EVERYDAY EXAMPLES OF ENGINEERING CONCEPTS

T2: 1st 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).

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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.

FIRST LAW CONCEPTS

2. Topic: **First law of thermodynamics**

Engage:

Take some bags of potato chips into class. Share them with the students.

Explore:

As the students hand the bags of potato chips round ask them to estimate amount of energy in the chips that they are eating (about 10 Calories❷ per chip 41.8kJ). Ask each student to write a list of processes in which that energy will be expended by them over the next couple of hours, e.g. heat loss to the environment, metabolic processes such as breathing, walking from the class. Ask a few students to read their lists while you construct a comprehensive list based on their responses.

Explain:

Let us take the simple case of a student sitting motionless and listening to the lecture. Then, neglecting physiological processes, we can assume that the energy taken in as food will be emitted as heat – this a form of the first law of thermodynamics which is that energy is conserved in all processes.

We can assume that heat transfer from a student in the classroom will occur as a consequence of convection and radiation to the surroundings; and that conduction through the feet or body to the chair is negligible.

A person's surface area can be estimated from a nomograph[4] used by physicians in the treatment of certain diseases. We can take a typical value to be 1.8 m^2. The convective heat transfer coefficient, h_c for a fully clothed person sitting in a chair is[5]

$$h_c = 1.222 \Delta T^{0.299} \text{ W/(m}^2\text{.K)}$$

where ΔT is the temperature difference between the person and the environment. So if a clothed person has a surface temperature of 30°C, then in a room maintained at 21°C they will experience a convective heat loss of

❷ The unit of Calorie declared on US food packaging is equivalent to a kilocalorie or 4.18kJ.

[4] Adelman, P., Casale, T.B., Corren, J., (eds) *Manual of allergy and immunology*, Lippincott Williams and Wilkins, Philadelphia, PA, 2002, p.483.

[5] Kurazumi, Y., Tsuchikawa, T., Ishii, J., Fukagawa, K., Yamato, Y., Matsubara, N., Radiative and convective heat transfer coefficients of the human body in natural convection, *Building and Environment*, 43(12):2142-2153, 2008.

$$\dot{Q}_{convection} = h_c A\left(T_{surface} - T_{environment}\right) = \left(1.222 \times 9^{0.299}\right) \times 1.8 \times \left(303 - 294\right) = 38.19W$$

There will also be heat loss by radiation to the surroundings which we can assume are at the same temperature as the air in the room, so

$$\dot{Q}_{radiation} = \varepsilon\sigma A\left(T^4_{surface} - T^4_{environment}\right)$$

where ε is the emissivity ($\varepsilon = 0.90$ for typical clothing) and σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W/m^2). Thus

$$\dot{Q}_{radiation} = \varepsilon\sigma A\left(T^4_{surface} - T^4_{environment}\right) = 0.90 \times \left(5.67 \times 10^{-8}\right) \times 1.8 \times \left(303^4 - 294^4\right) = 88\,\mathrm{W}$$

Hence the total rate of heat loss per person in the class is

$$\dot{Q}_{total} = \dot{Q}_{convection} + \dot{Q}_{radiation} = 38 + 88 = 126\,\mathrm{W}$$

So for a person sitting doing nothing else, and neglecting the energy required for physiological processes, it would take 5.5 minutes to loose the energy equivalent to one chip ([Energy in chip]/[rate of heat loss] = 41800/126 = 332 seconds).

Elaborate:

Consider the design of the air conditioning system required for the classroom with a capacity of *x* students who each have a heat loss of 126W and *y* light fittings of 100W each plus a 500W LCD projector. Use values of *x* and *y* for the class in front of you.

We can express the first law of thermodynamics, that energy is conserved, as an energy balance, in terms of energy rates:

$$\begin{pmatrix}\text{Rate of change}\\ \text{of energy in a}\\ \text{system}\end{pmatrix} = \begin{pmatrix}\text{Net rate of}\\ \text{energy inflow}\\ \text{as heat}\end{pmatrix} + \begin{pmatrix}\text{Net rate of}\\ \text{energy outflow}\\ \text{as work}\end{pmatrix}$$

Assuming that the room (the system) is in a steady state (no rate of change of energy in the system), then the heat outputs from the room will balance the heat inputs, i.e. ($\sum \dot{Q} = 0$) because there is no work being done on the system.

The heat generation in the room is given by

$$\dot{Q}_{generation} = 126x + 100y + 500$$

and let's assume *x* =50 and *y* =12, then $\dot{Q}_{generation} = \left(126 \times 50\right) + \left(100 \times 12\right) + 500 = 8000\,\mathrm{W}$

If it is desired to keep the room at a steady temperature of 21°C with an outside air temperature of 10°C then we must consider the heat loss from the room to its surroundings. If we assume that the room is surrounded on three sides and above and below by similar rooms, then we need only consider heat loss from one wall. Heat loss from the one external wall will occur mainly as a consequence of convection, i.e.

$$\dot{Q}_{convection} = h_c A\left(T_{surface} - T_{environment}\right)$$

where the coefficient of convective heat transfer[6], h_c is typically 12 W/(m^2.K) and A is the surface area of the wall (e.g. 2.5m × 9m)

$$\dot{Q}_{convection} = h_c A\left(T_{surface} - T_{environment}\right) = 12 \times (2.5 \times 9) \times \left(283 - 294\right) = -2970\,\mathrm{W}$$

Consequently, to maintain steady state conditions

$$\sum \dot{Q} = 0 = \dot{Q}_{convection} + \dot{Q}_{generation} + \dot{Q}_{aircon}$$

So $\dot{Q}_{aircon} = 2970 - 8000 = -5030\,\mathrm{W}$

i.e. the air conditioning system must extract 5030W of heat from the room.

Evaluate:

Invite students to attempt the following examples:

Example 2.1

In North America the primary energy consumption per person per year was 6 tonnes oil equivalent[7] (= 6 × 42 GJ) in 2008. If the maximum amount of solar energy that can be captured by photosynthesis is 25Wm^{-2} and assuming that at best 8% is stored as chemical energy in biomass (typical value for sugar cane), what is the minimum land area needed to sustain the energy consumption of average person in North America using biomass alone? Compare this with the population and area of arable farm land.

Solution

Using the first law of thermodynamics, equate energy captured from photosynthesis in biomass to energy consumption:

Energy captured per unit area by photosynthesis assuming year round growing season with an average of 12 hours of daylight $= 0.08 \times 25 \times \left(365 \times 12 \times 60 \times 60\right) = 31.54$ MJ/m^2

Thus area required per person $= \dfrac{6 \times 42 \times 10^9}{31.54 \times 10^6} = 7990\,\mathrm{m}^2$ (≡1.97 acres)

US population is 309 million living on a land area of 3,537,438 square miles of which about one quarter is arable or 1.83 acres per person.

[6] Emmel, M.G., Abadie, M.O., Mendes, N., New external convective heat transfer coefficient correlations for isolated low-rise buildings, *Energy and Buildings* 39(3):335-342, 2007.
[7] BP Statistical Review of World Energy 2009.

Example 2.2

It takes about 5 hours for a fully charged iPod nano to run out of power when its screen is left on and all other functions are switched off. Subsequently, it takes about 90 minutes to re-charge the iPod from a charging unit with a 5V and 500mA output. The same iPod takes about 24 hours to run out of power when only the audio function is used. Calculate:

(a) the power consumption of the screen and the audio output separately;

(b) when the power will run out if the user switches on the screen for 10 seconds every 3 minutes (i.e. about once every track).

Solution

Energy from charge, $E_{charge} = VIt_{battery} = 5 \times 0.5 \times (90 \times 60) = 13500\,\mathrm{J}$

(a) Based on the first law of thermodynamics, the energy input (from charging) will be equal to the energy output, so

$$E_{charge} = \text{Power}_{screen} \times t_{screen}$$

hence

$$\text{Power consumption of screen } = \frac{E}{t_{screen}} = \frac{13500}{5 \times 60 \times 60} = 0.75\,\mathrm{W}$$

and

$$E_{charge} = \text{Power}_{audio} \times t_{audio}$$

hence

$$\text{Power consumption of audio } = \frac{E}{t_{audio}} = \frac{13500}{24 \times 60 \times 60} = 0.15625\,\mathrm{W}$$

(b) as for above but with a combined usage cycle, from first law of thermodynamics

$$E_{charge} = E_{cycles} \times n_{cycles}$$

so,

$$\text{Energy consumed in single cycle, } E_{cycle} = (10 \times 0.75) + (3 \times 60 \times 0.15625) = 35.625\,\mathrm{J}$$

$$\text{Number of cycles} = \frac{13500}{35.625} = 378.95$$

$$\text{Battery life} = 378.95 \times \left(3 + \frac{10}{60}\right) = 1200\text{ mins} \equiv 20\text{ hours.}$$