An Application of Energy & Thermodynamics Principles to the Creation of Espresso

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Abstract

The aim of this thought experiment was to apply engineering thermodynamics fundamentals to the creation of espresso beverages. This involved using the Conservation of Energy Principle at steady-state; an understanding of heat transfer via conduction, convection, and radiation; and the changes of state of water. Though not physically completed in a laboratory, various parameters for chamber size and heat input rates were simulated and tested to observe how the processes within the closed system would change. Temperatures as functions of time, boiling temperatures, and energy required to create espresso were found and real-life in-cafe practices were also analyzed.

1 Experiment Background

The espresso coffee maker to be studied is comprised of a closed bottom pot filled with water, a strainer, a pressure relief valve, and a top chamber with a gasket seal where the espresso will ultimately collect and be poured out of. When placed on a stove-top, the bottom chamber with water will be heated considerably by some Q_{in} and then the water will rise through the grounds and into the top chamber at a specific temperature-dependent pressure, assuming the experiment to be successful. A simple illustration of the maker and its components are displayed in Figure 1.

2 Objectives

While not a typical laboratory experiment, this study aims to analyze thermodynamic processes that occur in the making of espresso with a stove-top instrument. Instead of completing a bench-top experiment and collecting data by varying specific parameters, this study serves as an in-depth thought experiment of mathematical observations. Temperature as a function of time at some rate of Q_{in}, boiling temperature, and amount of energy used for heating will be found for a hypothetical pot.

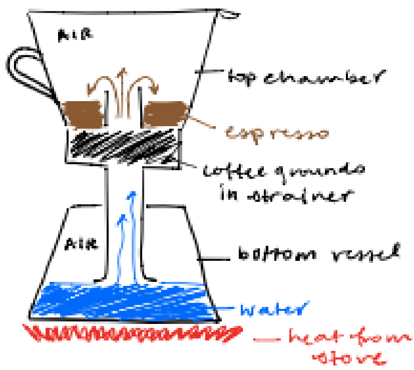

Figure 1: A schematic of the espresso maker.

3 Experimental & Analysis Procedures

Initially, the bottom pot of the espresso maker is filled with a volume of water and then becomes a closed chamber at atmospheric pressure once sealed. This contraption is then placed upon the stove where heat is then transferred to the bottom chamber though the bottom plate and into the volume of water. The heating of this water is an example of conduction, in which the rate of heat transfer $\dot{Q}_{in}$ is proportional the bottom plate area and the temperature gradient. (One must note that at the same time, the aluminum pot of density $\rho = 169\frac{lbm}{ft^3}$ is also losing heat to the room it occupies via convection and radiation by some rate $\dot{Q}_{loss}$ which can be described as $\frac{Q_{loss}}{dt} = \frac{Q_{conv}}{dt} + \frac{Q_{rad}}{dt}$.)

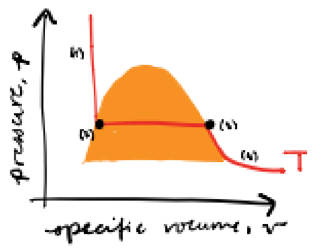

Figure 2: Pressure vs. Specific Volume.

Due to the heating of the water in the bottom pot, the temperature will begin to increase and the water will reach a saturated liquid state at its boiling point (point (2) in Figures 2 and 3). With more heat being added, the state of the water will begin to traverse the vapor dome at a constant pressure and constant temperature until it reaches a saturated vapor state. During this time, the specific volume of the water is increasing as it traverses the vapor dome because while the volume of the chamber remains constant, the mass of the water is decreasing due to the motive force of the pressure driving the water up out of the bottom chamber, through the strainer, and into the top chamber thereby creating the espresso. A simple sketch of the relationships between pressure, temperature, and specific volume of the water are displayed in Figures 2 and 3. Once at the saturated vapor state where the espresso has now been produced, marked as point (3) on the diagrams, further heat being added at a fixed pressure will cause the temperature and the specific volume to increase further and become what is referred to as superheated vapor.

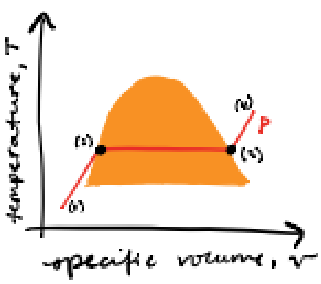

Figure 3: Temperature vs. Specific Volume.

In addition, Figure 4 displays what is expected to be the relationship between the temperature of the water and the pot with time. One can see that the temperature increases almost linearly until it reaches the boiling point at atmospheric pressure. When the water first reaches the boiling point, it is in its saturated liquid state (equivalent to point (2) on Figures 2 and 3). This is essentially very similar to the general process of boiling water that has been studied in Energy and Thermodynamics thus far.

Assuming hypothetical coffee pot dimensions of a diameter of 2.5 inches and height of 3 inches, the mass of the water needed to fill the bottom chamber is 0.5318 lbm (pound-mass). The volume of this bottom chamber is 0.008522 ft^3. This was found using Equation 1 below and the density of water ρ_w = 62.4 $\frac{lbm}{ft^3}$. The mass of the pot of wall thickness 0.125 inches, was found to be 0.2880 lbm (ρ_{Al} = 169 $\frac{lbm}{ft^3}$) using Equation 2.

$$m_w = \frac{\pi}{4}(2.5in)^2(3.0in)(\frac{1ft^3}{(12in)^3})\rho_w \tag{1}$$

$$m_{pot} = \pi(2.5in)(3.0in)(0.125in)(\frac{1ft^3}{(12in)^3})\rho_{Al} \tag{2}$$

4 Results

A relationship between the temperature of the water & pot and time was found for various rates of heat inputs using Equations 3 and 4, in which the heat transfer coefficient for convection h_A = 0.5 $\frac{Btu}{hr*F}$ and the proportionality constant of heat transfer for radiation K_{co} = 5*10^{-9} $\frac{Btu}{hr*R^4}$. (It is also important to note that these equations are only valid for temperatures less than or equal to the boiling temperature.) For example, at a heat rate input of 200 $\frac{Btu}{hr}$ temperature as a function of time (in seconds) can be described as T = -0.001t^2 + 0.0938t + 70.000 in degrees Fahrenheit, and a plot of this can be seen in Figure 5. Since the rate of heat input is a dependent variable and can be adjusted for different sized pots, one can also look at other heat input rates that will bring the temperature of the water to boiling. In Figure 5, the water temperature never reaches boiling at $\dot{Q_{in}}$ = 200 $\frac{Btu}{hr}$, but in Figure 6 one can see that water reaches a boiling point of about 212 °F with a heat input rate of $\dot{Q_{in}}$ = 1000 $\frac{Btu}{hr}$. For this heat input rate, temperature as a function of time (in seconds) can be described as T = -0.0004t^2 + 0.4919t + 70.000 until reaching the boiling temperature.

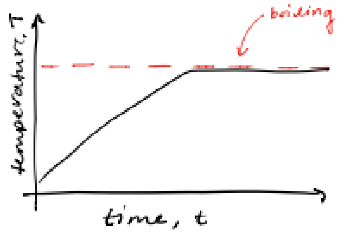

Figure 4: Expected Temperature vs. Time Plot.

$$\dot{Q}_{in} - \dot{Q}_{out} = m_{pot}c_{Al} + m_w c_w \frac{\Delta T_{system}}{\Delta time} \tag{3}$$

$$\dot{Q}_{out}[\frac{Btu}{hr}] = h_A(T_{system} - T_{room}) + K_{co}((T_{system} + 460)^4 - (T_{room} + 460)^4) \tag{4}$$

If given the resources to conduct this experiment in a laboratory setting, one could measure the heat input using various instruments and tools. A weight scale would be used to measure the mass of water and the bottom chamber before placing on the stop top, and then as heat is being added to the bottom of the pot from the stove, a thermister would be inside the bottom chamber measuring the temperature with a digital watch to record the time. The bottom chamber would then be weighed after the completion of espresso and the top chamber could also be weighed before and after to observe how the findings deviate from what was expected.

The boiling temperature was found using linear interpolation from steam tables data(Moran, Shapiro, Boettner, & Bailey, 2014) . At a boiling pressure that is equal to 14.796 psi [$\frac{lbm}{in^2}$], which is assumed to be the sum of the atmospheric pressure, pressure of the coffee grinds, pressure of the inverted water spout, and the pressure of the pour spout, the boiling temperature is found to be 212.33 °F.

Analyzing the situation of 1000 $\frac{Btu}{hr}$ as the heat input, it takes 0.1301 hours to reach boiling. The energy required to heat the water to produce espresso, Q_{in}, can be calculated using Equations 5 and 6 below in which Q_{in} = Q_{net} - Q_{loss}, and was found to be 171.48 Btu for this particular time to reach boiling. Though similar to Equations 3 and 4, the gravitational change in height of the water must now be considered (g = 32.174 $\frac{lbm}{ft^3}$ moving a height up by 0.25 ft). However, there is no kinetic energy ($\frac{V_i^2 - V_f^2}{2}$ = 0) and no work ($\dot{W_{net}}$ = 0) being done to the steady-state ($\frac{dE}{dt}$ = 0) closed system so these specific terms in Equation 5 reduce to zero, leading to Equation 6.

$$\frac{dE}{dt} = \dot{Q_{net}} - \dot{W_{net}} + \dot{m}(h_i - h_f + \frac{V_i^2 - V_f^2}{2} + g(z_i - z_f) \quad (5)$$

$$Q_{in} = (m_w c_w + m_{pot} c_{Al})\Delta T_{system} + m_w g \Delta height + \dot{Q_{loss}}(time) \quad (6)$$

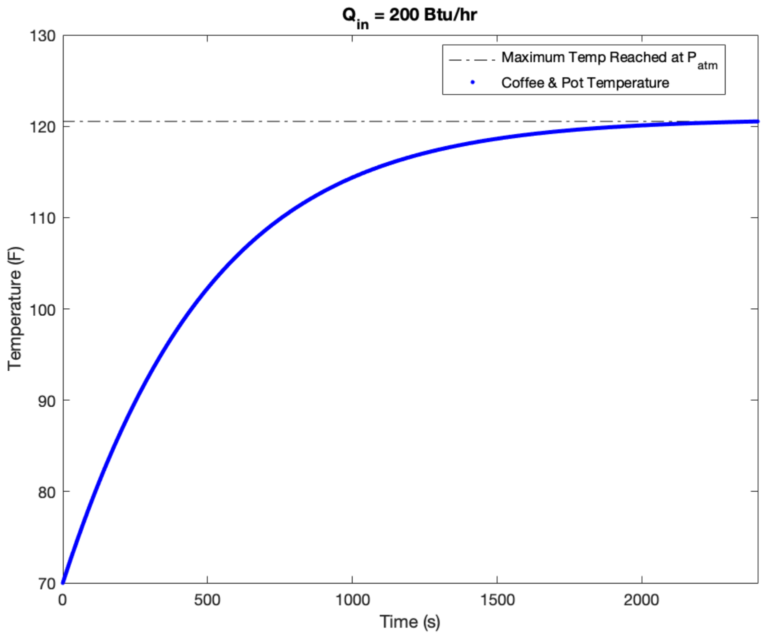

Figure 5: Temperature vs. Time for an input heat transfer rate of 200 $\frac{Btu}{hr}$.

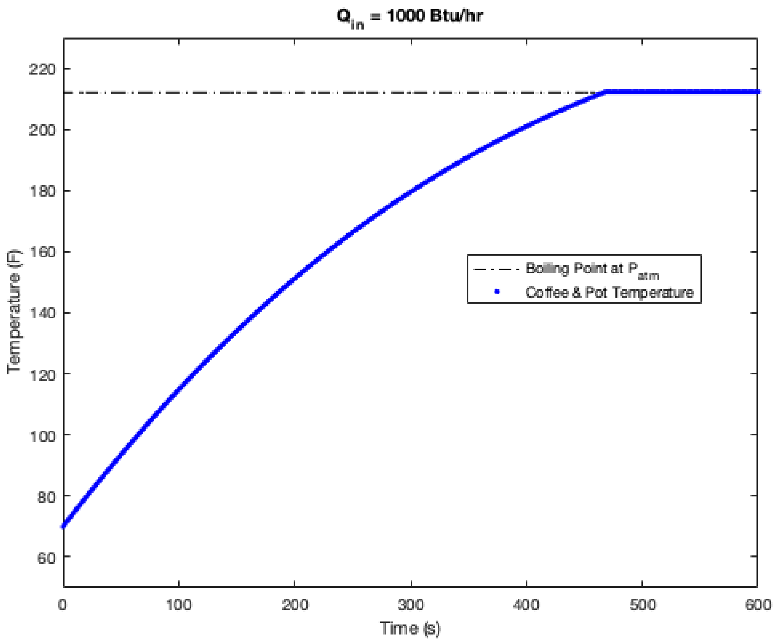

Figure 6: Temperature vs. Time for an input heat transfer rate of 1000 $\frac{Btu}{hr}$.

One can also picture a situation of adding milk to espresso and then analyze the thermal equilibrium. Assuming milk is refrigerated at a temperature of 45 °F and can only be heated to 110 °F before curdling, the exact mass of milk needed to maintain a coffee drink at 130 °F can be calculated, assuming that the espresso by itself is initially 180 °F. Using the specific heats of milk and water (c_{milk} = 0.9 $\frac{Btu}{lbm*F}$), Equations 7 and 8 provide the mass of milk needed to drink the beverage at 130 °F. The mass of cold milk needed is $m_{milk,c}$ = 0.3476 lbm and the mass of hot milk necessary is $m_{milk,h}$ = 1.4772 lbm. Since the mass of the cold milk is so much lower than that of the hot milk, this explains why often milk is steamed before being added to an espresso beverage. Lattes and cappuccinos require a considerable amount of milk foam so in order for the temperature of the beverage being created to not drop below a hypothetical 130 °F, the milk is best prepared steamed prior to pouring onto the espresso.

$$m_{milk,c}c_{milk}(130^{\circ}F - 45^{\circ}F) = m_w c_w(180^{\circ}F - 130^{\circ}F) \tag{7}$$

$$m_{milk,h}c_{milk}(130^{\circ}F - 110^{\circ}F) = m_w c_w(180^{\circ}F - 130^{\circ}F) \tag{8}$$

This situation of beverage preparation also sheds light on another practice that is often seen in cafes. It is common to press , or compact, the coffee grinds in the basket just enough so that there is a considerable amount of coffee grinds before brewing. Since this increases the pressure from the coffee grinds, the boiling pressure therefore also increases. As a result, the boiling temperature is also increased so more energy is then required and this will ultimately create a more flavorful and aromatic coffee (as opposed to much less and looser coffee grounds which would not increase the pressure).

5 Conclusion

While not able to complete the experiment in a laboratory environment, an espresso maker was analyzed from the perspective of engineering thermodynamics. Various parameters, such as the dimensions of the bottom chamber and input rate of heat transfer were adjusted to mathematically observe how the brewing process would change from one situation to the next. Exploring different rates of input heat transfer highlighted how temperature could be found as a function of time and how long it would take for the water to reach boiling. Though this "thought" experiment provides sufficient thermodynamic analysis, it would behoove future researchers to physically conduct the experiments and then compare the results with those found in this report.

References

Moran, J. M., Shapiro, H. N., Boettner, D. D., & Bailey, M. B. (2014). Table A-3E – Properties of Saturated Water(Liquid-Vapor): Pressure Table. *Fundamentals of Engineering Thermodynamics*, *8*$^{th} Edition, p.$997.