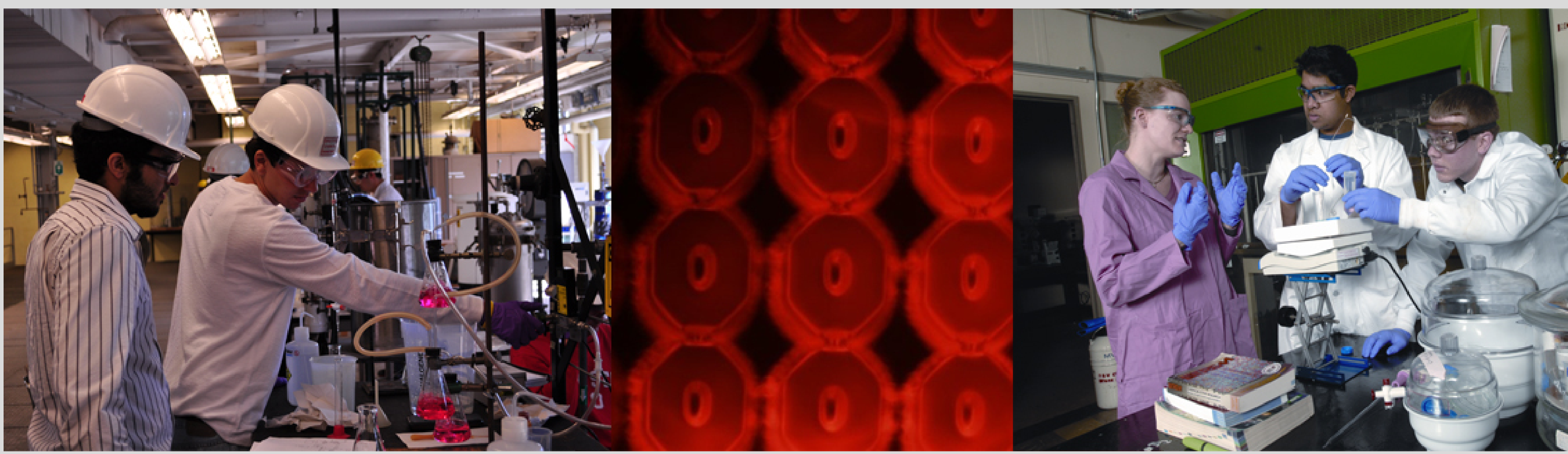
# INTEGRATION OF INDUSTRIALLY RELEVANT EXAMPLES IN A CHE COURSE

Energy Balance on an eCigarette

"The first step to knowledge is to know that we are ignorant."
Socrates



# OVERVIEW

- Benefits of integrating industrially relevant examples in a course
- eCigarette energy balance problem
  - Problem statement
  - Relevance to course learning objectives
  - Assumptions
  - Solution
  - Potential extensions
  - Student assessment
- Summary and conclusions
- Questions

# BENEFITS OF RELEVANT EXAMPLES

**Enhances the student learning experience**

**Linking theory and calculations to something concrete provides relevancy**

**Reinforces key aspects of a topic**

**Understand the assumptions necessary to solve a real-world problem**

# ECIGARETTE ENERGY BALANCE

**Over the last few years, many people have been switching from smoking cigarettes to a healthier alternative, e-cigarettes, sometimes called vaporizers. Instead of using tobacco, they use a mixture of Glycerin and Propylene Glycol liquid to create the vapor.**

**You decide you want to build your own vaporizer, but aren't sure of the minimum power needed for the device. You know that the liquid comes pre-mixed in a volumetric ratio of 70/30 glycerin to propylene glycol, and can be considered well mixed. Three (3) ml of liquid is poured into the main tank of the device, where it flows into a smaller tank that is connected to the mouth piece through a small tube. A coil inside of the small tank is connected directly to the battery, in which a voltage is applied as a button is held down to heat up the coil, providing the energy needed to vaporize the liquid.**

**You measure the large tank, which is a cylinder, to have a diameter of 1.6 cm. The smaller tank (also a cylinder) sits inside the large tank and has a diameter of 1.3 cm. When using the vaporizer with a premade battery, you measure the height change of the liquid in the large tank to be 4mm over a time of 2.3 minutes of use.**

**Solve for the power required to vaporize the liquid mixture.**

**Problem statement from Eric Collins, student in ChBE 2200, Fall, 2015**

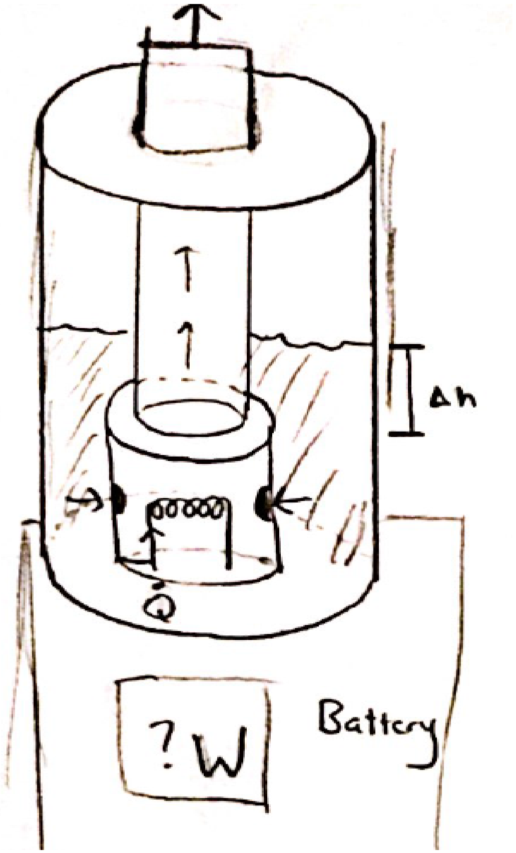
# RELEVANCE TO LEARNING OBJECTIVES

**Submission requires application of knowledge from multiple aspects of the Mass and Energy Balances course**

- **Material from five (5) different chapters**
- **Material from nine (9) different sections in Felder and Rousseau**
- **Direct links to seven (7) high-level learning objectives**

# ECIGARETTE SOLUTION

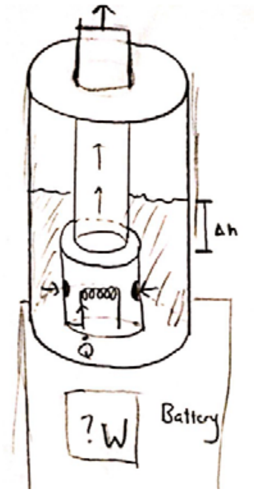
**1. Draw a schematic of the problem, labeling the fluid reservoir in the vaporizer, the heater, and key dimensions required to solve the problem**



# ECIGARETTE SOLUTION

**2. Identify the process type (batch, semi-batch, or continuous) and the process mode (steady-state or unsteady state)**

**The system is defined as the fluid reservoir. Therefore, this is a semi-batch process (mass leaves the system, but no mass enters the system). By definition, all semi-batch processes are unsteady state.**



# ECIGARETTE SOLUTION

**3. Use various resources to obtain the molecular weight, density, heat capacity, normal boiling point, and heat of vaporization for the two components in the liquid reservoir**

| Material | Mol Wt (g/mol) | Density ($g/cm^3$) | $C_p$, liq (J/(mol*K)) | $C_p$, vap (J/(mol*K)) | $T_b$ (°C) | $\Delta H_{vap}$ (kJ/mol) |
|---|---|---|---|---|---|---|
| Glycerol | 92 | 1.261 | 221.2 | 167.6 | 290 | 91.7 |
| Prop Glycol | 76 | 1.036 | 189.9 | 152.1 | 187 | 66.5 |

**Data obtained from: a) NIST (webbook.nist.gov)**

**b) Properties of Gases and Liquids, 4th ed., Reid, Prausnitz, and Poling**

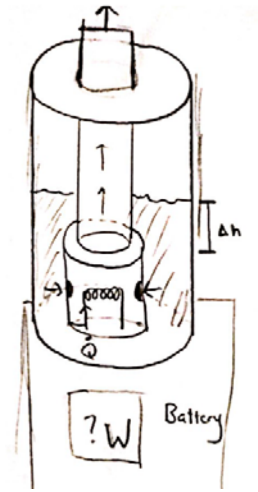
# ECIGARETTE SOLUTION

## 4. Calculate the average volumetric flowrate of the vapor, based on the reduction in liquid level over the observation time

**First, calculate the volume change over the observed time**

**The area of the annulus can be obtained from the given diameters:**

$$Area = \pi * \left( \frac{1.6cm}{2}^2 - \frac{1.3cm}{2}^2 \right) = 0.6833\ cm^2$$




**Next, use the change in height over the observed time to convert the area to volume:**

$$\Delta V = Area * \Delta h = 0.2733\ cm^3$$

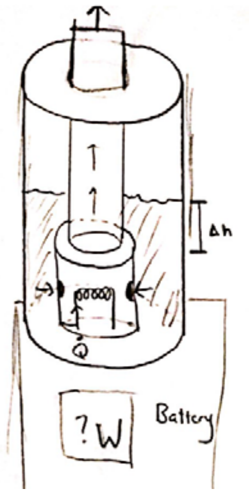
**The average volumetric flow rate is the change in volume divided by the observation time:**

$$\dot{V} = \frac{\Delta V}{\Delta t} = \frac{0.2733\ cm^3}{138\ s} = 0.001981\ cm^3/s$$

# ECIGARETTE SOLUTION

**5. Calculate the mass fraction of the glycerol and propylene glycol in the liquid reservoir based on the given volume fraction**

**The liquid composition has been given in volume fraction. Assuming the mixture is ideal, the total volume is the sum of the individual volumes. Using 1 ml as a basis, the volume of glycerin would be 0.7 ml, and the volume of propylene glycol would be 0.3 ml. With the given densities, this would equate to 0.8827 g of glycerin and 0.3108 g of propylene glycol, or 1.1935 g total.**




$$x_A = \frac{0.8827}{1.1935} = 0.7396$$

$$x_B = \frac{0.3108}{1.1935} = 0.2604$$

# ECIGARETTE SOLUTION

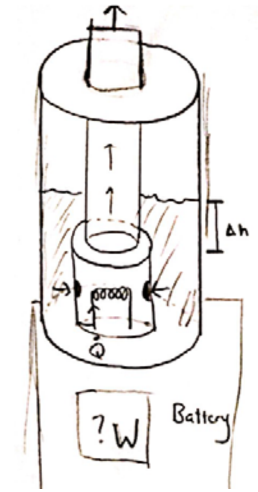
**6. Calculate the mass flow rate of the vapor using the average density of the liquid mixture**

**First, the average density must be calculated:**

$$\frac{1}{\bar{\rho}} = \frac{x_A}{\rho_A} + \frac{x_B}{\rho_B}$$

$$\frac{1}{\bar{\rho}} = \frac{0.7396}{1.261\ \frac{g}{cm^3}} + \frac{0.2604}{1.036\ \frac{g}{cm^3}}$$

$$\bar{\rho} = 1.1935\ \frac{g}{cm^3}$$




**The mass flow rate is equal to the volumetric flow rate times the density:**

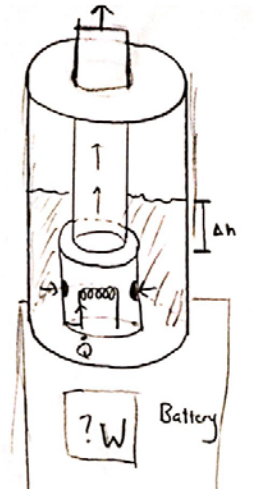
$$\dot{m} = \dot{V} * \bar{\rho} = 0.002364\ g/s$$

# ECIGARETTE SOLUTION

**6. Calculate the mass flow rate of the vapor using the average density of the liquid mixture**

**The mass flow rate is equal to the volumetric flow rate times the density:**

$$\dot{m} = \dot{V} * \bar{\rho} = 0.002364 \; g/s$$




**The mass flow rates of glycerin (A) and propylene glycol (B) can be obtained by multiplying the total mass flow rate by the mass fractions of the components:**

$$\dot{m}_A = \dot{m}_{tot} * x_A$$

$$\dot{m}_B = \dot{m}_{tot} * x_B$$

$$\dot{m}_A = 0.001748 \; g/s$$

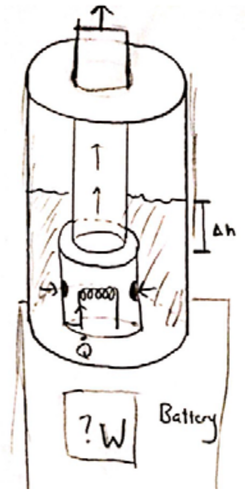
$$\dot{m}_A = 0.000616 \; g/s$$

# ECIGARETTE SOLUTION

**7. Calculate the bubble point and dew point of the mixture, assuming Raoult's Law is valid**

$P_{tot} = x_A * P_{vapA} + x_B * P_{vapB}$ **(Raoult's Law)**

$P_{vapA} = 10^{\left(A - \frac{B}{T+C}\right)}$ **(Antoine Equation)**




**Solve for the temperature at which the total pressure is equal to the atmospheric pressure**

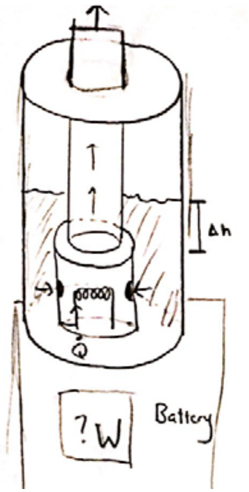
$$P_{tot} = x_A * P_{vapA} + x_B * P_{vapB}$$

$$Obj\ Fxn = P_{atm} - P_{tot}$$

**An Excel spreadsheet was set up to solve for the temperature when the objective function was equal to zero. The calculated bubble point temperature was 229.2°C. Similarly, the calculated dew point temperature was 275.7°C.**

# ECIGARETTE SOLUTION

**8. Set up the energy balance for the system, justifying any simplifying assumptions**

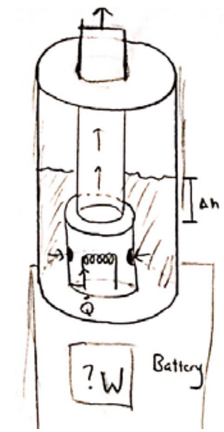



**The open system energy balance is applicable for this problem. Neglecting kinetic and potential energy changes and shaft work, the energy balance simplifies to the following:**

$$\Delta\dot{H} = \dot{Q}$$

**If heat transfer from the device to the environment is neglected, then the heat added to the system by the heater element is equal to the change in enthalpy**

# ECIGARETTE SOLUTION




**9. Set up an enthalpy table for the system, clearly identifying reference conditions and solve for Q, the heat required to vaporize the liquid**

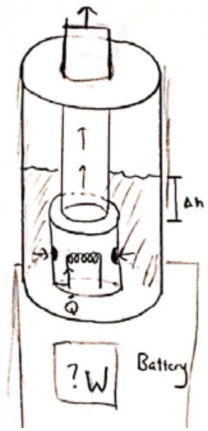
| References: Glycerin and propylene glycol liquids at 25C and 1 atm | | | | |
|---|---|---|---|---|
| Substance | $\dot{m}_{in}$ | $\widehat{H}_{in}$ | $\dot{m}_{out}$ (g/s) | $\widehat{H}_{out}$ (J/g) |
| Glycerin | 0 | - | 0.001748 | $\widehat{H}_1$ |
| Prop Glycol | 0 | - | 0.000616 | $\widehat{H}_2$ |

$$\widehat{H}_1 = C_{pA,liquid}*(T_{BPA}-25C) + \Delta H_{vapA} + C_{pA,vapor}*(T_f-T_{BPA}) = 1565.5\ J/g$$

$$\widehat{H}_2 = C_{pB,liquid}*(T_{BPB}-25C) + \Delta H_{vapB} + C_{pB,vapor}*(T_f-T_{BPB}) = 1410.8\ J/g$$

$$\dot{Q} = \dot{m}_A \widehat{H}_1 + \dot{m}_B \widehat{H}_2 = 3.605\ W$$

# ECIGARETTE SOLUTION




**10. Validate solution** $\dot{Q} = 3.605$ W

- **Remarkably, even with the assumptions made in solving this problem, the predicted heat input compares very well against actual values for batteries used in these devices**
- **Standard e-cigarette devices often use 3.7 volt batteries and use 5.5 watts of power (www.vaportrain.com)**
- **The predictions made in this analysis are slightly lower than the power delivered by the battery, which makes sense since we assumed the device was adiabatic**
- **Heat loss to the environment would increase the required power to provide a heat input of 3.6 watts**
- **In addition, the power supplied to an e-cigarette device needs to power LED lights and the control system**
- **Our solution has been validated by comparing it against an actual situation**

# POTENTIAL PROBLEM EXTENSION PROMPTS

1. **Do you expect the rate of vaporization rate to be constant? Why or why not? If you do not think the vaporization rate will be constant, what is the expected variation and does the assumption of constant average vaporization rate dramatically impact the results?**
2. **The problem statement assumed the fluid reservoir reached a temperature between the bubble point and dew point during vaporization. How would you expect the actual temperature to vary during the process? Do you expect your calculated result for the required power to be dramatically impacted by this assumption? Why or why not?**
3. **The power required to vaporize the liquid mixture was calculated based on the given set of conditions. Research the power delivered by different batteries. What type of battery would you recommend be used for this application? What would be the factors involved in making this selection (e.g. think of size, cost, safety, packaging, and reliability)? What is the efficiency of a typical battery?**

# STUDENT ASSESSMENT USING CLICKERS

**Initial assessment conducted after problem statement provided**

- **"After reading the problem statement, I have a plan of attack to solve the problem."**

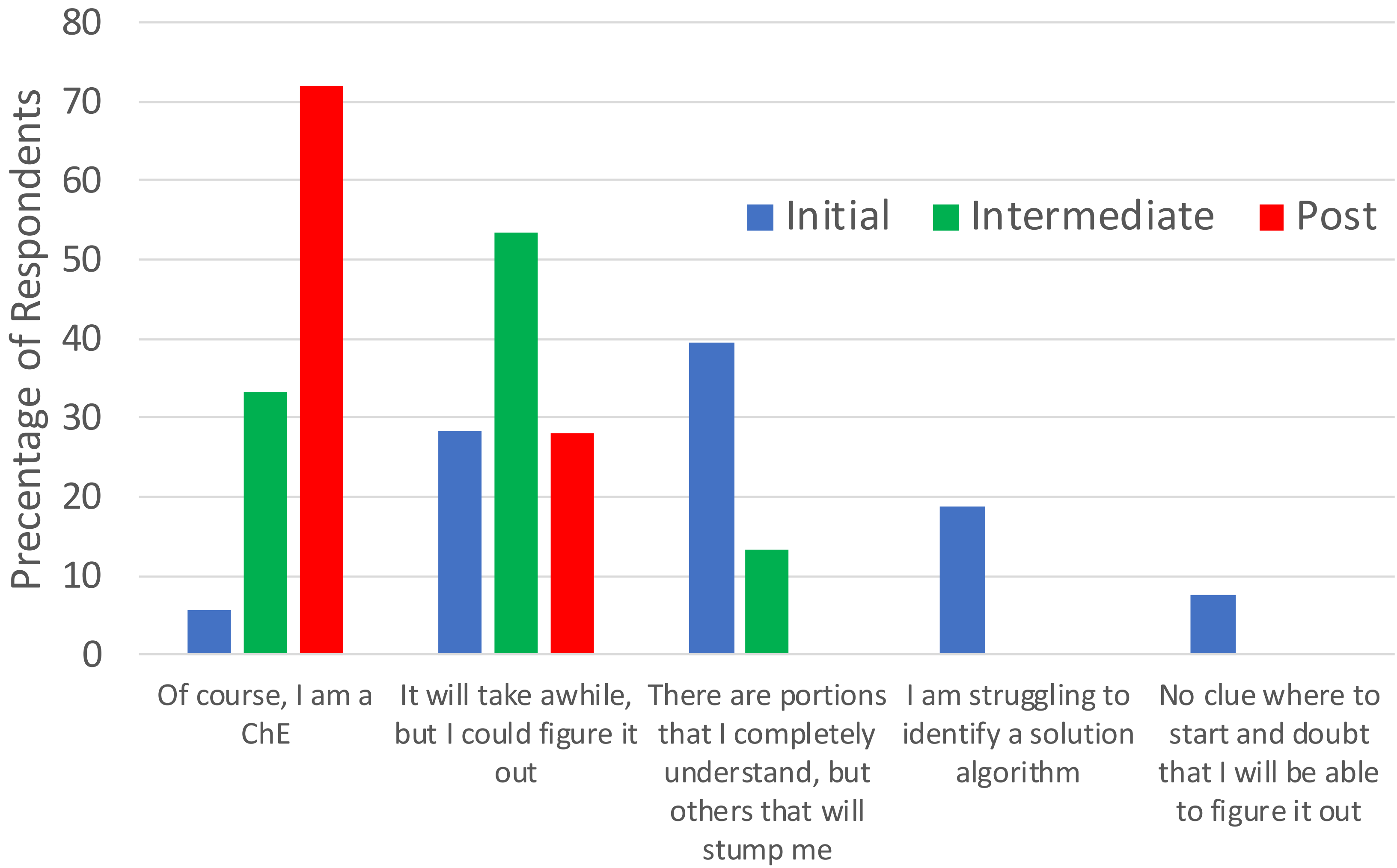
**Second assessment conducted after 30 minutes of working in 3-5 person groups**

- **"After working for 30 minutes, my assessment of my group's ability to solve this problem is..."**

**Final assessment conducted next day after the solution was worked out**

- **"After seeing the problem worked out, my assessment of my ability to solve this problem is..."**

# STUDENT ASSESSMENT




**Collaborative approach to solving the problem resulted in tangible benefits for problem comprehension**

# SUMMARY AND CONCLUSIONS

**The solution of an industrially relevant mass and energy balance problem was conducted in a sophomore level course**

**The solution blends in multiple chapters, sections, and learning objectives from the course**

**The problem requires selection of appropriate assumptions to permit solution**

**Collaborative work amongst students resulted in improved problem understanding and a dramatic increase in the ability to solve the problem**

# QUESTIONS