MEEG346 Thermal Laboratory

3. Visualization and Measurement of Temperature on a Heated Plate

Objective

The goal of this experiment is to investigate transient two-dimensional heat conduction in an aluminum plate (12 in. × 12 in. × 2 in. thick, see Figure 1) subjected to the following temperature boundary conditions:

- Two edges are heated using thermally bonded electrical resistance strip heaters (constant heat flux boundary condition).
- The other two edges are cooled using thermally bonded heat exchanger plates supplied with cooling water from a chiller (constant temperature boundary condition).
- The bottom face is insulated with glass wool.
- The top face has a thermochromic liquid crystal (TLC) sheet glued to it. The top face is also insulated from the surroundings by an air gap trapped underneath a glass plate. The glass plate allows a visualization of the color play of the TLC sheet which changes color with temperature, and provides an alternative means of measuring temperature instantaneously, and globally. Temperature will also be measured using 16 thermocouples inserted into tiny holes drilled into the plate on a 3 in. × 3 in. grid.

![Diagram](image)

(a) Top View  
(b) Side View  
(c) Bottom View

Figure 1: Schematic of heated plate

You will be given the freedom to select your own temperature and heat flux boundary conditions, for which you will record thermocouple readings and capture the TLC color play with a color CCD camera and frame-grabber.

Because the plate has a substantial thermal inertia, it takes time to reach steady state in response to the boundary conditions. This allows us the opportunity to study the transient behavior of the plate by recording temperatures from all 16 thermocouples.
Finally, you will perform a 2-dimensional numerical solution to Fourier’s heat conduction equation, subject to the identical boundary conditions as the experiment, and compare the isotherms from the simulation with the experiment.

Theoretical Considerations

Thermochromic Liquid Crystals (TLC) are organic long-chain molecules which have the useful property of being temperature-sensitive. They respond to temperature by changing their molecular structure, consequently, the wavelength of light that is preferentially reflected changes. TLC’s are specified by two numbers, Red Start and Color Bandwidth. Both are typically specified in °C. Red Start is the temperature at which color play commences, and the Color Bandwidth is the range over which the colors change over the entire spectrum from Red → Blue. Contrary to conventional representation of colors for temperature, TLC are red when cold and blue when hot. TLC’s can be ordered from the manufacturer for customized red start and bandwidth. TLC’s are available as a slurry that can be added to a liquid flow, or in the form of a sheet (as has been done in our application). TLC’s are used for strip thermometers in fish-tanks and also for battery tester strips.

![Diagram of a heated plate with boundary conditions](image)

Figure 2: Geometry and boundary conditions for heated plate

The chosen configuration lends itself to a two-dimensional description, i.e., \( T = T(x,y,t) \). (Under steady-state conditions, the time dependence will disappear.) The dependence of \( T \) on \( z \) is eliminated provided that the top and bottom faces are well-insulated; this experiment provides such an insulating boundary condition. With reference to Figure 2, we can solve for the time dependent temperature \( T(x,y,t) \) subject to the following initial condition:

\[
T(x,y,0) = T_o
\]
and boundary conditions:

\[ q(0, y, t) = -k \frac{\partial T(0, y, t)}{\partial x} = q_1 \]
\[ q(x, 0, t) = -k \frac{\partial T(x, 0, t)}{\partial y} = q_2 \]
\[ T(L, y, t) = T_1 \]
\[ T(x, L, t) = T_2 \]

where \( k \) is the thermal conductivity of the aluminum plate. Temperatures \( T_1 \) and \( T_2 \) are assumed to be equal to the chiller setting, while \( q_1 \) and \( q_2 \) may be estimated by noting the electrical power supplied by the variacs to each electrical heater. \( T_o \) is known from the thermocouples. Therefore, all four boundary conditions and initial conditions are completely determined and can be used to solve for the temperature distribution within the plate.

The heat conduction law may be written as

\[ \nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \tag{1} \]

where \( \alpha \) is the thermal diffusivity of the plate. For the steady-state condition, all time-derivatives are set to zero, and the right hand side of Equation 1 becomes zero. You are required to solve the transient conduction equation using the numerical technique from MEEG342 (Heat Transfer) and compare your results with the experiment.

The most convenient way to present your results is in the form of temperature contours along the plate.

**Procedure**

1. Record the initial plate temperature by cycling through all the thermocouples; also, snap an image of the color contours on the plate using the color CCD camera and frame grabber. This will provide the initial condition for your numerical simulation.

2. Set the chiller temperature to 20 °C and start the flow through the heat exchangers. This will set the boundary conditions \( T_1 \) and \( T_2 \) (assuming that the water temperature does not increase very much during its travel across the plate). Go immediately to the next step!

3. Set the variacs to provide any desired value of \( q_1 \) and \( q_2 \). The goal should be to obtain maximum color play in the TLC sheet. You may find that a setting between 70 and 80 V is suitable. Record the variac voltage \( V \), and determine the power \( P \) using \( P = V^2/R \) where \( R \) is the resistance of the heater (57.5 ohms). The heat flux is obtained using \( q = P/A \) where \( A \) is the area of the heater. Of course, we are assuming that all of the power generated by the heater is directed into the plate (is this a good assumption?).

4. You will find that the plate takes a while to reach steady state. During this time, record (once every 10 minutes) the temperatures from all 16 thermocouples by cycling through them as rapidly as possible. Also, simultaneously snap an image of the color contours on the plate.
using the color CCD camera and frame grabber. Note down the time for each measurement. (You may wish to separate the thermocouple readout and camera recording tasks in the group to make the measurement “simultaneous”.)

You may terminate your measurements when steady-state is reached. The best way to determine this is by verifying that the thermocouple readings are no longer changing with time.

**Analysis**

1. Plot all temperature contours obtained from the thermocouple readings to show the time-varying trend. You may use any plotting package that can render two-dimensional contour plots in color. Also plot temperature vs. time for a select few thermocouples.

2. Compare the temperature contours with the color printouts of images captured by the CCD camera.

3. Perform an unsteady numerical solution using the experimental boundary and initial conditions. Compare them with those obtained from thermocouple measurements, as well as the TLC pictures.

**Note:** Typical contour plotting packages use red for high values and blue for low values, whereas, the TLC color-play is blue for high values and red for low values. To make a better comparison between color contour plots, you may use the *invert* feature on the color map when you plot contours for (1) and (3).

**Discussion**

1. How well do the three sets of results compare: thermocouple, TLC color play, and numerical?

2. In the current implementation, the TLC results are *qualitative*. In order to make it *quantitative*, what procedure would you suggest? Essentially we have to calibrate color with temperature. Describe step-by-step a suitable calibration procedure.

3. What are the possible reasons for discrepancies between the three sets of results? Think about the differences between the desired and actual boundary conditions.

4. Estimate the temperature rise of the cooling water as if flows across the plate. You will need to know the amount heat being absorbed by the water, and the water flow rate (from the chiller specification sheet); an energy balance will give you the temperature rise.

**Error Analysis**

1. What is the typical error in your thermocouple readings? How does that affect your contour plots?

2. How much confidence do you have in your numerical technique? What is the error in the unsteady and steady-state results? Are they the same?