BYOE-Cold Boiling

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Cold Boiling

The goal of this experiment is to help students overcome misconceptions about the difference between heat and temperature. Specifically addressed is the misconception that a substance must be hot to boil. This experiment teaches that boiling requires heat but not necessarily be hot. The engineering application of this concept is fundamental to cooling systems.

One traditional experiment to determine the boiling temperature at a range of pressures instructs students to manipulate a small bubble within a tube. While this experiment does enable collection of accurate data, watching numbers change as data is collected lacks the impact to provide a memorable experience to change strongly held misconceptions.

In this experiment, students use a flask containing a liquid with a low boiling point and drop the pressure within the flask. The benefit of using this much larger quantity of liquid than the traditional experiment is that the student can hold the flask and use the sense of touch while the liquid is boiling at a range of temperatures including below 0°C. Using the sense of touch in addition to measuring the temperature and pressure electronically helps students reject the idea that a substance must be hot to boil and replacing this idea with the requirement that heat must be provided to the system for it to boil. In addition, the data gathered can be used with the Clausius-Clapeyron equation to determine the heat of vaporization as is the intent of the traditional experiment. Additionally, students locate the corresponding data in thermodynamic tables and plot the process on phase diagrams to improve understanding use of these tools.

Introduction

One of the most important things we do in educating engineers is to transfer knowledge of fundamental physical principles. In the process of educating, we must then break down misconceptions. These misconceptions can be difficult to change, requiring overwhelming evidence or a “crisis” to change from the normal beliefs [1]. In the experiment described below, students use a common water aspirator to drop the pressure of a volatile liquid in a flask. Use of a relatively large volume that students can touch gives them the experience of using multiple senses to help bring them to the point of “crisis” in their own theories of what is required to make a substance boil.

While teaching Thermodynamics, enrolling junior and senior level engineers, I have observed that students have particular trouble understanding thermodynamic properties, which Bakrania & Carrig [2] have also observed. In particular, students appear to have trouble with the idea that something can boil while cold. Students can repeat the fact that substances have different boiling temperatures and these temperatures can be adjusted by changing the pressure or adding a solute. But, students do not appear to have internalized this knowledge and thus have difficulty applying these concepts. Even though many students have observed the very cold boiling of liquid nitrogen, it is difficult to relate to this other materials because it is too cold and thus is a “special” case. Additionally, students have not likely had the opportunity to change the boiling point of a liquid by decreasing the pressure because this requires equipment typically only found in a laboratory setting.

It is important for students to understand the concept of phase changes because of the vast number of engineering applications. A typical Thermodynamics class covers heat cycles, including the refrigeration cycle, which requires the boiling of a liquid at low pressure to remove heat. Allowing the students to witness how pressure and boiling temperature are related is aimed at helping students better understand how these cycles work. Recently, Logan Maxwell and Dean Verhoeven displayed their understanding of phase changes by inventing a coffee mug that uses phase change thermodynamics to maintain coffee at the perfect drinking temperature [3]. The purpose of this experiment is to help students understand the concepts of boiling and to then better apply this understanding to find creative solutions to real world problems.

Experiments that utilize the Clausius-Clapeyron Equation, $\ln(P) = -\frac{\Delta H_m^{vap}}{R}\frac{1}{T} + C$, to determine the enthalpy of vaporization decrease the pressure and thus the temperature of a volatile liquid and are similar to the experiment described here. These experiments work very well for an accurate determination of the enthalpy of vaporization, but require an experimental setup that lack a tactile element. One such experiment requires the isolation of a small bubble within a tube [4], which is much too small to touch. Another variation of this experiment involves inverting a tube in a beaker of liquid [5] , [6]. In these experiments, students can see that the temperature decreases via the thermometer value, but seeing a number is fundamentally different then feeling that the liquid is in fact cold. Additionally obfuscating the fact the liquid is cold while it boils, particularly in the United States, is the use degrees Celsius, a scale that is relatively foreign to students understanding of hold and cold. This relatively foreign unit further exasperates a disconnect between the number on a screen and what the number actually means.

This experimental setup is designed to enhance student learning by allowing students to use multiple senses which is well documented to enhance learning [7] [8] [9]. The procedure for this lab is short and relatively simple, so it was paired with a triple point lab (described below) to work in conjunction with each other help students better understand phase changes. While this experiment is not complex, the simple nature of this experiment allows it to be targeted at overcoming common misconceptions. Students commented after the lab that this is one of the most memorable experiences they have had.

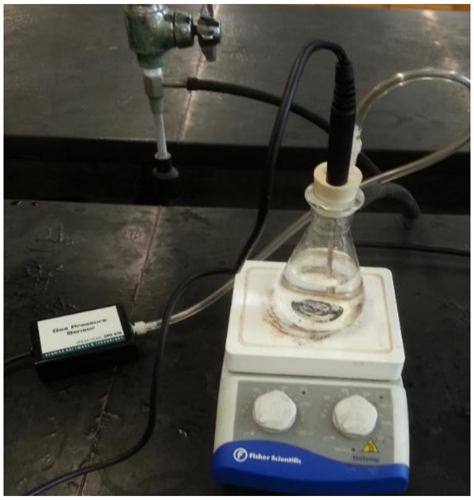
Due to the tactile element of this experiment, this procedure will work best in a setting where each student can feel the flask and therefore it is ideal for a laboratory setting, but could be used as a classroom demonstration. When this experiment was performed, it was part of a Thermodynamics class with 16 students. Students worked in groups of two with each student able to have direct contact with the experimental apparatus. Because two experiments were performed in the same session (cold boiling and triple point), half the group did each experiment and then the groups switched. This experiment could also be used in a Chemistry lab or Unit Operations lab, likely in conjunction with a unit on the Refrigeration Cycle. Additionally, due to the simple nature of this experimental set-up, this experiment could be easily used in a high school or junior high level Chemistry or Engineering classes, as long as the students are able to follow the safety procedures.

During this experiment, students make both visual and tactile observations. One part of this experiment has students observe a computer taking temperature and pressure data, a relatively common, but passive motif. In this experiment, the students additionally visually observe the bubbles forming as the liquid boils. Students can see that the boiling in this system is of a different nature than that seen when preparing boiling water for cooking. In this experiment, the bubbles form at the top of the liquid rather than the bottom. Additionally, students make a tactile observation that the liquid within the flask is in fact quite cold while it continues to boil. When methanol was used as the volatile liquid, students were able to observe temperatures close to 0°C in some cases, depending on the quality of the vacuum apparatus and seal.

Cold Boiling Experiment

In this experiment, students use a Büchner flask instrumented with both temperature and pressure probes to record how decreasing the pressure effects the boiling of a volatile liquid. The setup for this experiment is shown below in Figure 1. During this experiment, students not only use their senses of touch and sight, but can additionally generate meaningful thermodynamic data. Students compare their results to the liquid-vapor portion of a standard phase diagram as well as calculate the enthalpy of vaporization using the Clausius-Clapeyron Equation.

To start this experiment students are instructed to bring the liquid to the boiling point under atmospheric conditions using a hot plate, the conventional method of boiling a liquid. This is done to start the students with a familiar task, heating a liquid to boiling, as they would if they were to prepare pasta or to boil an egg. The flask is then removed from the hot plate and connected to a conventional water aspirator, typically used to aid in filtration. As the pressure drops, the liquid continues to boil, removing heat from the system. The removal of heat during the process of boiling causes the temperature to continue to decrease, similar to what happens in in air-conditioning system. As the temperature and pressure decrease, the liquid continues to boil. Once the liquid reaches a safe temperature (less than 30°C), the students are instructed to hold the bottom of the flask so that they can feel that it is in fact becoming colder. Depending on the choice of liquid, refrigerator-level temperatures can be achieved. The process to drop the pressure to the limits of the water aspirator takes less than 10 minutes.



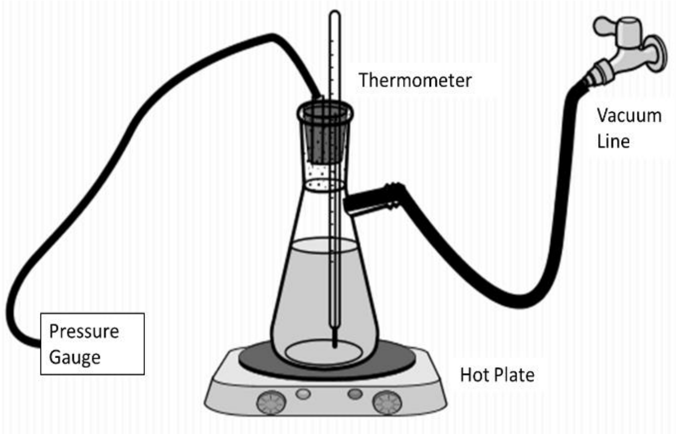


Figure 1: Experimental setup

After the temperature and pressure values level off, students were instructed to stop the cooling part of the experiment and move to re-warming the system gathering similar data while the temperature and pressure increased. To do this, students place the flask back on the already warm hot plate and then turn down the vacuum. The liquid continues to boil as heat is added and the temperature and pressure increase while the liquid maintains a balance between the pressure and temperature governed by the vapor pressure of the liquid.

In this case we have chosen to use Methanol as the fluid because at 1 atm, the boiling point is 64.7°C, far less than water and above room temperature. More importantly, the boiling point is less than 10°C when the pressure drops to about 1/20th of an atmosphere, a pressure achievable with the water aspirator. One challenge with this choice of liquid is that the surface tension suppresses bubble formation and thus the flask needs to be agitated or shaken to see the bubbles continuously escaping from the surface. An improvement might be to use a shaker table to maintain the visual quality of boiling as the pressure is decreased.

The main safety concern in this experiment is the flammability of the methanol. Risks of igniting the methanol vapor are lessened through used of a hot plate to heat the methanol rather than an open flame. Additionally, most of the methanol vapor created is removed from the area by the water aspirator. Students should wear typical safety equipment, such as goggles for this lab, and be informed of the risks of using methanol as well as the dangers of using a hot plate. This experiment can also be run without heating the methanol to obtain similar, but more limited results by starting at room temperature rather than the boiling point. Once the system is hooked to the vacuum system (aspirator), it will cool.

For the first part of the analysis, students are instructed to compare their pressure versus temperature curve, Figure 2A, to a standard phase diagram, Figure 2B. In particular, students correctly identified that their data corresponds to an area between the liquid and gas phases on the diagram. This exercise helps the students to better relate to the phase diagrams, how they are constructed, and what they mean.

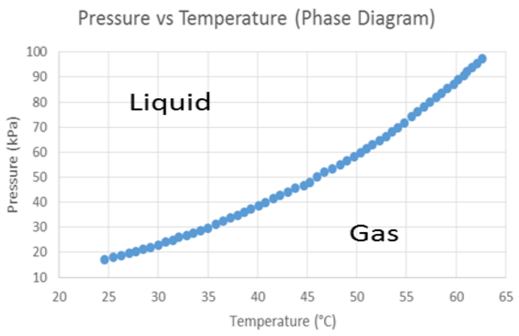


Figure 2A: Student generated Pressure vs. Temperature curve for Methanol.

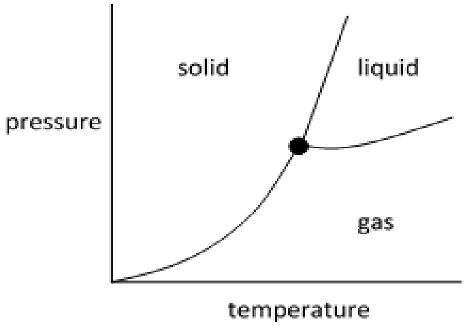


Figure 2B: Pressure-Temperature Phase diagram.

In the second part of the analysis, students use this data to calculate the enthalpy of vaporization using the Clausius-Clapeyron Equation, $\ln(P) = -\frac{\Delta H_m^{vap}}{R}\frac{1}{T} + C$. The enthalpy of vaporization for methanol is 35.21 kJ/mol at standard conditions, 1 atm and a boiling temperature of 64.6 °C. At the minimum temperature for this experiment, 0 °C, the enthalpy of vaporization is 38.9 kJ/mol [10]. Linearized plots of student data for both the warming and cooling processes are shown below in Figure 3. These students found that their data was more linear during the second part of the experiment, when the liquid was warmed, shown in Figure 2B. In this case, they found that the average enthalpy of vaporization for methanol at this temperature range is 37.7 kJ/mol, which falls with range of reported enthalpy values of 35.21 kJ/mol to 38.9 kJ/mol for this temperature range. The data obtained for this experiment, while cooling the system (moving the system from hot to cold) reported an average enthalpy of vaporization of 40.1 kJ/mol. The fact that this experiment obtains relatively 'good' data from this experiment is a fortunate additional outcome.

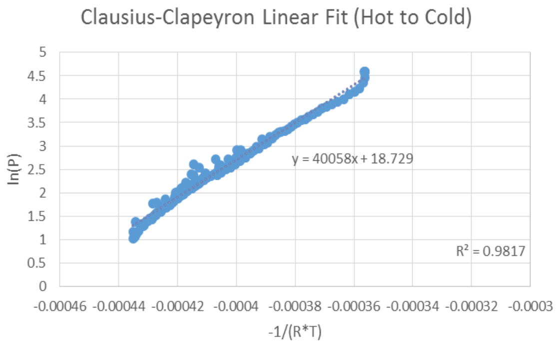


Figure 3A: Clausius-Clapeyron Equation fit to data gathered while cooling the liquid.

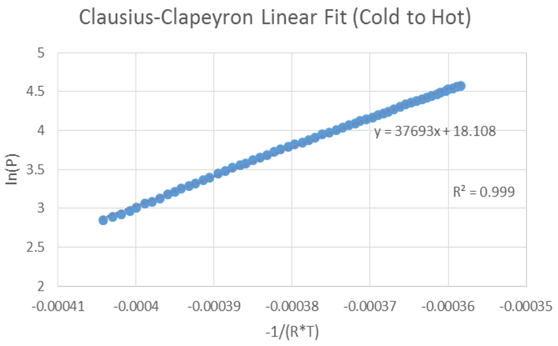


Figure 3B: Clausius-Clapeyron Equation fit to data gathered while warming the liquid.

To help students continue to experience phase change, both visually and tactilely, and because the cold boiling experiment was relatively short (the full procedure took well under an hour to complete), this was paired with an experiment to move CO_2 (dry ice) to the triple point describe more completely by Becker [11]. The triple point is achieved by placing crushed dry ice in a clear tube fitted with a pressure gauge. As the dry ice sublimates, it increases the pressure to approximately 4-5 atm, at which point all three phases exist and the triple point is achieved. We used plastic tubing because it can handle the pressure better (capable of holding < 10 atm, depending on the type) than a plastic pipette tip, which explodes very soon after the liquid phase can be observed. In addition, students are able to feel this tube to experience just how cold the dry ice is when the triple point occurs. This experiment made more of an impression with the students than the methanol experiment, but did not provide for as much useful data. Of particular note for the students was when the dry ice flash froze and vaporized when the pressure was released.

Student Response

Overall, students responded positively to the cold boiling experiment. Because I did not realize at the time how well this lab would work, a survey was not completed at the time this experiment was initially conducted. The following data represents student responses from two separate groups. The first group, Group A, is a mixture of science students (generally from engineering, chemistry, and biology) from various levels including freshmen through seniors (n=10). These students filled out surveys both before ("Group A : Before") and after ("Group A : After") performing the experiment. The second group, Group B are the engineers in the original

Thermodynamics class who were surveyed approximately 9 months after having completed the experiment (n=6). Responses from selected questions are included below. For free answer questions, answers were categorized. Therefore, the data below represents aggregate data, not quoted responses.

The first two questions were to define heat and temperature. All students correctly responded that temperature was a property of the material that represented the energy contained within the system. In defining heat, responses fell into two groups, that "heat was a property of the system" or "heat represented energy transfer". As shown in Figure 4 and Table 1 below, students more correctly answered this question after performing the experiment. Correct responses moved from 60% before the experiment to 80% afterwards. In addition, students who had taken Thermodynamics the previous year (Group B) answered correctly at a rate of 83%.

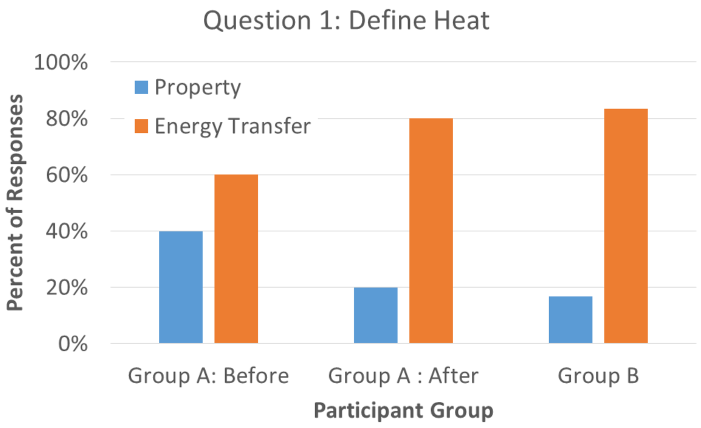


Figure 4: Plot of Responses to Question 1

Table 1: Responses Rates to Q1

	Property	Energy Transfer
Group A: Before	4	6
Group A: After	2	8
Group B:	1	5

Students were also asked "What would you do to boil a liquid?" Figure 5 and Table 2 show that students who had not taken Thermodynamics (Group A) all answered that they would add heat in some fashion to make a substance boil. After having performed the experiment, 45% of this group added that changing the pressure was also a possibility. Of students who performed the experiment about 9 months earlier (Group B), 67% included both adding heat and dropping pressure in their responses. Overall, a majority of students who performed this experiment more often included both the ideas of heat and pressure in their answers to this question. This improvement indicates that the experiment helped to expand students' knowledge in what parameters can be changed to cause a liquid to boil

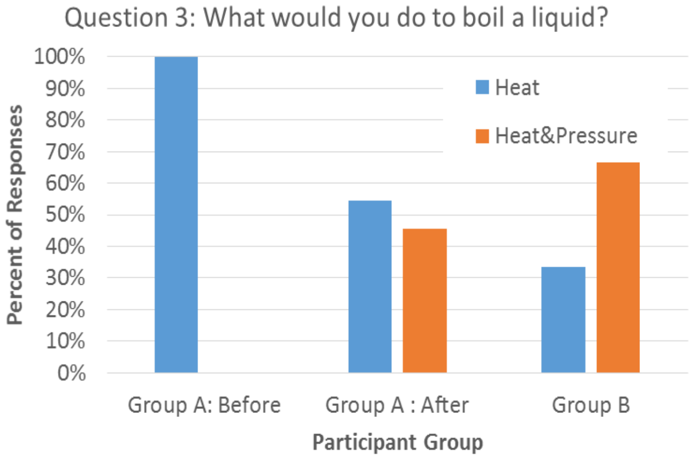


Figure 5: Plot of Responses to Question 3

Table 2: Responses Rates to Q3

	Heat	Heat & Pressure
Group A: Before	10	0
Group A: After	6	5
Group B:	2	4

To ascertain how aware students were of the fact that dropping the pressure was an alternate method to boil a liquid, but might not have included it in the previous answer, students were also asked “How would you change the boiling temperature of a liquid?” Response rates are shown in Table 3 and Figure 6. Here the responses from the group that had not performed the experiment (Group A) feel into four groups, “drop the pressure”, “add a solute”, “change the temperature”, and “Don’t know”. The answer that adding solute would change the boiling temperature is correct and likely the influence by taking chemistry. After having performed this experiment, all participants answered that dropping the pressure would change the boiling temperature. Students who had done the experiment in the previous year (Group B) answered correctly 100% of the time, with 83% answering that pressure would affect the boiling temperature and 17% answering that a solute could be added (1 student). These responses show that students indeed know that pressure is another variable that can be changed and effects the boiling temperature. It is interesting that even though 45% of the students knew that dropping the pressure was a method to boil a liquid, they did not initially include this in their answer to “What would you do to boil a liquid?”, indicating that decreasing the pressure was not a first choice even though they knew it is possible.

Table 3: Responses Rates to Q5

	Pressure	Add	Temperature	Don't know
Group A: Before	5	3	2	1
Group A: After	11	0	0	0
Group B:	5	1	0	0

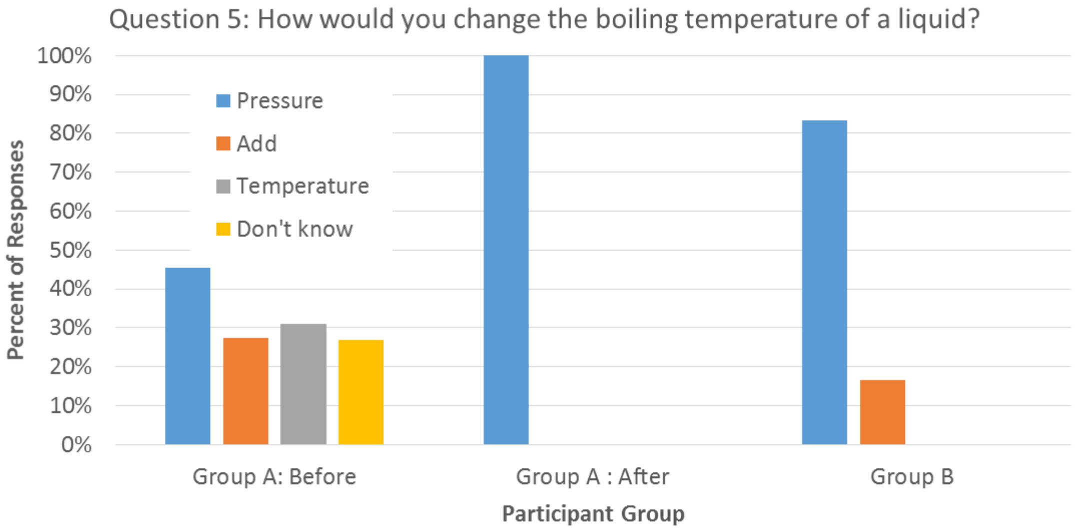


Figure 6: Plot of Responses to Question 5

After completing the experiment, students were asked two ranking questions on a 1 – 5 scale where 5 indicated the highest level of agreement. First, students were asked "Did this experiment help you learn about the difference between heat and temperature?" Results are shown in Figure 7. For the group performing the experiment the same day as the survey (Group A), the average was 4.1. For the group that did the experiment 9 months earlier (Group B), the average was 3.8. Average responses are plotted below in Figure 7. Second, students gave an "Overall rating of this activity". As shown in Figure 8, both students gave this activity an average rating of 4.5 out of 5.

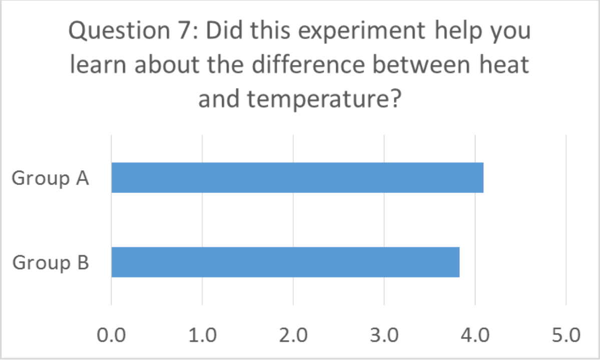


Figure 7: Plot of Responses to Question 7

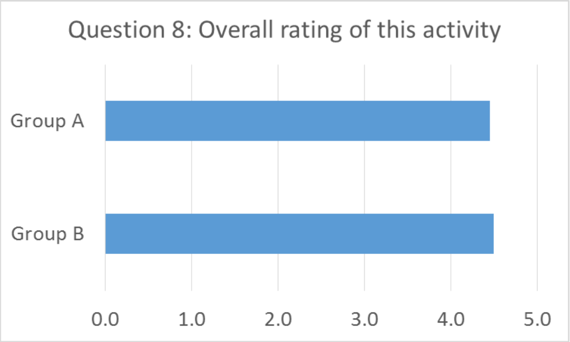


Figure 8: Plot of Responses to Question 8

Conclusion

Students overall benefited by experiencing a liquid boiling "cold". This experience helped students increase understanding that changing the pressure changes the boiling temperature. In addition, this experiment can be used to obtain thermodynamics data, specifically the enthalpy of vaporization as well as a portion of the phase diagram for the chosen liquid.

In the future I plan to work to improve this experiment. The first problem to explore is that the flask needs to be jostled to maintain boiling, likely due to the surface tension of methanol. This might be overcome by either using a shaker table or using a different fluid. In addition, it will likely be beneficial for students to use addiitonal liquids so that they can build a “consensus” and be even more convincing that boiling cold is not only possible but quite normal with a wide variety of applications.

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