ME 331 Transient Heat Transfer Experiment

The purpose of this experiment is to test whether or not the lumped capacitance method can be used to accurately estimate the surface temperatures of three different spheres as they cool by radiation and natural (not forced) convection. In the sixth week of the quarter, the data from this experiment will be used to estimate the different rates of natural convective heat transfer from the three spheres. In the final week of the quarter, the same data from this experiment will be used to predict the different rates of radiation heat transfer from the spheres. Predicted and measured rates of heat loss will be compared to gain further insight into the relative importance of natural convection and radiation modes of heat transfer.

Introduction and Background

Heat transfer theory provides a direct means of developing engineering estimates of the rate of heat transfer in various practical situations. For convective heat transfer, the theory is somewhat empirical and is developed using certain assumptions. As such, it represents an idealization that is not always met in practice.

The objective of these experiments is to evaluate the radiation heat transfer and natural convection heat transfer rates from three different solid spherical objects. A variety of spherical test samples are provided, which were chosen to demonstrate how radiation heat transfer and natural convection vary with sphere size, material, and surface finish. The goal is to compare the measured and predicted heat transfer rates for both natural convection and radiation from each of three solid samples: 1) gold plated copper sphere, 2) black coated copper sphere, and 3) a smaller rubber sphere.

Apparatus

A water bath is used to heat the spherical object, just before naturally cooling it by ambient air and the surrounding lab environment. The sphere's center point temperature is measured with a type K thermocouple (chromel/alumel) that is inserted through a stem into the center of the otherwise solid sphere. The thermocouple is connected to a data acquisition system and the temperature history is recorded. Another thermocouple is suspended in the ambient air to measure the air temperature.

Hazards

This experiment uses nearly-boiling water, which can scald you. Be careful not to splash hot water on yourself or others. The floor may be slippery from spills. Avoid spilling water on electronics. Use the stand to maneuver the sample after it has been in the water bath - the sample itself is hot. The lip of the water bath is also hot - avoid touching it.

Data Acquisition System

A computer program reads data from three thermocouples: ambient, water bath, and the sample's center. See the appendix for DAQ system instructions.

Experimental Procedure

1. Check that the heater is on and the water bath heater controller is set to 95°C. The plastic balls floating in the water bath are there to prevent evaporation, but you may still need to add water before beginning your experiment. Wait until the water temperature stabilizes before immersing a sphere in the water bath.

2. Use the rubber sphere or either of the two (gold or black) coated copper spheres. The coatings on some of the spheres are delicate so please avoid scraping the spheres against anything. Carefully feed the thermocouple through the stem, until it reaches the center of the sphere. Try not to get water on the thermocouple or inside the sphere. Start the DAQ system.

3. Hang the sphere from the stand, and with a plastic sheath surrounding the sphere, carefully lower it into the water bath until the sphere is completely immersed, but not touching the bottom. Be careful not to splash hot water on yourself or system electronics.

4. Monitor the sphere's temperature until it stabilizes. Lift the sphere out of the bath and swing the stand arm so that the sample hangs away from the water bath, then remove the plastic sheath. Let the temperature drop to 40°C or less. This may take 45 minutes, so if you decide to leave and come back later, turn off the water bath heater before you go. Leaving an experiment unattended carries risks, such as the DAQ system malfunctioning, or someone unwittingly disturbing your experiment.

5. Transfer your saved data file to a flash drive. Copy-paste works more reliably on Linux systems than drag-and-drop.

Transient Analysis: For each of the three spheres, plot the temperature at the center r = 0, as a function of time: $T_{r=0}$ versus t. Next, plot the natural logarithm of the normalized temperature, $(T_{r=0} - T_{\infty}) / (T_{initial} - T_{\infty})$ as a function of time. If the overall effective heat transfer coefficient, $h_{effective}$, due to both radiation and natural convection is nearly constant, then a plot of $\ln (\Theta / \Theta_{initial})$ as a function of time will be linear, and the slope of the line is directly proportional to $h_{effective}$. If it is variable, then a plot of $\ln (\Theta / \Theta_{initial})$ versus time will be a curve and the highest value of $h_{effective}$ occurs initially, at the very beginning of the cooling curve. Use a tangent to the curves / lines to obtain the slope and the highest values of $h_{effective}$ for each sphere. With appropriate thermal properties and sphere diameters, estimate each Biot number and determine whether the lumped capacitance method is or isn't valid for each case. ***Note:*** For low values of Biot number, the surface temperature and center point temperature of a sphere are practically the same.

Convection Analysis: Using an empirical correlation, estimate and plot as a function of time the heat loss rates $q_{convection} = h A_{surface} (T_{surface} - T_{\infty})$ by natural convection from each sphere for which lumped capacitance method is applicable. First, compute the values of the natural convection coefficient *h* and plot as a function of time. Estimate the film temperature and the Nusselt numbers $Nu = h * D / k_{air}$. Plot the Nusselt numbers as a function of time. Remember that Nusselt number depends upon the film temperature. ***Note:*** Natural convection heat transfer coefficients *h* are a function of time since *h* depends upon the difference between the sphere surface and ambient temperatures $(T_{surface} - T_{\infty})$.

Radiation Analysis
Estimate each sphere's emissivity. Calculate $q_{radiation}$ as a function of time for each sphere for which lumped capacitance method is applicable. Calculate and plot $q_{total} = q_{convection} + q_{radiation}$. Next, use the sphere's mass and specific heat and the derivative of the sphere's measured temperature with respect to time, to obtain q_{total}. Plot this measured q_{total} as a function of time on the same graph as the predicted $q_{total} = q_{convection} + q_{radiation}$.

Note: Radiation heat transfer rates from the spheres in this experiment are also a function of time since the rates depend upon the difference of fourth power absolute temperatures ($T_{surface}^4 - T_{surroundings}^4$).

Discussion
In the report discuss the following for each of the spheres:
1. Is the lumped mass model appropriate? Why or why not?
2. The variation of *h* with time.
3. Core and surface temperatures during cooling.
4. The effect of radiation.
5. How reasonable are the emissivity estimates?
6. Discuss differences between measured and predicted values of q_{total}.

APPENDIX - DAQ System Instructions
1. Open the ME331 folder on the desktop.
2. Open LumpMass.py (It will open two windows, a python shell that will show the program outputs, and the program code itself.)
3. In the LumpMass.py window, select Run > Run Module, or Press F5. It may take a minute for the program to load.
4. Once the program starts, press 'Start' to begin taking data and plotting.
5. After you've finished collecting data, press 'Save', and save your file in the ME331 folder on the desktop, using your last name in the file name.
6. To start over, press 'Start' again. **The previous data will be erased - press 'Save' before restarting.**
7. Transfer your data to a USB flash drive before leaving.

DAQ Troubleshooting
Serial Port Errors: Check that the Arduino (in the transparent blue box) is plugged into the computer (green board in clear case) or into the USB hub. If that doesn't fix the problem, restart the computer (lower right corner of screen).

'IndexError' or 'ValueError' messages printing in python shell: If these errors only pop up once in a while, you can ignore them. If you get an error message often (i.e., every few seconds), the specimen thermocouple might be wet - take the thermocouple out of the specimen and let it dry.