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Using a Toaster Oven for a Transient Heat Transfer Lab

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Abstract

At Penn State Behrend, the heat transfer lab is part of a 4-credit heat transfer course for the mechanical engineering technology students. The equipment budget for the lab has typically been low, and commercially available equipment is typically very expensive. In order to provide a quality lab experience for the students, several common, low-cost pieces of equipment have been used for the lab exercises. There are two reasons for this. Student learning in the lab tends to improve when they do not have to spend time trying to understand the operation of an unfamiliar looking devise. Students can concentrate on the concept rather than the devise. The other reason is that the common devises are inexpensive. This helps to stretch the equipment budget for the lab, which helps to provide a broader range of lab experiences for the students.

Over time, many such exercises have been developed and are being regularly used. With the help of these devices we can provide labs which address many of the core concepts being taught in the, but some important concepts have not yet been addressed. This paper gives a brief overview of the current exercises. It then describes new equipment which should begin to be integrated into the current lab curriculum in fall of 2020. An internally funded undergraduate research grant has provided some funds for student assistance on this project.

Introduction:

The thermal and fluid sciences lab for Mechanical Engineering Technology students at [name of university] has been evolving over the last few years to include not only existing exercises, but also to include a series of newer exercises. Most of the existing labs incorporate a traditional "cookbook" approach. This is a very common method used in a lab such as this. Kaminski[1], for example, has reported on a group of five exercises for use in a heat transfer lab. They use inexpensive hardware which is not difficult to replicate and are easy to incorporate into any heat transfer lab course. The author has used the transient heat transfer exercise from this paper pretty much unchanged from the description in the paper, and a variation of the thermal interface exercise. At [name of university] the budget for this lab is very restricted, so the idea of using inexpensive hardware is very attractive, and many of the newer exercises that are beginning to be used focus on doing just that. One of the advantages to doing that is the students are familiar, or somewhat familiar with the equipment. This helps the students to concentrate more on the principles involved rather than the logistics of running the equipment. Currently we use such things as hair dryers, blenders and other simple to understand devices.

This paper focuses on one such proposed new addition to that list. An exercise is being developed which incorporates a common toaster oven as the heating element in a transient conduction exercise. Most student have some familiarity with this kind of device, but for this instance there is a second level of familiarity which is helpful for this exercise. The same device is currently being used for a thermal expansion demonstration in an introductory course in strength of materials. The customized thermal expansion oven was created because of the high cost associated with standardized thermal expansion testing equipment. The oven is approximately 15 years old. At the time it was created, a standardized thermal expansion testing device, used in many physics labs at high schools and universities, cost approximately $700. The customized oven's total cost was under $100. Since the customized thermal expansion oven was created, it has been used in a freshman material properties lab for studying linear thermal expansion. Students collect experimental data such as original length of the test specimen (L_o), initial temperature (t_o), final temperature (t_f), change in length (ΔL) and calculate the coefficient of linear thermal expansion (α). The students then compare their results to tabulated data. Students test 5 materials: titanium, stainless steel, steel, aluminum and copper. The new exercise builds on the student understanding of this basic principle in a much more extensive lab experience.

The oven will now be used for a new exercise to demonstrate transient heat transfer. The bar geometry is such that a lumped mass analysis is appropriate. The goal is to first relate the thermal expansion to the temperature of the bar. A plot is then made showing the increase in temperature versus time. A theoretical lumped mass analysis is used to calculate a theoretical temperature curve. The two curves can be examined and compared as part of the lab report. This paper presents information about the hardware, the test set-up, data collection and the required analysis.

Overview of the Toaster Oven Exercise:

The purpose of this exercise is to conduct a transient heating exercise for a steel bar. The steel bar starts at room temperature and is heated to the temperature of the oven. The exercise is a hybrid between a traditional "cookbook" approach and a more active learning approach to lab work. The "cookbook" portion is used for the test set-up, data collection and initial analysis. At that point there is an apparent difference between the actual results and the theory. Students are then asked to use reasoning, based on their knowledge of heat transfer, to hypothesize about what is causing the differences.

Figure 1 shows a schematic of the test set-up. It consists of a common toaster oven with a hole in the side to accommodate a small diameter test sample. There is a thermocouple mounted to the inside of the oven to monitor the temperature. A dial indicator is mounted to measure the thermal expansion of the bar. A stopwatch (not shown) is placed next to the dial indicator. Students collect data consisting of the movement of the dial indicator and the time on the stopwatch using a video camera. The use of the video camera allows the students to get accurate readings of deflection and time for further analysis.

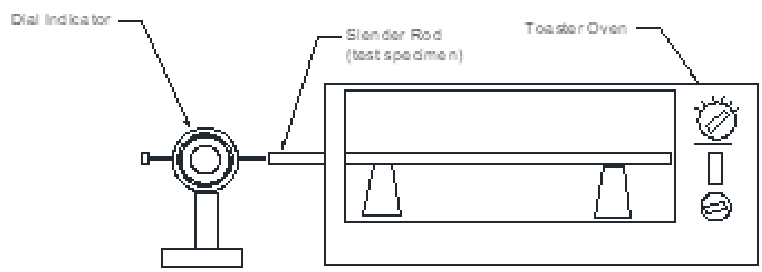

Figure 1

Overview of the Procedure:

This exercise is based on the concept of thermal expansion of materials. As the temperature of a material increases it will expand in a well-defined manner in all directions. For this exercise the expansion in the axial direction is measured and analyzed. This is a little different than the procedure that was used in the introductory strength of materials demonstration above. In that exercise the data includes the initial and final temperatures, the initial length and the change in length. The students then calculate the coefficient of thermal expansion. In this exercise a published coefficient of thermal expansion is used to determine the temperature of the part at any point during the heating.

In a typical transient exercise used at [name of school] the students must collect data that includes the initial part temperature and temperature vs. time data as the part is cooled from an elevated temperature. This can be done quite easily using an imbedded thermocouple and a data acquisition unit. In this exercise the students are studying the transient heat transfer from the heated oven to the aluminum rod. The length and the slimness of the rod make it very difficult to imbed a thermocouple into the part. A novel approach to determining part temperature was developed building on the coefficient of thermal expansion experiment that they had done before. The temperature of the rod is indirectly determined using expansion data.

The oven is first pre-heated to an elevated temperature, which becomes the ambient temperature for the test. The initial plan was to insert the test specimen, which is at room temperature, through an existing hole in the side of the oven and begin recording expansion vs. time data using the dial indicator and the stopwatch. It was soon determined that there was a problem with this. The part begins warming up before the dial indicator can be positioned to take the measurements. After a few failed attempts were made to account for this pre-warming of the test part we came upon a novel approach to solve this problem. The part is inserted into a room temperature oven and the dial indicator is zeroed. The part is then removed and the oven is heated to the desired temperature. The part is inserted into the pre-heated oven, the dial indicator is positioned and then an initial dial indicator reading is taken. From that reading it is possible to determine a new initial temperature for the part.

At this point, expansion vs. time data can be recorded. It was decided to take a video of the dial indicator and the stopwatch which proved to be an excellent method for recording the data, which can later be transferred to a spreadsheet. The spreadsheet is used to analyze the data and plot a part temperature vs. time graph. On the same set of axis, a theoretical curve can be plotted for comparison.

Test Set-up:

Below are pictures of the test set-up. Figure 2 shows the actual oven that is used for the test. If you look carefully you can see a test specimen in place inside the oven.

Figure 2

Figure 3 shows the inside of the oven. Notice that there is a rack on the inside to support the test specimen. Also, you can see on the left end of the rack an access hole going through the wall for the test specimen. The oven thermometer is not used for this test. It is there for the demonstration that is conducted in the strength of materials lab. If you look carefully you can see the thermocouple in the back of the oven to measure the ambient temperature during the test.

Figure 3

Figure 4 shows a close-up of the dial indicator in position and the stopwatch in the background. The dial indicator is permanently mounted to the base and is used for both the strength of materials demonstration and this transient heat transfer exercise. The stopwatch is on a temporary mount and is only used for this exercise.

Figure 4

Figure 5 shows the overall test set-up including the oven, dial indicator, stopwatch, digital thermometer to monitor the oven temperature and the video camera.

Figure 5

Theory[2,3]:

This exercise involves concepts that the student have learned, not only in heat transfer, but also in strength of materials. These include thermal expansion, lumped mass method for transient heat transfer, natural convection and some understanding of radiation heat transfer.

Thermal Expansion: The relationship between temperature change and thermal expansion is well known.

$$\boxed{\Delta L = \alpha L(\Delta T)} \qquad \text{(Equation 1)}$$

ΔL ~ Change in length
α ~ Coefficient of thermal expansion
L ~ Initial length
ΔT ~ Change in temperature

This relationship is used to determine the temperature of the part at any point in time.

Lumped Mass Analysis: Lumped mass analysis is used for transient heat transfer analysis when the temperature variation throughout the part is very low and negligible. It is assumed for the analysis that the part temperature remains uniform throughout the transient process. The criteria for determining if it is an appropriate method for a given situation is to determine the Biot Number (Bi). If Bi < 0.1 then this method provides a good approximation for the analysis.

$$\boxed{Lc = V/As} \qquad \text{(Equation 2)}$$

Lc ~ Characteristic length
V ~ Volume of part
As ~ Surface area of part
ΔT ~ Change in temperature

$$\boxed{Bi = (hLc)/k} \qquad \text{(Equation 3)}$$

Bi ~ Biot Number
h ~ Convection coefficient
K ~ Thermal Conductivity

Once it has been determined that the lumped mass approach is appropriate then a calculation can be made to determine a theoretical temperature vs. time curve for the transient. Equation 4 is the governing equation for this method. Solving this differential equation yields Equation 5, which is the equation that is used for the analysis of this exercise.

$$\boxed{-hA_s(T - T_\infty) = \rho V C p \frac{dT}{dt}} \qquad \text{(Equation 4)}$$

T ~ Temperature at any time
T_∞ ~ Temperature of the surroundings
Ti ~ Initial temperature of the part
P ~ Density
Cp ~ Specific heat

$$\frac{T_{(t)} - T_{\infty}}{T_i - T_{\infty}} = e^{-(\frac{t}{\tau})} \quad \text{(Equation 5)}$$

t ~ Time
τ ~ Time constant

Natural Convection: The part is being heated by natural convection in air. An appropriate convection coefficient must be determined to use in equation 6 to be able to calculate the time constant to be used in equation 5.

$$\tau = \frac{\rho V Cp}{hAs} = \frac{\rho L_C Cp}{h} \quad \text{(Equation 6)}$$

At the point in the course where this lab will be used the students have not yet been introduced to methods for calculating the convection coefficient. A reasonable value was calculated using a Nusselt correlation for a horizontal cylinder. This value will be given to the students to use. Later in the course when this topic is covered the students will be asked to revisit this lab and determine if the value used for h (convection coefficient) was reasonable.

Radiation: At this point in the course the students have only had a very brief introduction to radiation heat transfer. The important thing for them to know for this exercise is that radiation acts parallel to convection, and would add to the overall heat transfer that is occurring during the transient process.

Procedure For Set-up and Data Collection:

- Gather physical dimensions of the test bar and determine how much of the length of the bar is inside the oven during the transient process.
- With the oven at room temperature place the bar into the oven and zero the dial indicator.
- Remove the bar and pre-heat the oven to 200^0C.
- During the pre-heat set up the video camera to record the data.
- Once the oven is up to temperature start the video camera and place the part back into the oven.
- Put the dial indicator back into position to measure the expansion.
- Monitor the dial indicator. When the expansion is finished stop the camera and shut down the oven.

- Carefully remove the part and set it aside to cool.
- Once the exercise is complete, set up a spreadsheet to record the data and to be used for the calculations. Play back the video and pause it at regular intervals to record the data onto the spreadsheet.

Making Sense of the Data:

Below is a graph of the results of this exercise (Figure 6).

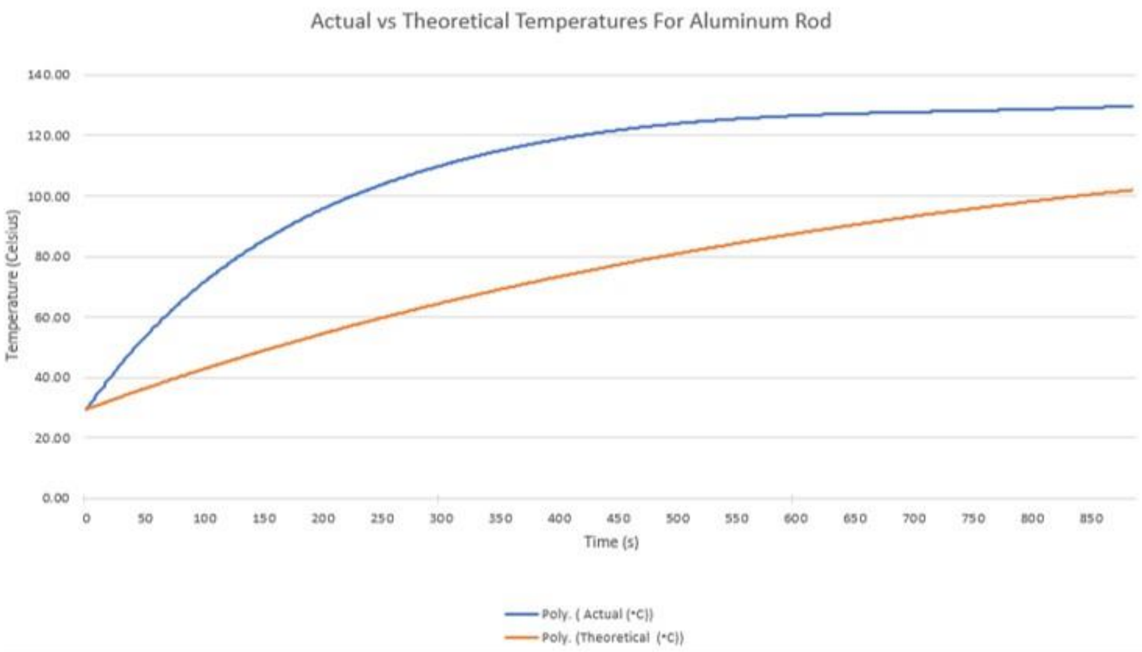

Figure 6

On Figure 6, the theoretical curve was generated from a lumped mass analysis of the transient heat transfer. The actual curve was generated from the data collected during the test. The results from this exercise do not seem to make sense when the actual results are compared to a lumped mass analysis. The students are asked to try to make some sense of the data. Their hypothesis needs to based on information they have learned in the classroom, not just on a guess. They first need to recognize that there is a problem with the results. Often students simply want to do the procedure and be done with it. They do not bother to ask themselves if the results make sense. Here there are forced into taking that step. The mechanical engineering technology students are doing this exercise as part of a first course in heat transfer which does not include more than an introduction to radiation. A transient radiation analysis is well beyond the scope of the course, however, they have been introduced to the basics of radiation calculations. They should be able to first recognize that convection alone is not heating up the rod as fast as the data shows. They should then realize that the only other mode of heat transfer that could be affecting this is radiation. They may also be able to devise a method to estimate the percentage of impact that radiation has on the overall heating process.

Conclusions:

This exercise has just recently been developed for inclusion in the introductory heat transfer course in the mechanical engineering technology program. It will be first implemented during the Fall, 2021 semester. As with any new exercise like this there will probably be some modifications made based on student feedback, and it will become a much needed, inexpensive addition to the lab curriculum.

References:

[1] W.R. Kaminski "A Series of Heat Transfer Experiments for the Mechanical Engineering Technology Student," Proceedings of the American Society for Engineering Education Annual Conference & Exposition, 1998.

[2] R.C. Hibbeler "Mechanics of Materials," Tenth Edition, Pearson, 2016.

[3] Yunus Cengel, Afshin Ghajar "Heat and Mass Transfer Fundamentals & Applications," Sixth Edition, McGraw Hill, 2020.