_3CH_2F as the refrigerant which is more commonly known as R134a then from thermodynamic tables[5].

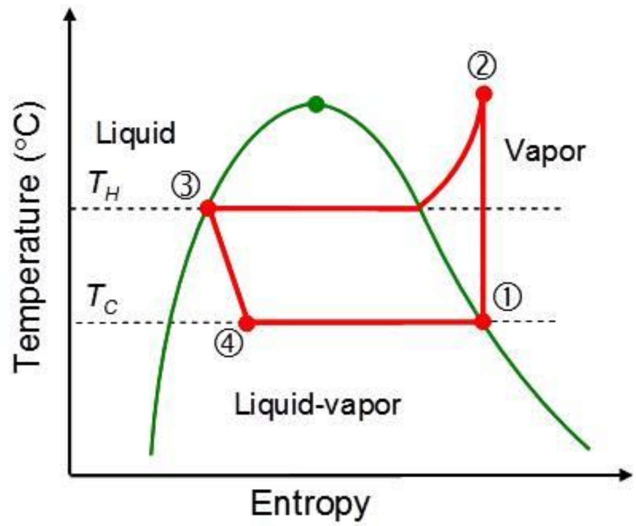
<u>State 1</u>: (*at the evaporator exit / compressor entry*)

The refrigerant is a saturated vapor, hence for $T_1 = 4\,°\text{C}$:

$$h_1 = h_g = 249.53\,\text{kJ/kg and } s_1 = s_g = 0.9169\,\text{kJ/kg}$$

[5] e.g. http://v5.sdsu.edu/testhome/Test/solve/basics/tables/tablesPC/TSatR134a.html





State 2: (*at compressor exit / condenser entry*)

following an isoentropic compression, i.e. $s_2 = s_1 = 0.9169\,\text{kJ/kg}$

The pressure corresponds to saturation pressure at 20°C, i.e. $p_2 = 0.57160\,\text{MPa}$

And the refrigerant is superheated, so using the tables of superheated R134a[6], $h_2 = 259.995\,\text{kJ/kg}$

State 3: (*condenser exit/expansion valve entry*)

The refrigerant is saturated liquid, hence for $T_3 = 20\,°\text{C}$

$$h_3 = h_f = 77.26\,\text{kJ/kg} \text{ and } s_3 = s_f = 0.2924\,\text{kJ/kg}$$

State 4: (*expansion valve exit / evaporator entry*)

The expansion through the valve is a throttling process that involves no change in enthalpy, i.e. $h_4 = h_3 = 77.26\,\text{kJ/kg}$.

If the design specification is to cool a 75cl bottle of champagne from room temperature (20°C) to 4°C in five minutes, then ignoring the glass bottle and assuming champagne to have the thermodynamical properties of water, the heat to be transferred out of the champagne is

$$Q_{champagne} = mC_p(T_2 - T_1) = 0.75 \times 4.1855 \times (4 - 20) = -50.226\,\text{kJ}$$

So $$\dot{Q}_{in} = \frac{Q_{champagne}}{time} = \frac{50.226}{5 \times 60} = 0.16742\,\text{kW}$$

Also, using the first law of thermodynamics to equate heat transfer to the change in enthalpy, $\dot{Q}_{in} = \dot{m}(h_1 - h_4)$

[6] e.g. http://v5.sdsu.edu/testhome/Test/solve/basics/tables/tablesPC/superR134a.html

so $\dot{m} = \frac{q_{in}}{(h_1 - h_4)} = \frac{0.16742}{(249.53 - 77.26)} = 9.718 \times 10^{-4}$ kg/s

The compressor work input can be found using the first law of thermodynamics to equate work done to the increase in enthalpy

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (9.718 \times 10^{-4}) \times (259.995 - 249.53) = 0.01\,\text{kW}$$

So by definition, the coefficient of performance is

$$\beta = \frac{\dot{Q}_{in}}{\dot{W}_{in}} = \frac{0.16742}{0.01} = 16.46$$

Note that the maximum coefficient of performance is given by a Carnot cycle for which

$$\beta_{\max} = \frac{T_C}{T_H - T_C} = \frac{277}{293 - 277} = 17.3$$

Of course, in reality, the champagne will not be chilled in 5 minutes because the effect of the thick glass bottle has been neglected and heat transfer through the wall of the refrigerator has been ignored. In addition, the refrigerant temperature in the evaporator will be lower than in the food compartment and its temperature in the condenser will be higher than the surroundings both of which adversely affect the performance.

Evaluate:

Invite the students to attempt the following examples:

Example 8.1

A soft drinks cooler is designed to chill six cans in 5 minutes from room temperature at 20°C to 4°C. If the metal of the cans is neglected and losses through the wall are ignored then find the coefficient of performance if it is assumed that the refrigerant (R134a) is 10°C warmer than the surroundings in the condenser and 10°C cooler than the cold box in the evaporator.

Solution:

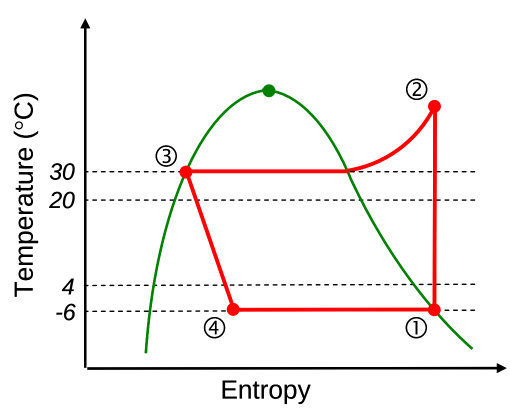
State 1: (*at the evaporator exit / compressor entry*)

The refrigerant is a saturated vapor, hence for $T_1 = -6$ °C and using the thermodynamic tables[7]:

$$h_1 = h_g = 243.72\,\text{kJ/kg and } s_1 = s_g = 0.9226\,\text{kJ/kg}$$

State 2: (*at compressor exit / condenser entry*)

following an isentropic compression, i.e. $s_2 = s_1 = 0.9226\,\text{kJ/kg}$



[7] e.g. http://v5.sdsu.edu/testhome/Test/solve/basics/tables/tablesPC/superR134a.html

The pressure corresponds to saturation pressure at 30°C, i.e. $p_2 = 0.77006\,\text{MPa}$ from the thermodynamic tables[17]

And the refrigerant is superheated, so $h_2 = 266.538\,\text{kJ/kg}$

<u>State 3:</u> (*condenser exit/expansion valve entry*)

The refrigerant is saturated liquid, hence for $T_3 = 30\,°\text{C}$ from the thermodynamics tables:

$$h_3 = h_f = 91.49\,\text{kJ/kg and } s_3 = s_f = 0.3396\,\text{kJ/kg}$$

<u>State 4:</u> (*expansion valve exit / evaporator entry*)

The expansion through the valve is a throttle process that involves no change in enthalpy, i.e. $h_4 = h_3 = 91.49\,\text{kJ/kg}$.

For six 0.33litre cans

$$Q_{cans} = mC_p\left(T_2 - T_1\right) = 2 \times 4.1855 \times \left(4 - 20\right) = -133.936\,\text{kJ}$$

So $$\dot{Q}_{in} = \frac{Q_{cans}}{time} = \frac{133.936}{5 \times 60} = 0.4465\,\text{kW}$$

Also, applying the first law of thermodynamics to the evaporator

$$\dot{Q}_{in} = \dot{m}\left(h_1 - h_4\right) \text{ so } \dot{m} = \frac{q_{in}}{\left(h_1 - h_4\right)} = \frac{0.4465}{\left(243.72 - 91.94\right)} = 2.941 \times 10^{-3}\,\text{kg/s}$$

The compressor work input is given by the first law of thermodynamics as

$$\dot{W}_{in} = \dot{m}\left(h_2 - h_1\right) = \left(2.941 \times 10^{-3}\right) \times \left(266.538 - 243.72\right) = 0.067\,\text{kW}$$

So the coefficient of performance is

$$\beta = \frac{\dot{Q}_{in}}{\dot{W}_{in}} = \frac{0.4465}{0.067} = 6.655$$

<u>*Example 8.2*</u>

In motels air-conditioning and heating of guest rooms is often provided by a heat pump fitted beneath the window. In air-conditioning mode it operates on the same cycle as a refrigerator with the interior heat exchanger operating as the evaporator transferring heat out of the room at T_C to provide cooling and the exterior heat exchanger acting as the condenser transferring heat into the surroundings at T_H. A reversing valve is used to convert the unit to a heat pump with the exterior unit operating as the evaporator absorbing heat at T_C and the interior heat exchanger operating as a condenser to transfer heat into the room at T_H.

Outline the design of such of unit for your own room and in particular calculate the flow rate and power required for the compressor.