A Simple Classroom Demonstration of
NATURAL CONVECTION

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Natural or free convection results when there is a fluid density gradient in a system with a density-based body force such as the gravitational force. In an otherwise quiescent fluid, a density gradient can be caused by temperature gradients and/or species concentration gradients. Natural-convection currents enhance heat and mass transfer relative to conduction and diffusion in a quiescent fluid.[1] This is an important process for engineers to understand. For instance, natural convection is a key process in the passive cooling of people, machinery, and computer chips, and in the volatilization of exposed liquids in an indoor or windless environment.

The topic of natural convection is typically covered during two or three classroom hours in a junior-level heat and mass transport course. One of the difficulties in such math-intensive courses is helping students get a qualitative and physical understanding of the phenomena. It is easy for students to get lost in dimensionless numbers and correlations when they don't have basic engineering sense. One way to remedy this is for students to observe the relevant phenomena and to discuss their observations and how they relate to the equations.

This article explains a simple way to demonstrate natural convection in the classroom using an overhead projector. The demonstration is based on the principle of schlieren imaging, commonly used to visualize variations in density of gas flows. The demonstration requires a few hours of preparation time but very little in materials cost, assuming an overhead projector is already available. It could be prepared by the instructor or by students as part of a class-related project. In the discussion below, I assume the reader is more familiar with the principles of natural convection than with schlieren imaging. Therefore, I focus on the principle behind the schlieren technique, the preparation required for the demonstration, and the results that one can expect.

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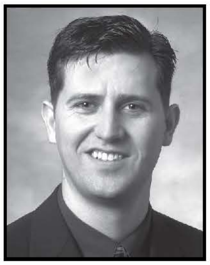

SCHLIEREN IMAGING

Schlieren images, along with shadowgraphs and interferometry, are a means of visualizing density variations in transparent media.[2] These techniques work on the principle that the index of refraction of a fluid depends on its density. The path and phase of a light wave passing through the fluid therefore depends on its density and its spatial derivatives. Schlieren optics as such was invented in 1864 by August Toepler, a German chemist and physicist (*schlieren* means "streaks" in German).[3] The technique has been extensively used to visualize shock waves in supersonic flight. The wavy appearance of the

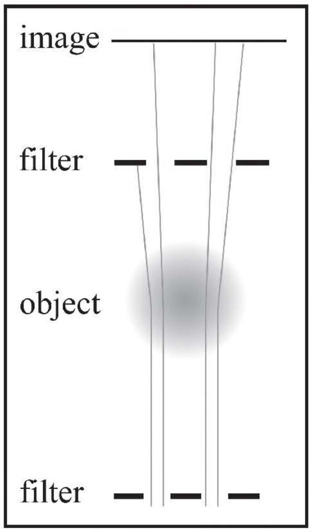

Figure 1. *The principle of schlieren imaging. Rays of light, moving from bottom to top, encounter a filter, a refractive object, a second filter, and then the image plane. Density gradients in the refractive object bend light rays such that some are screened out by the second filter, resulting in intensity variations on the imaging surface.*

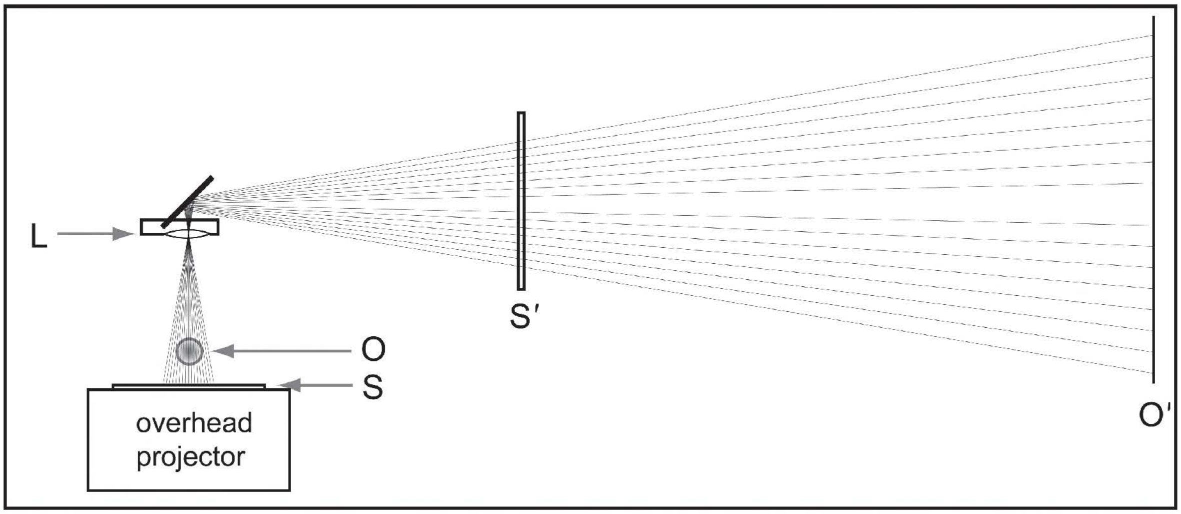

Figure 2. *View of the optical setup from above. Point L indicates the overhead-projector carriage lens. Points S and S´ indicate the small and large stripe filters, respectively. Points O and O´ indicate the free-convection object and its projected schlieren image, respectively.*

horizon above a hot road is a simple example of schlieren imaging of natural convection.

Figure 1 illustrates the principle of schlieren imaging. A series of two filters with periodically alternating transparent and opaque stripes is used in combination with a light source. The fluid to be imaged has a gradient in its index of refraction, which causes spatial variations in the amount of light that passes through both filters. This produces an image in which light and dark areas correspond to variations in the fluid density gradient. Conversely, if the fluid object has a uniform density gradient, the image will be uniformly gray.

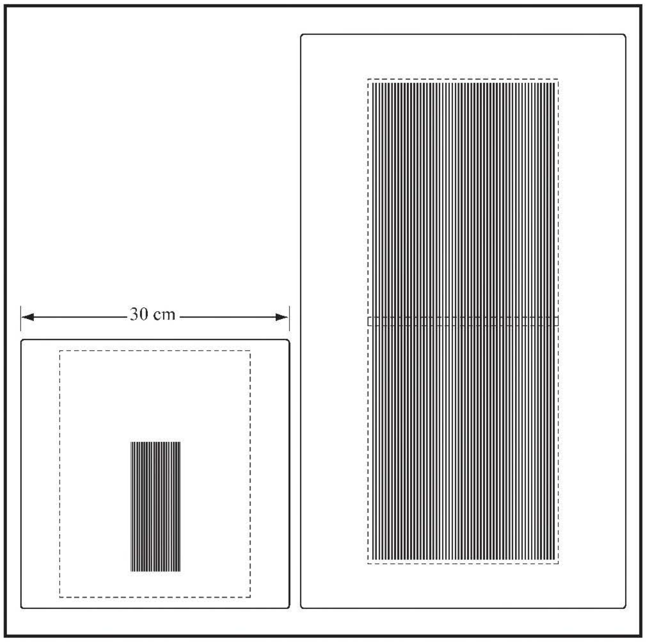

Figure 3. *Schematic of the small and large stripe filters. The dotted lines indicate boundaries of single-page transparencies that are taped onto frames made of foam-core board.*

DEMONSTRATION SETUP

How can one adapt the schlieren technique for classroom use? Figure 2 shows how the optics that are part of an overhead projector can be used to project a schlieren image of an object onto a screen. The schematic is a view from above, which means that the overhead projector is turned on its side. This is necessary so that vertically traveling fluid currents around the free-convection object are largely orthogonal to the light path. The optical principles of this setup, including the use of striped filters, is the same as in Figure 1, except that a focusing lens increases the brightness of the projected image by collecting and distributing the light from the projector lamp. The smaller filter (point S) is attached to the surface of the overhead projector, and both filters have their stripes in a vertical orientation.

In order for the setup in Figure 2 to work, the optical planes associated with points O and O´ must be "in focus" with each other, as must the planes associated with points S and S´. Assuming the lens is ideal, this means that

$$\frac{1}{d_O} + \frac{1}{d_{O'}} = \frac{1}{d_S} + \frac{1}{d_{S'}} = \frac{1}{f} \tag{1}$$

where d_X indicates optical distance between the lens and point X, and f is the focal length of the lens. Because the projector lens is mounted on a movable carriage, we have a great deal of freedom in positioning the various optical elements.

Figure 3 shows the two striped filters used in my optical setup. They were made by creating the black-and-white striped patterns in a computer graphics program, laser printing onto transparent sheets, and attaching the sheets onto frames constructed from foam-core board purchased from the art supplies section of the campus bookstore. The smaller filter has a size comparable to the free-convection object to be imaged and has black stripes of thickness 0.5 mm and periodicity of 1 mm. (Because of the vagaries of my laser printer, it was necessary to make the black stripes 0.67 mm thick in the graphics program to affect a printed thickness close to 0.5 mm.) The larger filter is basically an enlarged image of the smaller filter—in this case enlarged by a factor of 3.7. The enlargement factor is equal to the ratio of optical distances $d_{S'}/d_S$.

It is advantageous to make the large filter as small as the optics allow and customize it for the overhead projector to be used. To determine the optimal large filter

- *Make the small filter, place it on the overhead projector surface, and project its image onto a wall.*
- *Move the lens carriage to its uppermost (furthest) position relative to the surface. This maximizes distance* d_S *and hence minimizes* $d_{S'}$*, according to Eq. (1).*
- *Move the entire projector relative to the wall until the striped image is exactly in focus. The wall is then at position S′ of Figure 2 and thus establishes distance* $d_{S'}$.
- *Measure the thickness and periodicity of the stripes projected on the wall to determine the enlargement factor. The stripes on the large filter should exactly match the stripes of the focused wall image.*

The large filter is created, as is the small filter, by printing onto transparency sheets from a computer graphics program. The sheets are mounted onto a rigid frame. Additional apparatus will be required to hold the frame in the proper position during the demonstration. For instance, I built a stand that accomplishes this from leftover pieces of foam-core board, wooden toothpicks, and glue.

In preparing for the demonstration, some optical tuning is required. The lens carriage should continue to be in its uppermost position, whereas the projector will be located further from the wall in the classroom than in the above experiment. One must first ensure that the two stripe filters are in focus with each other. This step requires patience and a steady hand. Success comes when the projected image is uniformly gray and all Moiré patterns from the interacting filters have been eliminated. Next, the free-convection object is placed in the path between the small filter and the lens carriage (see Figure 2). The object is then moved relative to the lens so that the object's wall image is in focus.

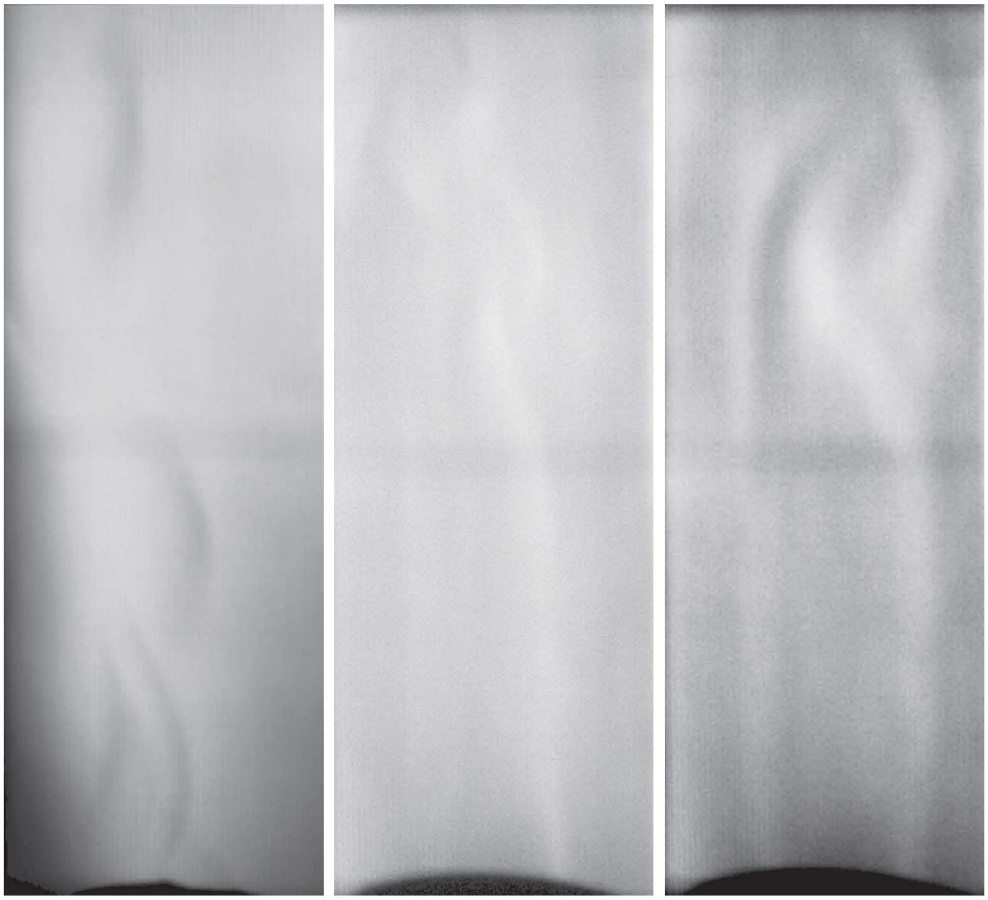

Figure 4. *Projected images of convection currents above a tea candle.*

RESULTS AND STUDENT LEARNING

High-quality schlieren images require precise construction and positioning of the optical elements. In this case, the precision is not as great as can be achieved in a laboratory, and hence the "overhead projector" method is less sensitive to density variations. For this reason, the setup here is only practical for imaging an object with large density variations, such as a flame. Figure 4 shows three images obtained of the convection currents above a tea candle. Two difficulties should be noted. First, the pictures in Figure 4 have been rotated 180°. That is, using the above setup results in a projected schlieren image that is upside down—students will have to adapt their perception to this fact. Second, careful positioning of the optical elements requires several minutes, so it is preferable to set up the demonstration in the classroom prior to the start of class. It is also a good idea to do a "dry run" during a time when the classroom is not in use.

How can this demonstration reinforce student learning of natural convection? The most obvious answer is that images (particularly live moving images) of natural convection fluid currents generate interest and excitement about the topic. In this demonstration, students are able to visualize the dynamic nature of free convection. While it is probably unrealistic in an undergraduate class to attempt a quantitative analysis of heat and mass transport for a diffusion flame,[4] the demonstration can serve as a launching point for discussion of general concepts or a review of concepts already introduced. The following questions can be posed to the class as a whole or to small groups of students:

- Why would it be more difficult to use schlieren imaging to view natural convection currents from your hand, compared to currents from a candle flame? *(Answer: The schlieren technique depends on fluid density differences, which in turn depend on fluid temperature difference. The temperature differences around a flame are much larger.)*
- How would the fluid currents around a candle flame change if the candle were inside a quiescent-air-filled spaceship orbiting the earth ? *(Answer: Natural convection depends on gravity. The convection currents would cease and the flame would be spherically symmetric. Transport of reactants, products, and heat will be due to diffusion and conduction only.)*
- Discuss your observations concerning the transition from laminar to turbulent flow in the boundary layer around a lit candle. What factor(s) seem to affect the behavior of the transition? *(Answer: Students should observe that the transition position varies in time. The smallest hydrodynamic disturbances, such as air currents in the room, affect the transition point and the motion of the boundary layer.)*
- Empirical correlations of natural convection treat it as a steady-state process. Comment on the validity of this assumption. *(Answer: As with the currents around the candle flame, natural convection is nearly always a non-steady-state process, particularly with the onset of turbulence. On the timescale of most heat/mass transfer problems, however, one can average the results in time to obtain reasonable heat/mass transfer coefficients.)*

The demonstration is based on the principle of schlieren imaging, commonly used to visualize variations in density of gas flows. [It} requires a few hours of preparation time but very little in materials cost, assuming an overhead projector is already available.

The qualitative understanding that comes from direct observation of phenomena can serve as a framework students can use to organize equations and quantitative problem solving. So far, I have used this schlieren demonstration only one time in my class. The students were highly interested, and I feel the demonstration and subsequent discussion were classroom time well spent.

Videos of the projected images corresponding to Figure 4 are available at Ref. 5. As an aid to readers, electronic versions of the graphics used in Figure 3 are available at the same website.

References 6 and 7 are websites for two leaders in the field of schlieren imaging, Professor Gary Settles of Penn State and Professor Andrew Davidhazy of Rochester Institute of Technology. Their sites contain a number of beautiful schlieren images of natural convection that can complement the live demonstration and lead to further discussion of how dimensionless numbers and empirical correlations relate to students' observations of natural convection currents.

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