EVERYDAY EXAMPLES OF ENGINEERING CONCEPTS

T1: Systems, properties & substances

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.

Eann A. Patterson
A.A. Griffith Chair of Structural Materials and Mechanics
School of Engineering, University of Liverpool, Liverpool, UK
& Royal Society Wolfson Research Merit Award Recipient+

---

[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

1. Topic: **Systems, properties, & pure substances**

Engage:

Take a coffee maker (filter machine), flask of water, and, if you have one, a coffee grinder and beans. The coffee grinder will make a lot of noise and the process of grinding beans and preparing the coffee maker to brew coffee should engage the attention of the class.

Explore:

While preparing to brew your coffee you can discuss closed systems and control volumes (open systems). The filter machine while it is brewing the coffee can be considered a closed system in which no mass is transferred across its boundaries, assuming no steam escapes from it. If you wanted to consider the chemical process in which the coffee is produced then you might define a control volume as the cone containing the coffee grounds, i.e., it has a prescribed boundary across which mass flows (water in and coffee out).

Explain that intensity properties, such as the temperature of the water in the filter machine, are independent of the size or extent of the system; whereas extensive properties such mass are dependent on the extent and size of the system. The coffee is brewed at the same temperature regardless of how much coffee and water you put in the machine. However, the mass of the system is strongly a function of the amount of water and coffee in the closed system.

Note that the filter machine is not in equilibrium during the brewing process because there is a significant temperature gradient. Also, comment on the water being a pure substance, i.e., uniform and invariable composition, whereas the coffee is not a pure substance because its chemical composition will change with a change in phase.

Explain:

Take an old filter machine into class and remove its base. Explain that there is a hole in the bottom of the reservoir connected via a one-way valve to a pipe that runs under the hot-plate on which the coffee pot sits. The heating element in the hot plate heats the cold water that is supplied by the pipe from the reservoir. Steam forms in the pipe and the bubbles are forced along the pipe and up into the hopper containing the coffee by the increase in pressure caused by the expansion of the heated water. The one-way valve prevents the hot water and steam returning to the reservoir. The rest of the process is driven by gravity as the hot water percolates through the coffee grounds and falls into the coffee pot where it is kept warm by the hot plate.

Elaborate:

When the coffee is brewing it drips very slowly into pot; so the flow through the system is slow and, hence, the level of the water in the reservoir drops very slowly. So, if the level of water in the reservoir is nearly constant we can assume that the water in the pipe under the hotplate is being heated at constant pressure. When brewing is started, the temperature will be ambient (≈ 21°C) and the pressure will be 2158N/m^2 $(=\rho g h = 1000 \times 9.81 \times 0.22)$ above atmospheric pressure assuming the surface of the water in the reservoir is 22cm above the pipe under the hot plate. On a temperature-volume plot, this state lies somewhere between *1* and *f* (in the *T-v* diagram below) in the compressed liquid phase.

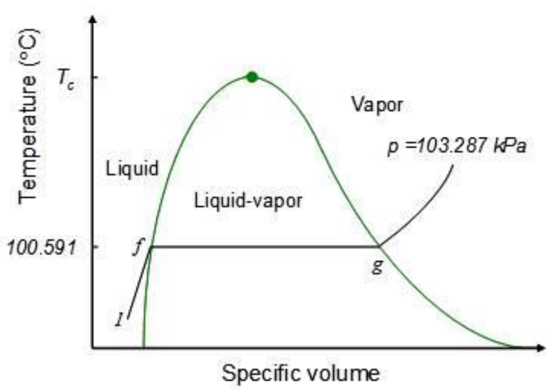
Using thermodynamics tables (www.dofmaster.com/steam.html)[❶] it is possible to establish that the specific volume for water at p = 101.325 + 2.158 = 103.483 kPa and T = 21°C is v = 0.0010m^3/kg with a saturation temperature of 100.5913°C, i.e. the head of water raises the boiling point, (≡ T_{fg}) slightly above 100°C.

As heat is transferred to the water in the pipe, at constant pressure, its state moves along *1-f* until it reaches *f* when it is saturated water, $T_{fg} = 100.5913\,°\text{C}$.

With further heat transfer the water becomes a two-phase, liquid-vapor mixture and its state progresses along *fg* on the *T-v* diagram. In this state the liquid phase is saturated liquid and the vapor phase is saturated vapor; and the mixture begins to move up the pipe and eventually falls on the coffee. The quality of the mixture, x is the ratio of the mass of vapor to the total mass of the vapor:

$$x = \frac{m_{vapor}}{m_{liquid} + m_{vapor}}$$

Even after moving only 5% of the distance along the *fg* line (x = 0.05, T = 100.5913°C), the specific volume will have increased from 0.0010 to 0.0830 m^3/kg, according to the thermodynamic steam tables and this expansion is probably sufficient to drive it up the tube to fall onto the coffee.



Evaluate:

Invite students to attempt the following examples:

<u>*Example 1.1*</u>

For the water in the coffer filter machine already discussed, estimate the energy supplied by heating when brewing a cup of coffee.

<u>Solution:</u>

Heat transferred to water = change in internal energy of water

❶ These steam tables are available as a download to your iPod Touch or Phone (price: $11.99 at time of going to print).

Using thermodynamic steam tables, internal energy, u_1 for water at p = 103.483 kPa and T = 21°C is 88.0347 kJ/kg.

And at p= 103.483 kPa and x = 0.05, internal energy, u_2 = 525.5212 kJ/kg

So the change in internal energy, $\Delta u = u_2 - u_1 = 525.5212 - 88.0347 = 437.4865$ kJ/kg.

There is about 260g of water in a mug of coffee so the energy supplied is 114kJ (= 437.4866×0.26).

Example 1.2

After a tiring trek in the Rocky Mountains, you return to your lodging in Park City Resort (elevation 6900ft) and place a storage container with 500g of soup in the microwave to reheat it, forgetting to take off the top. For the sake of simplicity ignore the other ingredients in the soup and treat it as being pure water and find:

(a) at what temperature will it just start to evaporate?

(b) if the container can withstand an increase in volume of 1/5th before failure, what would be the quality of the mixture in the container the instant before it bursts?

(c) how much energy must be supplied to induce the container to burst?

Solution:

(a) Approximate pressure at 6900ft (≡ 2123m)

$$= p_{atm} - \rho g h = 101325 - (1 \times 9.81 \times 2123) = 80498 \text{ Pa}$$

From the thermodynamic tables the saturation temperature at this pressure (x = 0) is 93.6794°C, so the water vapor would appear at the temperature, i.e. boiling would begin.

(b) The specific volume of the water at 80.498 kPa and room temperature is 0.001m^3/kg. Note that this value does not change even at saturation temperature. So, a 1/5th volume change would give a specific volume of 0.0012. From the thermodynamic steam tables, this specific volume is achieved at a quality of x = 0.0001 for a pressure of 80.498 kPa.

(c) From the thermodynamic steam tables, the internal energy, u

at a room temperature of 21°C, u_1 = 88.0362 kJ/kg

and for the condition in (b) u_2 = 392.5533 kJ/kg

so, the change in internal energy, u_2 - u_1 = 304.5171 kJ/kg

Thus, the energy required to heat 500g of soup is 152.26kJ (=0.5 kg × 304.5171 kJ/kg).

Note: if a 1000W microwave with an efficiency of 64% is used only 704W (= 1100 × 0.64) of power will be converted to heat energy, i.e., 704 J/s so it will take 3 minutes and 36 seconds (= 216 seconds = 152,360/704) to supply the 152.26 kJ needed to heat the soup; plenty of time to catch it before the container bursts!