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Open Source Software Problems in Heat Transfer to Explore Assumptions and Models

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Introduction

This document provides a detailed description of the adaptation of a freely available software program, Energy2D [1], for problems focused on the exploration and limitations of assumptions made in models commonly used in an undergraduate heat transfer course. The motivation for creating homework problems that use Energy2D is to explore the accuracy and limitations of the models used in heat transfer. The models are commonly utilized because they are easy to use and accurate even when not entirely valid, so these problems will provide students with a better understanding of their accuracy and of when they break down. Examples of models that are used here include 1D steady conduction with no generation, assuming a uniform base surface temperature or uniform convection coefficient for extended surfaces, using shape factors for 2D steady conduction, and the lumped capacitance method for transient conduction. Additional problems were in the process of being developed and will be continually developed during the Spring 2021 semester. The reminder of the document will be organized by problem in order of their coverage in MAE 3440 Heat Transfer at Utah State University.

Problem 1 - Introduction to Energy2D (From Homework 01)

Visit the Energy2D site at: http://energy.concord.org/energy2d. Under the Examples Heat and Temperature menu option, determine the equilibrium temperatures of the first 3 examples (identical, different specific heats, and different densities). Note: make sure they reach equilibrium.

Problem 2 - Equivalent Resistance Thermal Circuits - Parallel Resistances (From Homework 02)

In undergraduate heat transfer, conduction is usually covered first of the three modes of heat transfer. When covering conduction at the undergraduate level, the heat diffusion equation is typically introduced in its full form, which includes three spatial dimensions, one-time dimension, a heat generation term, and some assumptions about the thermophysical properties. This equation is quickly simplified by making the assumptions of one spatial dimension, steady (time independent) and no generation. From here, the commonly used equivalent thermal resistance circuit method is developed and applied to a wide range of problems. One area in which care must be taken to ensure its accuracy is in cases of parallel resistances. To explore this, an Energy2D model has been created and students are asked to complete

the problem:

> Using Energy2D and the equivalent resistance circuit method covered in class, complete the following table. The Energy2D model has been created for case 1 and is available on Canvas in the homework directory (hw02p6.e2d). For the Energy2D values, you can average the results of the heat flux sensors positioned normal to the direction of heat transfer. The temperature difference across the composite wall for each case is constant and can be obtained from the Energy2D file. Once you complete the table, do you feel the equivalent resistance method is acceptable for all cases?

Case	k_A (W/m-K)	k_B (W/m-K)	Equiv. Res. q^{11}	Energy2D q^{11}	% Error
1	10	10			
2	100	1			
3	1000	0.1			
4	10000	0.01			

Note: when calculating using the equivalent thermal resistance model, you can factor out the A, but keep in mind that the areas of each portion of 1/2 of the total area.

When students perform this problem, the goal is that they observe the power that a 1D model has, even in cases where 1D transport does not occur. They will also find that the 1D model is conservative and very useful for quick calculations.

Problem 3 - Extended Surfaces (From Homework 04)

Problem 3 is aimed at exploring the limitations of the commonly used fin equations, which are used to understand the efficiency and effectiveness of increasing the surface area for convection heat transfer by adding extended surfaces (fins). One of the most difficult parts of extended surface analysis is in appropriately assigning the boundary condition at the end of the surface. The options include Convective, Insulated, Infinitely Long, and Constant Temperature. In this problem they will compare each of the solutions to the results from Energy2D for 4 different configurations. The problem description given to students is below:

> In this problem you will be comparing the derived fin equations for the different tip conditions (convective, adiabatic, and infinite fin) to an Energy model. Specifically, you will compare the temperature distribution and the fin heat rate (per unit depth into the page/screen) for a straight fin. Complete the following table and plot the temperature distribution for each case using each end condition along with the average temperature data from each case in Energy2D.
>
> The fin dimensions are fixed with a length of 6 m and a thickness of 0.5 m. The equations derived in

the book were based on 2D analysis and then presented based on 3D geometry. In this case you will be analyzing an infinitely deep fin, so we will calculate the heat rate on a per unit depth into the page/screen. In order to do this we must assume P = 2D and A_c = tD. With those assumed, $m^2 = \frac{2h}{kt}$ and M = D®2hktΘb.

With this, we can eliminate D from our heat rate equations to give $q^1{}_f = q_f/D$, and in Energy2D we can convert the measured heat flux to the heat rate per unit length using $q^1{}_f = q^{1,1}{}_f t$.

For the data plots, use a plotting software of your choice and plot T vs. x separately for each case where the temperature distributions of the derived solutions are plotted as lines and the Energy2D data points are individual averaged values at the location they were measured. For averaging your temperature and heat flux data, please allow the simulation to reach a steady state condition (not changing with time). This could take a couple minutes so plan ahead. An example plot is given below the table to be completed. In addition to completing the table and making 4 plots, comment on which end condition is most appropriate for each case and which end condition is most appropriate for all cases (if you're lazy and don't want to calculate them all). Explain any difference you see between the Energy2D data and the 3 models and provide your reasoning for the difference.

| case	$k_{f\ in}$ W/m-K	h W/m²-K	mL	$q^1{}_f$convective	$q^1{}_f$adiabatic	$q^1{}_f$infinite	$q^1{}_f$E2D
1	10		3				
2	30		3				
3	100		6				
4	400		7				

Problem 4 - 2D Steady Conduction (From Homework 05)

Download the Energy 2D file (hw05.e2d). Go through the 4 cases by changing the properties of the 4 boundaries. For each one write what type of boundary condition this is and comment on the isotherms and heat flux lines at the boundary for each type of boundary condition. When you are finished, look at the same types of boundary conditions and what the isotherms and heat flux lines are doing at the boundary (do they cross the boundary, and if they cross, are they perpendicular to the boundary?). Finally, for each type of boundary condition, describe the isotherms and heat flux lines. Note: when you right-click an object, in this case these will be the blocks surrounding the center, under Source you have options to specify a constant temperature (when a temperature is given), Not a Source when Not a Source is given, or a Power Source when a volumetric heat generation is given, which will be entered in the Power Density field. An example is shown on the next page.

Case	Left bound.	Top bound.	Right bound.	Bottom bound.
1	0°C	0°C	0°C	10°C
2	0°C	0°C	0°C	50 W/m³
3	0°C	10°C	0°C	50 W/m³
4	Not a source	-15 W/m³	Not a source	15 W/m³
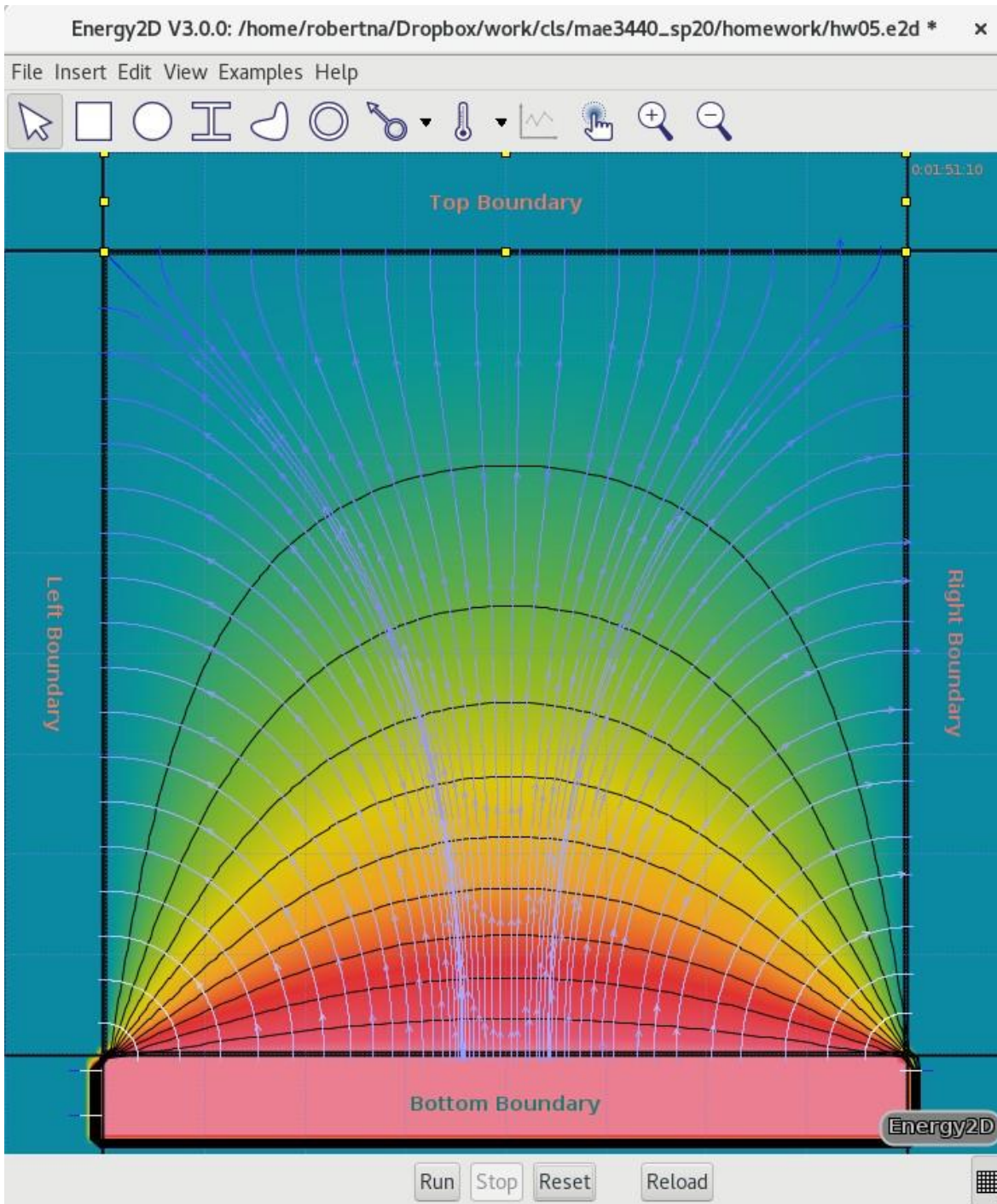
For example, case 1 is shown here. Each boundary is a 1st kind or prescribed temperature boundary condition. The isotherms (black lines) do not cross the boundaries and the heat flux lines (white to blue) cross the boundaries and are perpendicular at the intersection with the boundary.

Problem 5 - Transient Conduction (From Homework 06)

The goal of this problem is to gain physical insight into transient conduction by using Energy to explore the validity of the lumped capacitance method. To complete this problem, we will be calculating the Bi number, thermal diffusivity (α), and the Fo number for several cases and comparing temperature values using the LCM and by using Figure 5.8 for r/r_o = 0, 0.5, and 0.75 to those obtained from Energy using Figure 5.8, you will need to recalculate Bi and Fo with $L_c = r$ to determine the normalized temperature. Use your best estimate for values. Assume h = 15 W/m²-K for the convection coefficient for calculating Bi. To complete this problem, follow the procedure given below.

1. Download the Energy 1.

2. Run the simulation for 10 seconds of actual time (you can watch the timer in the top right).

3. Open the sensor data window and record the value of each sensor at Time = 400.0 s.

4. Change the thermal conductivity of the sensors for the next case and click Reset.

5. Repeat steps 2–4 until you have completed all cases.

6. Calculate Bi, α, Fo, T_{LCM}, T_0, $T_{0.5}$, and $T_{0.75}$ for each case and compare to the Energy results.

case	k	Bi	α	Fo	T_{LCM}	T_0	$T_{0.5}$	$T_{0.75}$	$T_{0,E2D}$	$T_{0.5,E2D}$	$T_{0.75,E2D}$
1	400										
2	40										
3	8										

Problem 6 - Forced Convection in External Flow

A problem was not included in the homework due to the shift to online classes. A demonstration was provided that showed the transition from laminar to turbulent flow and the plot of the average temperature of an infinite cylinder with uniform volumetric heat generation over time. This showed the enhanced convection heat transfer coefficient in turbulent flow.

Problem 7 - Forced Convection in Internal Flow

A problem was not included in the homework due to the shift to online classes. A demonstration was provided to compare analytic solutions for uniform surface temperature and uniform surface heat flux to a case where a pipe is heated uniformly in a furnace and the actual solution differs from the two commonly used approximations.

Problem 8 - Natural Convection

A problem was not included in the homework due to the shift to online classes. A demonstration was provided that shows the different regimes of natural convection on horizontal and vertical flat plates and cylinders.

Problem 9 - Radiation Exchange - View Factors

A problem was not included in the homework due to the shift to online classes. A demonstration was provided that compares the analytic view factors to those from Energy2D, which uses a ray tracing algorithm.

References

[1] Charles Xie, "Energy2d," http://energy.concord.org/energy2d/index.html.