EVERYDAY EXAMPLES OF ENGINEERING CONCEPTS

T5: Exergy

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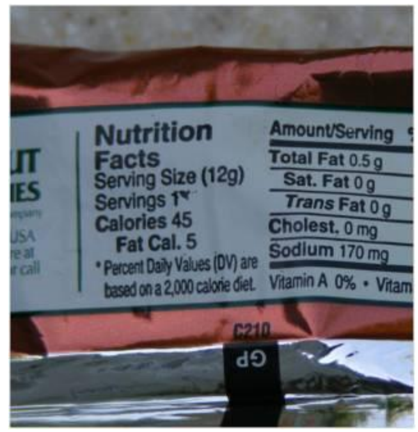
[1] Engleman, Laura (ed.), *The BSCS Story: A History of the Biological Sciences Curriculum Study*. Colorado Springs: BSCS, 2001.
[2] Atkin, J. M. and Karplus, R. (1962). Discovery or invention? *Science Teacher* 29(5): 45.
[3] e.g. Trowbridge, L.W., and Bybee, R.W., *Becoming a secondary school science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

SECOND LAW CONCEPTS

5. Topic**: Exergy**

Engage:

Take some individually wrapped candy, or small packets of nuts into class that have the energy content and nutritional values on the packet❹. Share them around the class.



Explore:

As the students enjoy the treat, remind them about the analysis in lesson 2 where we estimated the time required to loose, by heat loss, the energy gained from eating a chip while sitting doing nothing else; about 5½ minutes per chip. Then, ask the students, working in pairs, to consider how and why the heat is generated.

Explain:

The second law of thermodynamics requires that entropy is created in all real processes; during the metabolic processes in our bodies entropy is generated as heat and needs to be dispersed. All living organisms continually generate entropy in every process and during every event, so that they progress towards a state of maximum entropy in which they are in complete equilibrium with the environment, i.e. death. Living organisms remain alive by continually drawing negative entropy, known as exergy from the environment[4]. Plants use sunlight as their source of exergy (negative entropy) and animals eat plants or other animals to gain their exergy. Thus, to be really useful, the labeling on food packets should include the exergy content.

Engineering systems are described as being in a 'dead state' when they are in thermodynamic equilibrium with their environment, i.e. at the temperature and pressure of the environment with zero velocity and relative elevation (KE = PE = 0) and chemically inert. In a dead state a system has no potential to perform work because there is no 'available energy', or exergy.

Elaborate:

Exergy is a measure of the available energy of a system relative to its dead state. Of course we cannot always run a system down to its dead state, unlike the battery a mobile phone. Exergy is destroyed during all real processes. It can only be conserved in reversible processes and can never be created. This is a consequence of the second law of thermodynamics. In heat transfer processes the destruction of exergy is related to the creation of entropy:

$$X_{destroyed} = T_0 S_{generated}$$

[4] Schrödinger, Erwin, What is life? Cambridge University Press, Cambridge, 1944.

Heat can be considered to contain exergy since in the appropriate circumstances it is able to perform useful work. The exergy level of heat depends on the temperature at which the heat is available and the temperature at which heat can be rejected and this is maximized in the Carnot cycle for which the efficiency is

$$\eta = 1 - \frac{T_L}{T_H}$$

in these circumstances the exergy is given by

$$X = Q\left(1 - \frac{T_L}{T_H}\right)$$

The exergy of a system at a specified state is the sum of the internal, kinetic and potential energies of the system where the internal energy is taken as the total useful work output as the system undergoes a reversible process from the specified state to the dead state which is equivalent to the enthalpy of the fluid contained in the system, so that

$$X = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + KE + PE$$

Exergy is sometimes known as the irreversibility, I where for a system producing work

$$I = W_{rev} - W_{use} = X_{destroyed}$$

where W_{use} and W_{rev} are useful and reversible work and need to be interchanged when considering a system consuming work.

Evaluate:

Invite students to attempt the following examples:

Example 5.1

(a) Measure the temperature adjacent to the interior and external walls of your room; and calculate the exergy destroyed in the wall as a consequence of heat transfer through the wall.

(b) How is this related to value of the entropy found in Example 4.2?

Solution:

(a) Solving this example for the editor's study in December in Michigan:

$$T_{\text{int}} = 68\,°\text{F} = 19.44\,°\text{C} = 292.44\,\text{K}$$

$$T_{ext} = 28\,°\text{F} = -2.22\,°\text{C} = 270.78\,\text{K}$$

and $\dot{Q}_{out} = h_c A(T_{room} - T_{environment})$

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 = 2.7×4.05 = 10.935 m^2) we have

$$\dot{Q}_{out} = 12 \times 10.935(292.44 - 270.78) = 2842\,\text{W}$$

We can consider the wall to be a closed system since there is no mass transfer. Assuming the temperatures on each side of the wall to be approximately constant (changing very slowly) then the rate of change of exergy across the wall is zero, i.e.

$$\frac{dX_{system}}{dt} = 0 = \dot{X}_{in} - \dot{X}_{out} - \dot{X}_{destroyed}$$

Or using $$\dot{Q}\left(1-\frac{T_0}{T}\right)_{in} - \dot{Q}\left(1-\frac{T_0}{T}\right)_{out} - \dot{X}_{destroyed} = 0$$

so $$\dot{X}_{destroyed} = 2842\left[\left(1-\frac{270.78}{292.44}\right)-\left(1-\frac{270.78}{270.78}\right)\right] = 210.5\,\text{W}$$

(b) Alternatively, the same answer could have been obtained by using the value of the entropy generated which was calculated in Example 4.2 as 0.777W/K and multiplying it by the temperature of the environment, T_0=270.78K (i.e. $X_{destroyed} = 0.777 \times 270.78$)

Example 5.2

Cars running on compressed air are a reality, see for example: www.mdi.lu.

(a) Use an exergetic analysis to calculate how much work can be performed by the compressed air in the tank of a typical car with a capacity of 175 litres (≡0.175m^3) containing air compressed to 350bar (≡35000 kPa) at 25°C.

(b) If about 15% of the 32MJ/litre exergy content of 87 Octane gasoline fuel is converted to motive force in a typical car powered by an internal combustion engine[5], how many litres of gasoline is the tank of air equivalent to when used in 90% efficient air motor.

Solution:

(a) Assume the air in the tank to be at state 1, and T_1=T_0=25°C where subscript 0 refers to the state in the environment, we can calculate the mass of air stored in the tank using the ideal gas equation.

$$m_1 = \frac{P_1 V}{RT_1} = \frac{35\times10^6 \times 0.175}{287\times298} = 71.6\,\text{kg}$$

Considering the exergy of the system:

$$X = (U-U_0) + p_0(V-V_0) - T_0(S-S_0) + KE + PE$$

In this case there is no change in internal energy, kinetic or potential energy of the air, so

$$X_1 = m_1\left[P_0(v_1-v_0) - T_0(s_1-s_0)\right]$$

[5] http://www.fueleconomy.gov/FEG/atv.shtml

And using the ideal gas equation $m_1 P_0 (v_1 - v_0) = m_1 P_0 \left(\frac{RT_1}{P_1} - \frac{RT_0}{P_0} \right) = m_1 RT_0 \left(\frac{P_0}{P_1} - 1 \right)$ because $T_1 = T_0$ and, similarly for an ideal gas

$$ds = c_p \ln \frac{T_1}{T_0} - R \ln \frac{P_1}{P_0}$$

so $$T_0 (s_1 - s_0) = T_0 \left(c_p \ln \frac{T_1}{T_0} - R \ln \frac{P_1}{P_0} \right) = -RT_0 \ln \frac{P_1}{P_0}$$

Hence $X_1 = m_1 RT_0 \left(\frac{P_0}{P_1} - 1 + \ln \frac{P_1}{P_0} \right) = 71.6 \times 287 \times 298 \times \left(\frac{1 \times 10^5}{3.5 \times 10^7} - 1 + \ln \frac{3.5 \times 10^7}{1 \times 10^5} \right) = 2.97 \times 10^7 \text{ J}$

(b) So the available energy is 29.7MJ and MDI claim to achieve 90% efficiency in their air motors giving 26.8MJ of motive energy available.

One litre of 87 Octane gasoline has an energy (exergy content) of 32MJ/litre and 15% of this energy gets used to generate motive energy, i.e. 4.8MJ/litre. So the AirPod has a range equivalent to about 5.58 litres (= 26.8 / 4.8).

An equivalent size gasoline-powered car (e.g. Ford Focus) has an urban cycle fuel consumption of about 3.6 litres/100km[6] so 5.58 litres would take you 155 km (= [5.58 / 3.6] × 100).

(a) MDI claim their AirPod, which can carry 3 to 4 people, will have a range of 220km (137 miles) at a maximum speed of 70km/hr (44 mph).

[6] http://www.vcacarfueldata.org.uk/search/vehicleDetails.asp?id=22655