Procurement of Undergraduate Transient Heat Transfer Lab Experiment at No Budget

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Abstract

Mechanical engineering professors teaching lab courses often face the challenge of running meaningful experiments, when funding to purchase such experiments is meager or nonexistent. Heat transfer lab is no exception. This paper describes how an experimental set-up targeting transient heat transfer is fabricated in order to teach the lump system analysis method. The experiment was designed to meet the requirements for the lumped system assumption to be valid, and to be conducted in relatively short time (about 20 minutes) so that multiple groups of students can run it within the allocated lab time period. This paper includes details of the construction of the experiment and an instructions sheet as well as the minor equipment needed for the experiment. The analysis requirement of the data collected by students is also given. A typical actual data set obtained by running the experiment is shown. The experiment worked very well. As importantly, this paper also reports on an assessment of students' learning and satisfaction with the experiment. Students evaluated the experiment in various aspects including its ability to target and be linked to theory of thermal lumped systems covered in the heat transfer course, the time to run the experiment and whether the experiment can make them remember lumped systems in the future. From the answers of students, the experiment is deemed very valuable in all of the above areas and students were very satisfied with it, and they felt it was a good tool to learn the concepts involved. It is hoped that the experiment can be constructed by, and can help, other mechanical engineering professors struggling with limited funds to procure hands-on set-up for teaching heat transfer concepts.

Introduction

Engineering and science departments offer various laboratory courses with experiments designed to enhance the learning experience of students. These experiments tie theories to practice, and show concepts in action. Experiments also allow students to have a 'feel' for how things work, how big things are and how long some physical processes take. Students also get to measure various quantities and become familiar with measuring devices. Such practical aspects are not typically given in lectures and text books.

Even though various academic departments in science and engineering realize the value of lab experiments, they are often faced with underfund laboratories due to budgetary limitations. To complicate things further, commercially-available experimental packages for academic engineering laboratories have been very expensive indeed. All one has to do is look at some companies' web sites to see these steep prices. Engineering professors thus find themselves in need to develop experiments with little money or no money at all.

Another issue engineering professors are faced with is the number of students taking a given lab. For a large cohort of students registered for a lab, there is often a lack in the number of experimental stations to run the same experiment for all students in the time slot allocated for the lab. Professor are forced to group four, five or sometimes six students in one team. This lowers the quality of the learning experience, as some students 'tag along' without really paying attention or trying to learn from the experiment. Students nowadays are so used and attached to their iPhones. They expect things to be done fast; their attention span has shrunk over the past few years. So, new engineering experiment designs have to take this into account. In thermal science, an experiment that take over 40 minutes to reach steady state is considered very long and 'boring' by today's students.

Based on these trends, engineering professors are led to look for experimental designs that:

- can be constructed in-house with no money or little money
- can be duplicated to create more than one experimental station
- take relatively short time to perform
- have a clear and direct connection to theoretical concepts (not convoluted, so that students do not miss the point(s) of the experiment while trying to make sense of what they are doing in the lab).

It should be noted that the above conditions are not meant to, and should not, compromise the learning value of the experiment and the hands-on experience of the students. In this article, a design for a heat transfer experiment is described with the above points in mind. The experiment targets the thermal lumped system analysis, which is typically covered in the heat transfer course undergraduate mechanical engineering students are required to take. The lumped system analysis allows determination of the transient response of a thermal system undergoing cooling or heating from a given starting temperature. The paper also assesses the attitudes of students and their reactions to the experiment.

Design and Description of Experimental Set-Up

Preliminary calculations of the thermal lump system theory [1] were performed in order to determine the appropriate size of the two lumped systems. The requirement as that they must cool to room temperature from 100 ºC in less than 20 minutes, and that they are made from aluminum. Scrap aluminum pieces were available at the department's machine shop. The cooling is achieved by natural convection and some radiation in stagnant room air. The calculations led to the sizes of two lumped system designs: a) a cube with a side length of 10 mm and b) a cylinder of dimeter 10 mm and height 10 mm. With reference to Fig. 1, and considering the sizes of these two systems and the

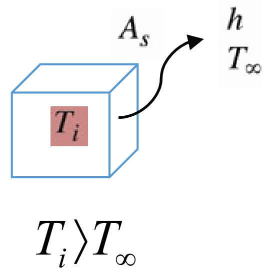

Fig. 1 Schematic of lumped system

themophysical properties of aluminum, and using a value of the heat transfer coefficient 11.1 W/(m^2.K) for the cube and 9.6 W/(m^2.K) for the cylinder (will be discussed later). Biot numbers can be calculated as

$$Bi = \frac{hL_c}{k} \tag{1}$$

where h is the combined (free convection and radiation) heat transfer coefficient and k is the thermal conductivity of aluminum. The characteristic length is given by

$$L_c = \frac{V}{A_s} \tag{2}$$

where V and as are the volume and A_s surface area of the lumped system.

For the cube and cylinder, Bio numbers were 0.00054 and 0.00047, respectively. Both are less than 0.1, and hence the lumped systems analysis is valid. Some books refer to this as lumped capacitance assumption [3]. It should be noted that students are asked to verify this condition as part of their exercise. This condition on Biot number was used to size the cube and cylinder for the experiment.

Application of the First Law of thermodynamics to the lumped system shown schematically in Fig. 1 leads to the following equation for the transient temperature $T(t)$ of the lumped system as a function of time t [1]:

$$\frac{T(t) - T_\infty}{T_i - T_\infty} = e^{-bt} \tag{3}$$

where T_i is the initial temperature of the lumped system and T_∞ is the ambient temperature. The quantity b is given by

$$b = \frac{h\ A_s}{\rho V c_p} \tag{4}$$

where ρ is the density of aluminum and c_p is its specific heat.

The heat transfer coefficient h used in Eq. (1) is the sum of the free convection and the radiation heat transfer coefficient. The free convection heat transfer coefficient can be estimated from charts and correlations [2]. The radiation heat transfer coefficient can be obtained from [1]:

$$h_{rad} = \varepsilon\sigma \left(T_s^2 + T_{surr}^2\right)\left(T_s + T_{surr}\right) \qquad (5)$$

σ is a constant called the Stefan-Boltzmann constant = 5.67 x 10^{-8} W/(m^2.K^4),
T_s is the temperature of the lumped system in K, and
T_{surr} is the temperature of the surroundings in K.

Because the system is lumped in the thermal sense, its surface temperature is the same as its transient temperature $T(t)$. Because this temperature varies with time, the radiation heat transfer coefficient also varies with time. However, the variation in the current case was not large (for cub 2.4 to 2.9 W/(m^2.K), and for cylinder 2.3 to 2.9 W/(m^2.K); the difference was in the second digit after the decimal point), and an average value of 2.5 W/(m^2.K) was used for both of them.

A photograph of the experimental set-up is shown in Fig. 2. Basically, what is needed is a lumped system and its duplicate (for measuring dimensions), a thermocouple to measure temperature, hand-held thermocouple reader to read the temperature of the lumped system and ambient temperature, water boiler or torch to heat the lumped system, a stopwatch or an iPhone to monitor time intervals, a caliper to measure the dimensions of the lumped system and a stand to hold the lumped system in place while it cools down. Most, if not all, of these items are typically found in any heat transfer lab and/or in a machine shop serving mechanical engineering departments.

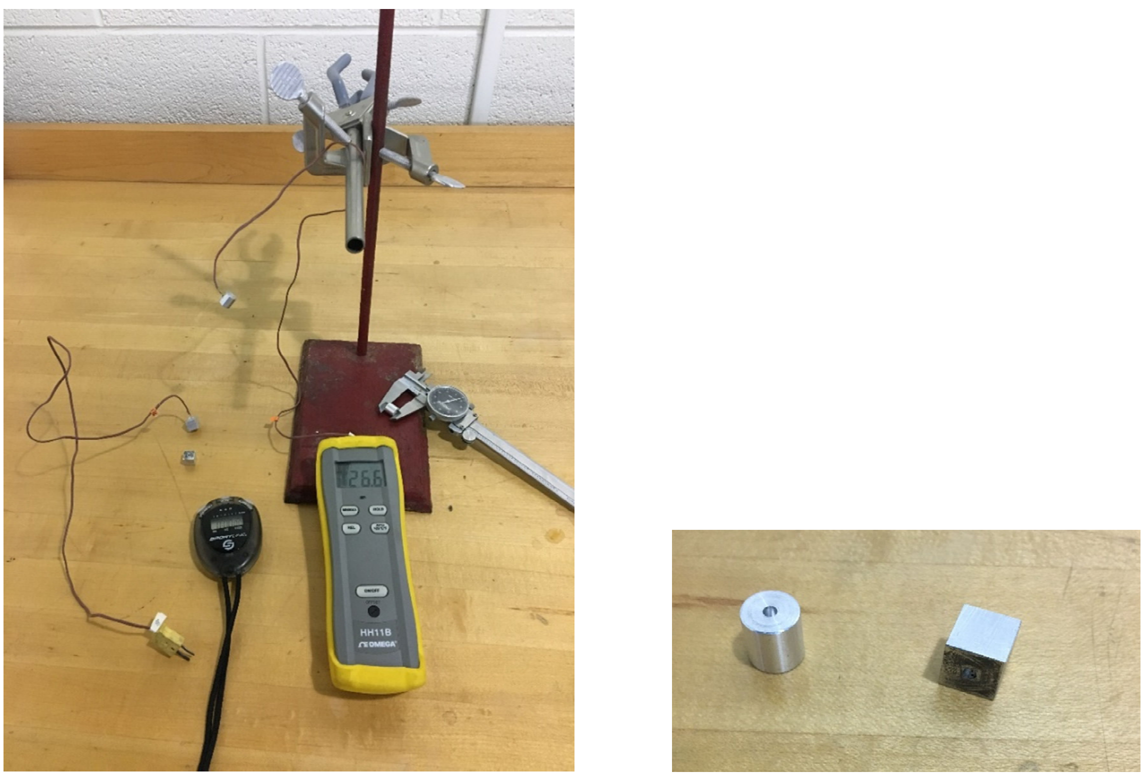

Fig. 2 Experimental set-up showing all items needed to conduct the experiment, and a close-up of the two lumped systems

Instruction/Procedure

The lab sheet shown as Fig. 3 includes the instructions given to student in order to run the experiment, as well the analysis required and some questions.

TRANSIENT ANALYSIS OF A LUMPED THERMAL SYSTEM

Objective: To gain experience transient heat transfer; to show how theory can be used to estimate thermal behavior of lumped systems.

Procedure: When you get to the lab, lumped system will be placed in boiling water in order to raise its temperature.

1) Measure and record the room temperature.

2) The instructor will remove the hot a lumped system from the boiling water (used to raise the temperature of the lumped system well above ambient) and will suspend in room air to be cooled.

3) The initial temperature of the system, when removed from boiling water, should be around 100 ºC. Wait for the system to reach 70 ºC. This will happen very quickly.

4) When the system's temperature reaches 70 ºC, start recording its temperature every 20 seconds, until it reaches the ambient temperature.

5) Using a duplicate, measure all the dimensions of the system.

For Aluminum, use the following properties:

Conductivity k = 237 W/(m.K)

Specific Heat c_p = 903 J/(kg.K)

Density ρ = 2702 kg/m^3

Assume that the combined free convection and radiation heat transfer coefficients h = 13.6 and 12.1 W/(m^2.K) for the cube and cylinder, respectively.

Analysis

1) Verify that the lumped analysis is valid for the system you tested.
2) Plot the experimental and the theoretical (by lumped system analysis) temperatures as functions of time on the same plot.
3) From experimental measurements, determine the time it took for the system to reach 35 ºC.

4) From lumped system analysis, determine the theoretical time it takes the temperature of the system to reach the same temperature of step 3.
5) Calculate the percent difference between the time obtained in steps 3 and 4.
6) State the sources of error responsible for this difference.
7) Calculate the amount of heat that was lost by the system in Joules, as it went from 70 ºC to ambient.

Fig. 3 Laboratory sheet handed to students to run the experiment and perform the analysis

Typical Results

The experiment typically took less than 20 minutes to complete. Typical results for the temperature of the cube lumped system as a function of time is given as Fig. 4. The theoretical predictions agree well with the experimentally-obtained values as show in this figure. Maximum percentage error was 1.6%, which is surprisingly small considering the various assumptions imposed during the analysis and in estimating heat transfer coefficients.

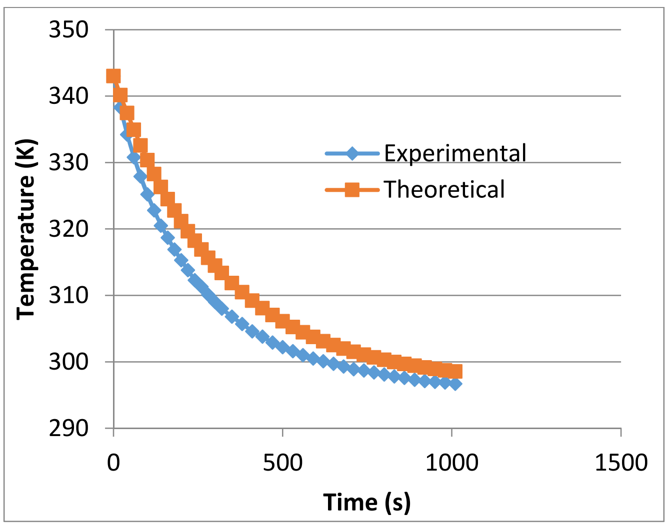

Fig. 4 Experimental and theoretical data for the transient temperature of the cube lumped system

Evaluation of Students' Attitudes

A short questionnaire was administered to students who performed the lumped system lab. There were four questions designed to gauge students' thoughts regarding the experiment. The questions addressed strengthening students' understanding, linkage between the experiment and theory, length of time to complete the experiment, and the likelihood that students will remember the lumped system analysis as a result of running the experiment. The questions are shown in Fig. 5.

Evaluation of Lumped System Experiment

Each experiment in the heat transfer lab is designed to provide a hands-on experience of heat transfer concepts for students. Please answer the following questions regarding the lumped system experiment.

1) How would you rate the value of the experiment in strengthening your understanding of lumped systems?
    a. extremely valuable
    b. very valuable
    c. average
    d. somewhat valuable
    e. not valuable
2) The experiment was strongly and directly linked to the lumped system analysis we studied in the heat transfer course
    a. strongly agree
    b. agree
    c. do not agree
3) The time to complete the experiment was
    a. too short
    b. short
    c. long
    d. very long
    e. Just right
4) Do you think that running the lumped system experiment will make you remember lumped system analysis in the future?
    a. absolutely
    b. maybe
    c. no

Fig. 5 Questionnaire administered to students propping their thoughts regarding the experiment

A total of 30 students responded to the questionnaire- 17 in 2019 and 13 in 2018. The responses were primarily positive. Figure 6 part (a) has the responses to the first question regarding enhancing understanding. As seen in part (a), most of students (70%) thought the experiment was either very valuable (4 students) or valuable (17 students). Eleven students thought the experiment was average. There were no negative responses.

With regard to linkage between the experiment and theory, part (b) of Fig. 6 shows that all students either strongly agreed (77%) or agreed (33%) that there was a strong and direct linkage.

With the regard to time needed to complete the experiment, part (c) shows that 67% of students though the time was just right, while 30% thought it was short and the remaining 3% thought it was long. Part (d) shows that 37% of students indicated that they will absolutely remember the lumped system theory and 67% said that they may remember, while one student said that s/he would not remember. These results are generally positive and the experiment is deemed as a valuable addition to the heat transfer lab targeting the lumped system analysis.

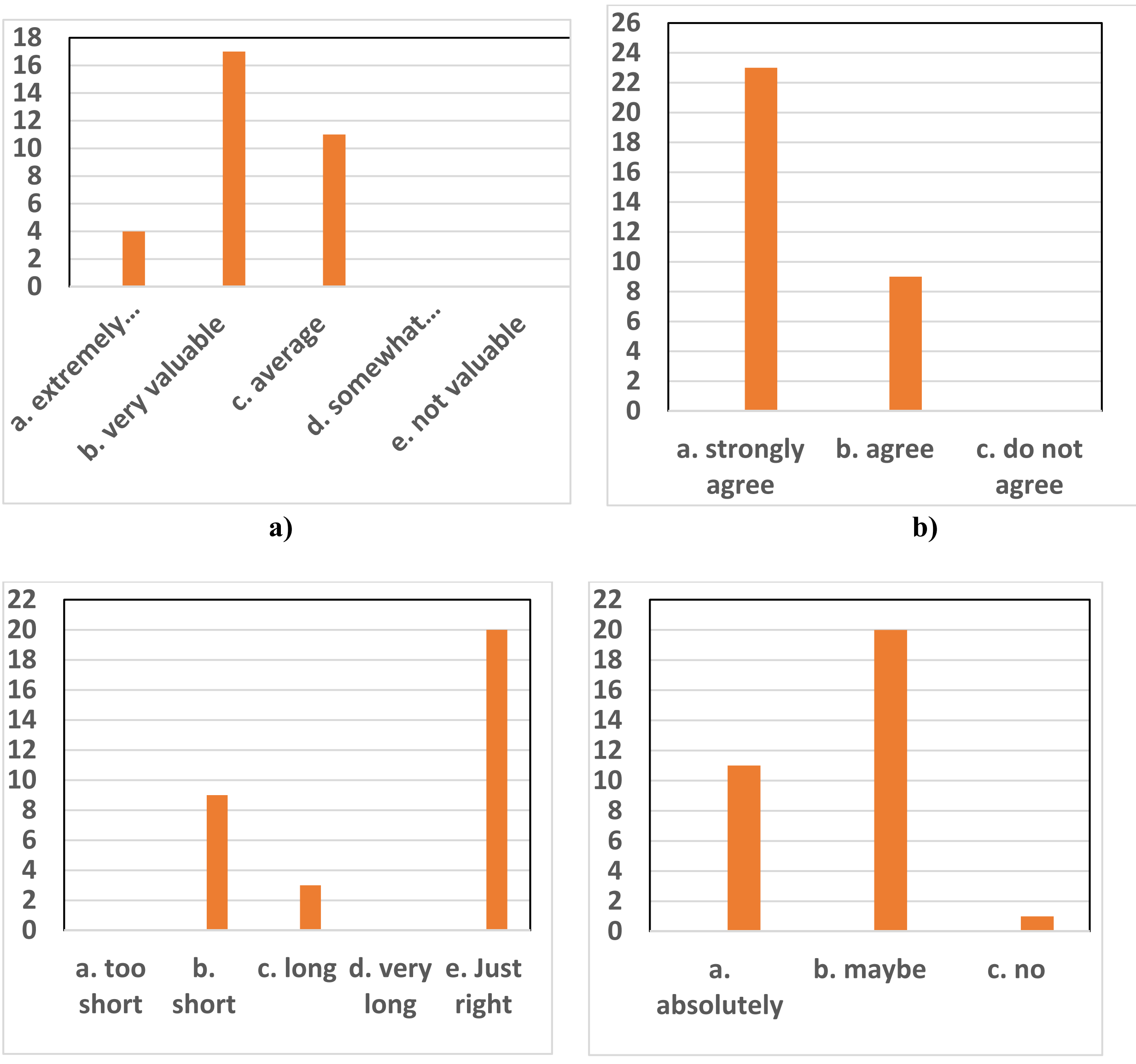

Fig. 6 Results of questionnaire: a) question 1, b) question 2, c) question 3 and d) question 4

Conclusion

In order to overcome the fact heat transfer laboratories are usually underfunded, and that purchasing commercially-made experimental set-ups is prohibitively expensive, an experimental set-up was homegrown. The experimental designed was described in detail, and it used materials and instruments often available in heat transfer labs and mechanical engineering machine shops. Results obtained from experiment was high-quality in terms of matching theoretical predictions. The design proved to be inexpensive (almost zero cost), efficient (experiment run is completed in about 20 minutes) and effective in illustrating the concept of lumped system and directly linking the experiment to the theory of lumped systems. Students' responses showed that the experiment was favorable in terms of the above areas. The design of the is experiment is recommended to thermal science faculty looking for easy-to-construct and inexpensive heat transfer experiments.

References

[1] Cengel, Y., *Heat and Mass Transfer: A Practical Approach,* 3rd Ed., McGraw Hill, 2007
[2] I. Granet and M. Bluestein, Thermodynamics and Heat Power, 6th Ed., Prenctice Hall, New Jersey, 2000, pp. 571, J.P. Holman, Heat Transfer, 10th Ed., McGraw-Hill, New York, 2010, pp. 332-336
[3] G. Nellis and S. Kline, Heat Transfer, Cambridge University Press, New York, 2009, pp.28