CASE STUDY 2: THERMAL SYSTEMS

MODELING AND SIMULATION

SEPTEMBER 22, 2008

Overview

Please choose one of the following three cases. The first case involves the design and performance of a passive solar house. The second case involves the Mpemba effect—the bizzare (and not entirely understood) fact that, under some circumstances, hot water freezes faster than cold. The third case involves the Leidenfrost effect—another strange effect related to phase changes.

Each case expects you to do something a little different. For example, in the *Solar House* case you are asked to create a model of a simple passive solar house, and to use the model to make recommendations about the design of the house for a particular climate. The *Mpemba* case asks that you develop a model that explains an observed phenomenon and predicts the conditions where it is likely to occur. Finally, the *Leidenfrost* case requests that you develop a model that is consistent with known experimental results, and use the model to make predictions about future experiments.

While each case has more or less guidance about what you should do, there are certain expectations that are common to each. You are expected to formulate and/or implement a model using MATLAB. You are expected to work with a teammate. You are expected to write a final report of one kind or another. And finally, you are expected to create a set of *interim deliverables* that look something like the following:

Model Diagram, Equations, and Explanation: Create a clearly annotated diagram for your model. The diagram should include a caption that describes the parameters and relevant equations that describe your model. *Please be sure to specify the units of all parameters, and to give approximate ranges that you expect them to fall in.* Post this diagram in your workspace no later than the end of class on *Friday, September 26*.

Script: Write a MATLAB script that implements the model. The script should be well commented and easy to read. You should plan to post your working code in your workspace no later than the end of class on *Monday, September 29*.

Validation and Preliminary Results: Create one or more figures with descriptive captions. These should be completed and posted in your workspace no later than the end of class on *Wednesday, October 1*.

By our next meeting you should have chosen (with your teammate) a case study to pursue.

Passive Solar House Design

Introduction

In 1944 Frank Lloyd Wright designed the Jacobs II house. This house, located in Middleton Wisconson, included multiple design features intended to take addvantage of passive solar heating: the house faces south with a wall of glass; the house is only one room deep, so that all rooms can benefit from solar heating, and the roof overhang is designed to keep out summer sun while admitting winter sun.

Figure 1: The Jacobs II House. The glass facade faces south to maximize passive solar heating. Image from `www.dgunning.org`.

Despite these many design features, recent owners of the house have required thousands of gallons of oil each winter to keep the house warm[1]. Temperature dynamics in the Jacob's house are largely to blame for the enormous heating cost of this seemingly well-designed house. The original owners of the house reported that the house's heating system would often turn off by 9AM on sunny winter days—but they also reported that the house was so cold in the early morning that they would have to all dress together in the bathroom, as that was the warmest room in the house[2]. While the house is well-designed for solar heating, it is not well-designed for heat retention—it is almost completely uninsulated, and (perhaps) lacks sufficient thermal mass.

[1] M. Utzinger and J.H. Wasley. Building balance point. Technical report, University of California, Berkley, CA, August, 1997.

[2] How romantic!

In order to avoid problems like those seen in the Jacobs house, the Department of Energy now provides simple guidelines for homeowners[3], and identifies the key components that designers must consider: the *aperture*, which allows photons to enter the house; the *absorber*, which absorbs rather than reflects the photons; the *thermal mass* which stores the thermal energy; the *control*, which ensures that summer sun does not overheat the residence; the *distribution*, which ensures that heat reaches living spaces; and finally, the *envelope*, which controls loss of heat back to the environment (see Figure 2). Furthermore, for each of these components, designers and house builders have developed rules of thumb from years of experience (and building codes) in a particular climate; e.g., in the southwest, the rule of thumb is "one pound of thermal mass per square foot of aperture", or in another area, "walls must be insulated to R10 and ceilings to R30."

[3] EERE Clearinghouse. Passive solar design for the home. Technical report, US Department of Energy, Washington, DC, February, 2001.

Unfortunately, rules of thumb are not terribly helpful for predicting performance...which is what we would like you to do.

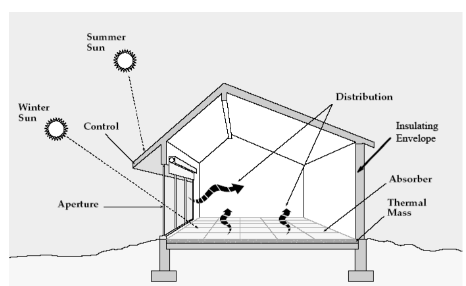

Figure 2: A schematic diagram showing key components of a passive solar house. Image adapted from *Passive Solar Design for the Home*, EERE Clearinghouse, February 2001.

Deliverables

Your objective for this project is to create a dynamic model of a passive solar house. At a mimimum, your model should allow you to investigate the effects of changing the aperture, control, envelope, absorber, thermal mass, and size of the house. Ideally the model should allow you to investigate the nature of daily temperature swings both in the summer and in the winter, and should also somehow account for the location of the house (particularly its latitude and possible altitude).

Using the model, we would then like you to propose a reasonable schematic design for a house in your chosen location. Here "schematic design" refers to a design that specifies masses, aperture sizes, etc.—not something that suggests a particular floorplan. Your design should be supported by appropriate simulations that demonstrate that the house would be comfortable to live in without the use of excessive supplemental heating or cooling. If you wish, you might choose to try to model the Jacobs house and propose changes to the design to address the problems seen by the house's owners.

The final deliverable for this case study is a short document written that describes your proposed house design, and that justifies the design with simulation results. It should likely include a schematic diagram that highlights important design decisions, and should also include graphs that show the predicted behavior of the system (e.g., predicted internal temperature over a 24 hour period under different seasonal conditions, predicted additional heating/cooling load, etc.). This document is due by *Friday, October 3, at 5PM*.

The Mpemba Effect

According to the Wikipedia:

> The [Mpemba] effect is named for the Tanzanian high-school student Erasto B. Mpemba. Mpemba first encountered the phenomenon in 1963 in Form 3 of Magamba Secondary School, Tanzania when freezing hot ice cream mix in cookery classes and noticing that they froze before cold mixes. After passing his O-level examinations, he became a student at Mkwawa Secondary (formerly High) School, Iringa, Tanzania. The headmaster invited Dr. Denis G. Osborne from the University College in Dar Es Salaam to give a lecture on physics. After the lecture, Erasto Mpemba asked him the question "If you take two similar containers with equal volumes of water, one at 35°C and the other at 100°C, and put them into a freezer, the one that started at 100°C freezes first. Why?"

Figure 3: "Mpemba Effect is the latest groove machine in the African Cream Music stable. Inkolo is their debut album, with a fresh sound to go with their quirkily selected name." `www.africancreammusic.com`.

Your job is to answer that question. You might want to start by reading the Wikipedia page on the Mpemba effect, following the links there and searching for additional resources.

As you will see, there are many hypotheses about what exactly causes the effect and what conditions will demonstrate it. You will have to make decisions about which factors to include in your model and which can be ignored. There are a number of parameters that characterize the conditions; it might take some work to understand these parameters, choose appropriate values (or ranges of values) and understand the effect of each.

The deliverable for this project is a report, appropriate for publication in *New Scientist*, that uses a dynamic thermal model to explain the Mpemba effect and predict the conditions where it will occur. This document is due by *Friday, October 3, at 5PM*.

The Leidenfrost Effect

Introduction

Figure 4: Droplets of water dance across the bottom of a pan to the infectious beat of the Leidenfrost effect. Image from *http://www.natuurkunde.nl*

If you've ever sprinkled droplets of water on a hot pan, you've probably observed that if the pan is hot enough, the droplets of water skitter across the hot surface, and can survive on the surface for quite a long time (e.g., a minute or so). What you might *not* have observed is the fact that if the pan is not so hot, the droplets actually disappear much more quickly—in a few seconds, rather than in a minute.

This effect has been known of for hundreds of years. It was first explored extensively by Johann Gottlob Leidenfrost in his 1756 paper, "A Tract About Some Qualities of Common Water." Since 1756, there has been a reasonable amount of exploration of this effect, ranging from full-blown scientific papers to more informal investigations (see). Basically, the effect is due to *film boiling*.[4] A thin film of water vapor separates the water droplet from the pan; consequently, the rate of heat transfer between the pan and the droplet is substantially reduced, and the droplet "survives" longer.

A similar film boiling effect accounts for the fact that it is possible[5] to (1) dip a wet hand into molten lead, (2) hold liquid nitrogen in your mouth without incurring frostbite, and (3) walk across hot coals, so long as your feet are sweaty. **We do not want you do to any of these things.**

[4] J. Walker. Boiling and the leidenfrost effect, available at *http://www.wiley.com*.

[5] Albeit incredibly stupid.

Deliverable

What we **would** like you to do is to develop a model for the Leidenfrost effect; that is, we want you to model the lifetimes of water droplets on hot skillets. This has little if any practical application[6], but it is pretty interesting (if you're curious about the way the world works), and is easily tested through experimentation. Your model should allow you to investigate the effects of changing the droplet size, initial droplet temperature, and skillet temperature.

[6] Well, actually, it is pretty useful for nanoscale pumps.

The final deliverable for this case study is a report, appropriate for publication in *New Scientist*, that describes your model and presents and explains the key predictions of your model with respect to droplet size and skillet temperature. If you are feeling ambitious, you might also try to do some experimentation—but this is in no way required. This document is due by *Friday, October 3, at 5PM*.