In Class Boiling Demonstration to Illustrate the Transient (Time Dependent) First Law of Thermodynamics Equation

Abstract

Phase transition between a liquid and a vapor is extremely important in the study of Thermodynamics and systems engineering. This paper deals with one very inexpensive way to study transient boiling and to teach students about phase changes in fluids such as water. Both sensible and latent heating can be demonstrated in this simple demonstration/experiment. Starting with an insulated (on the sides only) 3-inch copper pipe cap, a heating plate, water, a measuring cup, a timer and a k-type thermocouple, a measured amount of water that is heated to boiling. The time it takes to go from a measured room temperature to the onset of boiling is measured. The heat is continued until the water has completely vaporized. The time from the onset of boiling to complete vaporization is also recorded. The students can compare their recorded times to the theoretical times based on the transient first law of thermodynamics. How close are actual times to theoretical and what are the possible errors?

Introduction

In the study of thermodynamics, sensible and latent heat transfer is very important. The first law of thermodynamics can be used to study the transient nature of sensible and latent heat transfer. This paper deals with a very inexpensive method to demonstrate this phenomenon to students with a minimal amount of laboratory equipment. Starting with a heat source (a hot plate) and a copper cup (copper pipe cap). The cup is filled with a measured amount of water and the time it takes to heat from the known starting temperature to the onset of boiling is measured. The time from the onset of boiling to complete vaporization is also measured. These two times can be compared to the theoretical times based on the transient first law of thermodynamics.

This paper details a simple and inexpensive way to demonstrate the importance of understanding transient boiling for engineering students. It also incorporates an analytical method for helping the understanding of this phenomenon. This experiment was intended for student learning and not for scientific rigor. There are just too many variables that are not controllable in a classroom setting. The lecture on thermodynamics can explain the concept, but a physical demonstration enhances learning objectives. Students pay attention more to a demonstration than a lecture. Thermodynamic lectures do not normally have associated laboratory classes. This experiment can easily be conducted in a class room without extensive laboratory equipment. This type of teaching method promoted active learning as the primary learning objective.[1] Allowing students to actually see a problem and then formulate a solution, enforces the concept through an active learning technique. [2]. Research has shown that this is a far superior method to learning than the traditional lecture-based class. Michael [3] demonstrates the importance of active learning and compiled evidence to state this case.

Background

This boiling experiment has two time-dependent components, latent heat of vaporization and sensible heating. To heat the fluid from room temperature to the onset of boiling is definitely a transient process. The volume is changing as well as other properties such as internal energy. Once the liquid starts to boil, the fluid goes from a saturated liquid to a saturated vapor. This is definitely a transient process due to properties such as specific volume, specific internal energy, specific enthalpy and specific entropy, for example, changing with respect to time and heat supplied.

The two segments are timed to quantify the phenomenon. A measured amount of water at a known temperature is heated in a copper cup. This copper cup is a 3" copper pipe cap. The water filled cup is placed on a heating source and allowed to heat up to the boiling temperature. The interface temperature between the heating plate and the cup is measured along with the inside bottom of the cup. These measurements will be used to calculate the heat transferred to the water.

Several researchers have studied the transient nature of water boiling in recent years. Rosenthal {4} studied rapid boiling to simulate nuclear reactor excursions. Other researchers have investigated the nature of boiling in a transient situation [5].

The analysis starts with the first law of thermodynamics. During the initial heating process, the first law becomes,

$$\frac{dU_{cv}}{dt} = Q - W \qquad Eqn\ 1$$

This equation assumes no potential or kinetic energy. Modifying equation 1, yields'

$$m(u_2 - u_1) = \dot{Q}\Delta t - W \qquad Eqn\ 2$$

Solving for the time, yields:

$$\Delta t = \frac{m(u_2 - u_1) + W}{Q} \qquad Eqn\ 3$$

The mass can be directly found by the water volume. The specific internal energies can be found from the steam tables. The work is found by,

$$W = \int_1^2 pdV = mp(\vartheta_2 - \vartheta_1) \qquad Eqn\ 4$$

The heat, Q, is found by measuring the interface temperature of the copper cup and the hot plate as well as the temperature of the bottom of the cup. The thickness of the bottom of the cup must be known to complete this calculation. Equation 5 gives this value.

$$Q = kL\Delta T \qquad Eqn\ 5$$

It is assumed that the heat transfer is one dimensional. Since most students take thermodynamics in their junior year and heat transfer in their senior year, a complicated heat transfer analysis would be beyond their experience and education. For a finite elements course, this could be an excellent project.

Once boiling begins, the first time is stopped and recorded and the second time is started. During the boiling process, the mass of the control volume decreases with the exiting vapor. The mass continuity equation is shown in Equation 6.

$$\frac{dm_{cv}}{dt} = -\dot{m}_e \qquad Eqn\ 6$$

The energy rate balance becomes:

$$\frac{dU_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} - m_e h_e \qquad Eqn\ 7$$

Substitution and integration yields,

$$m_3 u_3 - m_2 u_2 = \dot{Q}_{cv} \Delta t - W_{cv} + (m_3 - m_2) h_e \qquad Eqn\ 8$$

The mass at the end of the process, state 3 is zero. Therefore, solving for the time yields,

$$\Delta t = \frac{m_2(h_e - u_2) + W_{cv}}{Q_{cv}}$$

With everything measured and calculated, students can run the experiment and compare the measured time to the calculated, theoretical time. At this point, the students should be assigned to think about and opine on why the theoretical time differs from the experimental time.

Experimental Setup

This simple test setup was very inexpensive and easy to set up and conduct. The first piece required, was a heat source. A simple inexpensive hot plate for cooking worked very well (see Figure 1).

On top of the hot plate, a flat metal plate was heated to give a better distribution of heat to the copper cup. This metal can be any type of metal but the greater the heat transfer coefficient, the more uniform the surface temperature. Figure **2** shows this setup. The copper cup is simply a 3-inch copper pipe cap (see Figure **3**). The sides were insulated to minimize heat loss due to natural convection. This is optional but will add more error to the experiment.

The selection of insulation is important in the sense of timing of the experiment. Initial experiments were limited to how fast the heat could be added due to the maximum temperature of the insulation and the price of the insulation. The fact that the class has a time limit, 50 minutes, the insulation became unnecessary for the demonstration of the concept. It will be lumped into the "error" category.

Natural convection will affect the times. Also, if the HVAC system is creating a slight movement of the room air, force convection will occur. Again, the thermodynamic students have not had heat transfer, so this can be lumped into the "error" category, i.e., stray heat loss. The insulation is shown in Figure **4**.

Figure 1 shows the hot plate used for the heat source

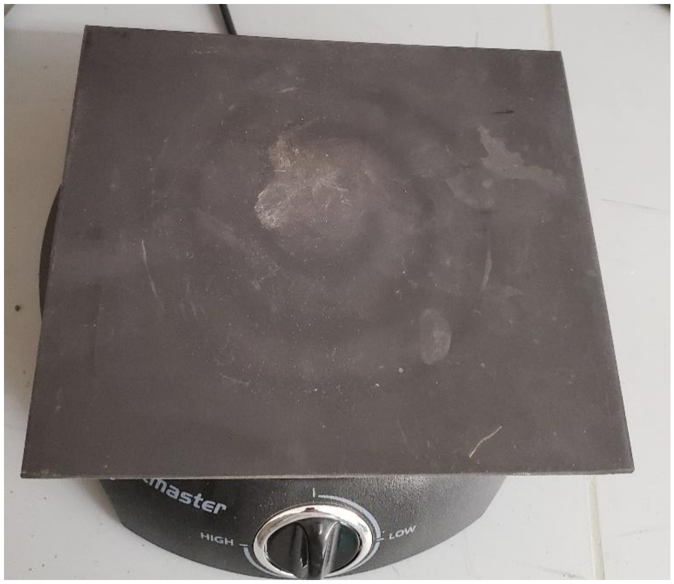

Figure 2 shows the heating plate's position atop the hot plate.

Figure 3 The copper cup used for containing the water..

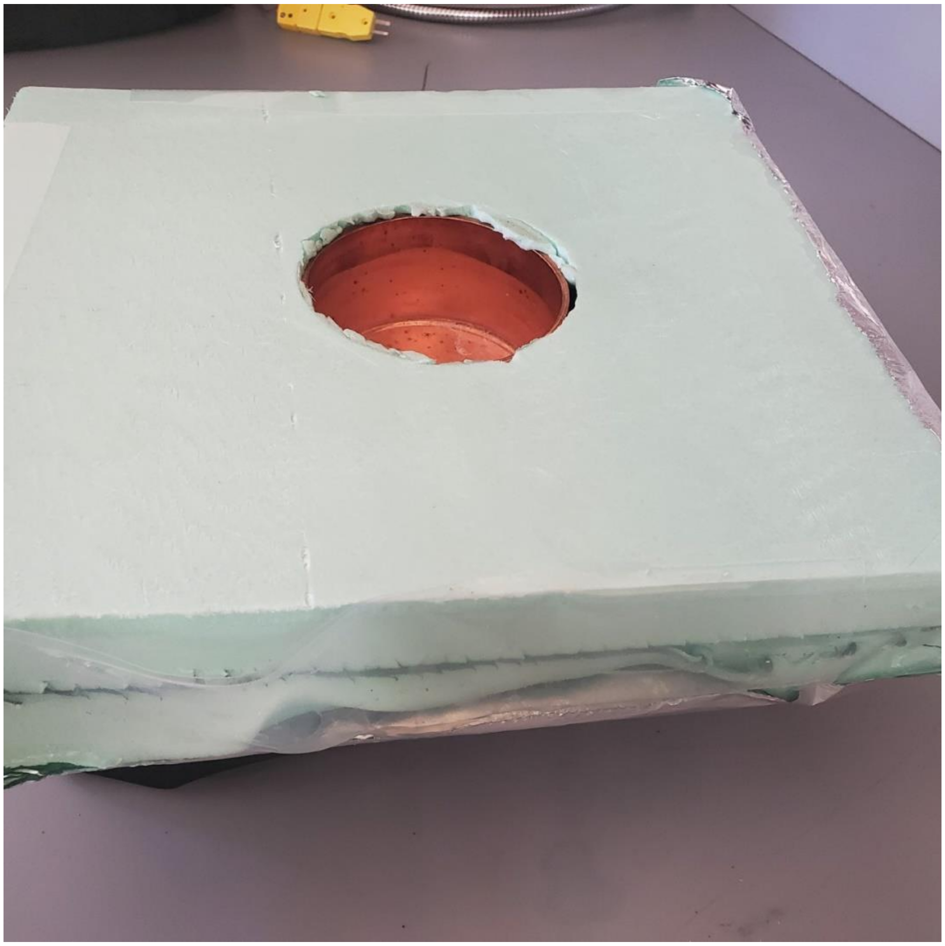

Figure 4 shows the copper cup insulated and resting on the hot plate.

Conclusions

This experiment demonstrates the concept of transient heat transfer resulting in the vaporization of a liquid, water. This demonstration shows through visual learning the concept of sensible heating and latent vaporization of a small amount of water. Although, students are to calculate the theoretical times as well as measure the actual time for each process, the times will be significantly different. This is due to extraneous heat transfer losses that could not be totally accounted for. One very important concept for student learning, is this demonstration shows students how hard it is to take meaningful data and it also affords the opportunity for students to think about the possible errors that could be present and how to prevent the errors.

References

[1] Sarah E. Bonner (1999) Choosing Teaching Methods Based on Learning Objectives: An Integrative Framework. Issues in Accounting Education: February 1999, Vol. 14, No. 1, pp. 11-15.

[2] Diane F. Wood (2003) ABC of Learning and Teaching in Medicine: Problem Based Learning. Clinical Review, BMJ Publishing group, BMJ2003;326:328

[3] Michael, Joel (2006) Where's the evidence that active learning works?, American Physiological Society, https://doi.org/10.1152/advan.00053.2006.

[4] M. W. Rosenthal (1957) An Experimental Study of Transient Boiling, Nuclear Science and Engineering, 2:5, 640-656, DOI: 10.13182/NSE57-A25431

[5] Heat transfer and critical heat flux in transient boiling, J. Nucl. Sci. Technol. (March 1968)