EVERYDAY EXAMPLES OF ENGINEERING CONCEPTS

T3: 2nd Law of thermodynamics

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
Many of these examples have arisen through lively discussion in the consortium supported by the NSF grant (#0431756) on "Enhancing Diversity in the Undergraduate Mechanical Engineering Population through Curriculum Change" and the input of these colleagues is cheerfully acknowledged as is the support of National Science Foundation. The comments on an early draft made by Robert D. Handscombe of Handscombe Associates are gratefully acknowledged.

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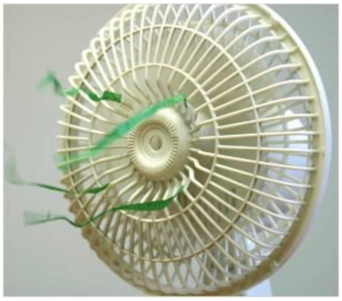
[1] Engleman, Laura (ed.), *The BSCS Story: A History of the Biological Sciences Curriculum Study*. Colorado Springs: BSCS, 2001.
[2] Atkin, J. M. and Karplus, R. (1962). Discovery or invention? *Science Teacher* 29(5): 45.
[3] e.g. Trowbridge, L.W., and Bybee, R.W., *Becoming a secondary school science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

SECOND LAW CONCEPTS

3. Topic**: Second law of thermodynamics**

Engage:



Take the largest fan you can find into class, preferably a pedestal fan or an air circulator. Try to borrow a large floor-mounted industrial air circulator in order to make a bigger impression on the class (e.g. www.airmasterfan.com). If this doesn't work out, then borrow all of the desk fans from the staff in the departmental office – this should make an impact.

Run the fan(s) for a minute or so while students prepare for the class. Then switch it off and ask the students to stand-up and energetically exercise on the spot in an attempt to make the fan blades go around.

Explore:

Discuss the fact that when the fan is operated, the electricity consumed by the fan becomes an energy input to the room, i.e. the room gains energy at the rate of 500W (for a 500W fan), according to the first law of thermodynamics. Due to this work input, W_{in} (energy), the temperature of the room will begin to rise and as it does so there will be heat loss to the surroundings until this loss equals the input from the fan, i.e. using the first law of thermodynamics

$$\dot{E}_{in} - \dot{E}_{out} = \dot{Q} + \dot{W} = 0$$

then $$\dot{W}_{in} = \dot{Q}_{out} = h_c A\left(T_{room} - T_{environment}\right)$$

thus if the coefficient of convective heat transfer[6], h_c=12 W/(m^2.K) and heat loss is through one wall to the outdoors (A = 2.5×9 = 22.5 m^2), we have

$$\Delta T = \frac{\dot{W}_{in}}{h_c A} = \frac{500}{12 \times 22.5} = 1.85 \ ^\circ\text{C}$$

i.e. the fan will cause the temperature of the room to rise by 1.85°C. Here we have assumed that the room is surrounded on three sides and above and below by rooms at approximately the same temperature so that there is negligible heat transfer across these boundaries.

Low impact aerobic exercise for a 91 kg (200lb) person burns about 455 Calories/hr[4] or 529W (= 455×4187/3600). So for x people in the class we just generated heat equal to about x times the power consumption of the fan, but it did not turn – why? Ask the students in pairs to discuss this conundrum.

[4] Ainsworth, B.E., Haskell, W.L.; Whitt, M.C.; Irwin, M.L.; Swartz, A.M.; Strath, S.J.; O'Brien, W. L.; Bassett, D.R. Jr.; Schmitz, K.H.; Emplaincourt, P.O.; Jacobs, D.R. Jr.; Leon, A. S., Compendium of Physical Activities: an update of activity codes and MET intensities, *Medicine & Science in Sports & Exercise*, 32(9):S498-S516, 2000.

Explain:

The experiment with the fan demonstrates what we know intuitively, i.e., that work can be converted completely and directly to heat quite easily but that it is rather more difficult to convert heat to work. A 'heat engine' is needed to convert heat into work; there are many different types of heat engine which share the following characteristics:

i. a high temperature heat source;
ii. only part of the supplied heat is converted to work;
iii. waste heat is rejected to a low-temperature sink; and
iv. they operate on a cycle.

Heat engines are special devices designed to cope with the implications of the second law of thermodynamics which states that processes occur in a certain, specific direction.

The inability of the heat generated by our aerobic exercise to do work on the fan is an illustration of the Kelvin-Planck statement of the Second Law of Thermodynamics: '*It is impossible for any system that operates on a thermodynamic cycle to receive heat from a* <u>*single*</u> *reservoir and produce a net amount of work*'.

Re-engage:

Take a cup of black tea or coffee into class. Now add milk to it and stir. Blow on it to cool it before taking a sip.

Explore (part II):

Ask the students to identify the two irreversible processes that they have just watched you perform, i.e. mixing the tea and milk together then cooling the tea by blowing on it.

Explain (part II):

Explain that the second law of thermodynamics states that processes occur in a certain, specific direction, and so there are irreversibilities in all real processes, e.g. mixing of two fluids and heat transfer across a finite temperature difference.

This second irreversibility is associated with the Clausius statement of the second law of thermodynamics: '*It is impossible for any system to operate in thermodynamic cycle and produce* <u>*no effect*</u> *other than the transfer by heat from a cooler to a hotter body*.'

Ask the students to identify other forms or sources of irreversibility with which they are familiar, e.g. friction, unrestrained expansion, inelastic deformation, chemical reactions.

Elaborate:

We know that heat does not on its own transfer from a cold body to a hot one; and yet a refrigerator arranges for exactly this to happen – heat is removed from the cold food compartment to the warmer surroundings. However, this does not violate the 2nd law of thermodynamics because the refrigerator does work and so consumes external energy.

For example: if 4kW of heat needs to be removed from the cold compartment of a refrigerator to maintain it at 3°C (=$T_{L(ow)}$ = 277K) , and the power input is 1.5kW then conservation of energy (1st law of thermodynamics) requires

$$\dot{W}_{in} = \dot{Q}_{dumped} - \dot{Q}_{removed}$$

And so the heat dumped into the surroundings at 21°C (=$T_{H(igh)}$ = 294K) is

$$\dot{Q}_{dumped} = \dot{Q}_{removed} + \dot{W}_{in} = 4 + 1.5 = 5.5\,\mathrm{W}$$

The coefficient of performance is defined as

$$COP = \frac{1}{\dot{Q}_{dumped} / \dot{Q}_{removed} - 1} = \frac{1}{5.5/4 - 1} = 2.67$$

An 'ideal' reversible refrigerator operating between two temperatures, $T_L$and T_H is known as a Carnot refrigerator and has a coefficient of performance defined as

$$COP = \frac{1}{T_H / T_L - 1} = \frac{1}{294/277 - 1} = 16.29$$

This is the ideal coefficient of performance for a refrigerator operating between these temperatures. Real refrigerators, such as the one mentioned above, have lower values due to the 2nd law of thermodynamics.

Similarly, an ideal, reversible heat engine is known as a Carnot engine and has the highest efficiency of any heat engine operating between these two temperatures

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 1 - \frac{277}{294} = 0.058$$

It is clear that a larger temperature difference will produce a greater efficiency.

Evaluate:

Invite students to attempt the following examples:

Example 3.1

Calculate the maximum efficiency of a heat engine for your home using a geothermal source with a constant all-year temperature of 50°F (=10°C) about 50ft below ground?

Solution

Assume the maximum temperature difference is achieved in winter when the lowest temperatures are 0°F (=-18°C), so

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 1 - \frac{255}{283} = 0.099 \text{ or about 10\%.}$$

Example 3.2

Discuss what the Carnot efficiency means in terms of the design of a heat pump and why you can't achieve this efficiency in a design for your home using geothermal energy.