Infrared Imaging for Inquiry-Based Learning

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Based on detecting long-wavelength infrared (IR) radiation emitted by the subject, IR imaging shows temperature distribution instantaneously and heat flow dynamically. As a picture is worth a thousand words, an IR camera has great potential in teaching heat transfer, which is otherwise invisible. The idea of using IR imaging in teaching was first discussed by Vollmer et al. in 2001.[1-3] IR cameras were then too expensive for most schools. Thanks to the growing need of home energy inspection using IR thermography, the price of IR cameras has plummeted and they have become easy to use. As of 2011, the price of an entry-level handheld IR camera such as the FLIR I3 has fallen below $900 for educators. A slightly better version, FLIR I5, was used to take the IR images in this paper. As easy to use as a digital camera, the I5 camera automatically generates IR images of satisfactory quality with a temperature sensitivity of 0.1°C. The purpose of this paper is to demonstrate how these affordable IR cameras can be used as a visualization, inquiry, and discovery tool. As the price of IR cameras continue to drop, it is time to give teachers an update about the educational power of this fascinating tool, especially in supporting inquiry-based learning.

Science experiments

In the following sections, we will describe how IR imaging can be used to teach basic mechanisms of heat transfer in a vivid way that may not have been done before in the classroom. These experiments are all easy to implement. As the goal of these experiments is to help students rapidly acquire a conceptual understanding, quantitative analysis of IR images is not required.

• ***Seeing conduction:*** Figure 1 shows a heat conduction experiment. An aluminum strip and two cardstock strips were laid out on a foam board base, as schematically illustrated. A piece of paper covered up the aluminum and cardstock strips entirely. The assembly was taped together tightly to ensure good contacts. A hot water jar was placed at different locations on top of the paper to heat the system up and then removed for IR imaging. In the contact area between the bottom of the jar and the cover paper, heat diffused into the aluminum and/or cardstock strips underneath and in turn warmed up the cover paper above them as it spread out. An IR image of the cover paper shows how heat flowed beneath it. The difference in emissivity between aluminum and cardstock is not an issue, since the IR radiation that reached the IR camera was emitted from the cover paper.

In one experiment, the jar was placed above the center of the aluminum strip to warm it up. The IR image taken after the jar was removed clearly reveals the shape of the underlying aluminum strip, indicating that heat conducted quickly in the metal [Fig. 1(a)]. In another experiment, the jar was above a cardstock strip. The IR image shows a circular area of concentrated heat slightly larger than the cross section of the jar, indicating that heat conducted slowly in cardstock [Fig. 1(b)]. In a third experiment, the jar was placed at such a position that half of it sat above the aluminum strip and the other half above a cardstock strip. An interesting pattern emerged [Fig. 1(c)]. This pattern shows a direct comparison of heat conduction through the two different materials.

The educational effect of these experiments may be enhanced by using a predict-observe-explain pedagogy. Students can first predict what will happen, then do an experiment, and then explain the observed phenomena. This activity can also be made more exploratory by using aluminum and cardstock strips of different shapes, covered by a piece of dark paper, and having students discover the locations and shapes of the aluminum strips.

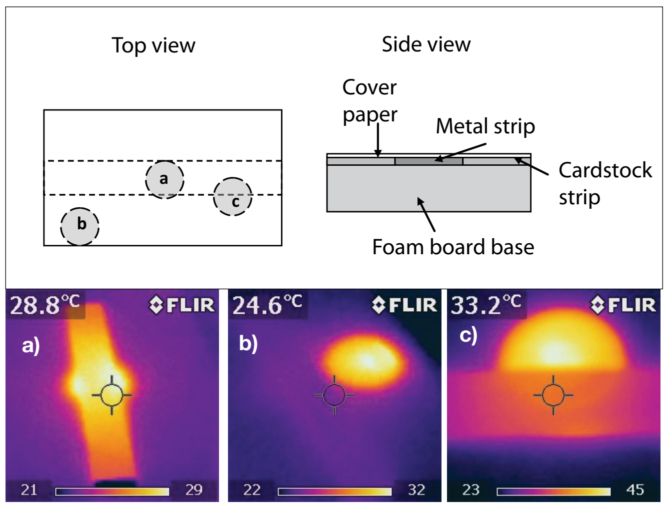

Fig. 1. Using an IR camera to visualize heat conduction on a plate consisting of areas with different thermal conductivities. A hot water jar was used as the heat source and then removed for observation in three cases: (a) The jar was placed above the center of the metal strip, (b) the jar was placed entirely above a cardstock strip, and (c) the jar was placed half on the metal strip and half on a cardstock strip. The IR images were taken immediately after the jar was removed. Image (c) is a close-up. The emissivity factor of the camera was set to 0.8. In an IR image, the number at the upper-left corner is the temperature of the spot to which the crosshair points (it acts like an IR thermometer). The numbers at the bottom are the lower and upper bounds of the temperature. The IR camera automatically sets the bounds based on the lowest and highest temperature it detects in the view. These images use the "Iron" color palette of the FLIR I5 camera (see the heat map bar at the bottom of each image for a reference).

• *Seeing convection* Air convection cannot be seen directly because air is invisible, but it can be visualized using an IR camera if the heat can be captured. Figure 2 shows an apparatus in which a rotatable screen can be used to "intercept" rising heat from different angles. When the screen is upright above a heater, the rising hot air will warm it up and create a trace of convection that can be seen through an IR camera. A light bulb can be used as a heat source. In order for most of its energy to be used to drive the air convection, one can wrap it with aluminum foil that has low emissivity, thus minimizing heat transfer through radiation. For the heating effect to show up quickly on the screen, it should have low heat capacity. For example, a piece of thin paper or a sheet of fine fiberglass or nylon wire mesh can be used to make the screen. Fine wire mesh might be a better choice as it can heat up and cool down more quickly—it has larger surface area exposed to the air. A wire mesh screen also lets air through, thus reducing its obstruction to the convection flow.

Students can rotate the screen to take different "slice views" of three-dimensional flow field. For example, what will the IR image look like if the screen is rotated to be horizontal? Students can move the heater around or adjust the power output of the heater to see changes in the convection pattern. They can also add structures to the screen to see how the air flow is affected.

• *Seeing radiation* IR imaging is naturally the method of choice for studying radiative heat transfer, because objects at room temperature emit radiation in the IR range. Since

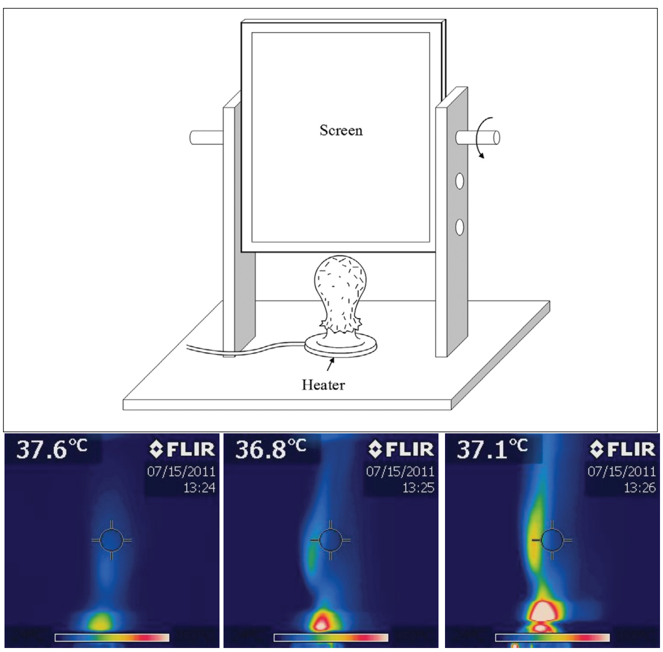

Fig. 2. Visualizing the natural convection of air. Top: an apparatus for taking a "slice view" of the three-dimensional temperature field by intercepting heat with a rotatable screen. Bottom: a sequence of IR images that shows the rising heat plume. These images use the "Rainbow" color palette of the FLIR I5 camera. The temperature range is 24°C -100°C.

thermal radiation goes both ways between two objects, the radiative heat transfer is the net flux of radiant energy from one to the other. The reason why we feel cold when facing a cold object is because the human body radiates more energy to the cold object than the cold object to the human body. This is often not intuitive to students. To help students gain a better understanding of this heat transfer mechanism, we have designed an experiment that allows them to capture the effect of invisible thermal radiation.

The experiment uses a "radiation projection screen," depicted in Fig. 3(a). The screen is simply made of a piece of paper. The radiative heat transfer occurs between a jar filled with hot (~70°C) or cold (~5°C) water and the paper screen. Because the screen is thin, radiant heat will be conducted to the other side quickly. To avoid getting direct radiation from the jar, students should take IR images of the back side of the screen. The radiative heat transfer can be stopped by wrapping a piece of aluminum foil around the jar. This experiment works best for a tag team. One student monitors the IR view of the backside while the other adds and removes the foil.

The difference between Figs. 3(c) and 3(d) is due to the net thermal radiation flux from the hot water jar to the paper screen [(d) was taken a few seconds after the jar was wrapped with aluminum foil]. The difference between Figs. 3(e) and 3(f) is due to the net thermal radiation flux from the paper screen to the cold water jar [(f) was taken a few seconds after the jar was wrapped]. The dramatic differences clearly show the effect of radiative heat transfer.

The result in the case of the hot water jar is easy to understand, but the result in the case of the cold water jar is somewhat counterintuitive. One might expect to detect nothing significant from the cold water jar because it emits much less thermal radiation according to Boltzmann-Stefan's law. Why should this "shortage of radiation" show up on the screen then? The answer lies in the fact that IR radiation behaves just like visible light. There is always ambient IR radiation in the room, just like ambient visible light. The cold water jar somehow "blocked" the background radiation from reaching the screen, just like it would cast a shadow on the screen with visible light. When it was wrapped by aluminum foil that has low emissivity and high reflectivity, the ambient radiation got bounced off from the foil and was able to reach the screen.

• *Seeing latent heat* This simple experiment involves only a cup of water and a piece of paper. If we leave a cup of tap water in a constant-temperature room for a few hours, the water will appear to be slightly cooler than the room temperature because of the evaporative cooling effect. Exactly how much cooler depends on the humidity of the room, which varies from season to season and location to location, as well as the ratio of the surface area to the volume of the water in the cup.

Now, let's put a piece of dry paper on top of the cup of water [Fig. 4(a)]. Many people would expect to see a cooling process. But the result is exactly opposite. The part of the paper above the cup warms up immediately after the paper is placed.

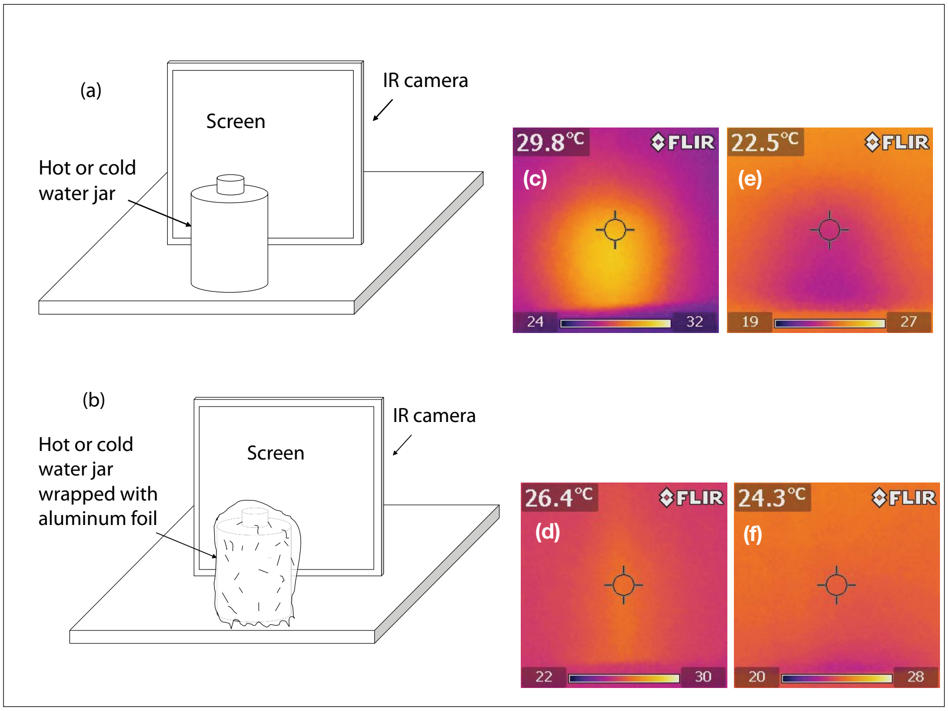

Fig. 3. (a) A hot/cold water jar was placed in front of a piece of paper used as the "radiation projection screen." All the IR images (c–f) were taken from the other side of the screen. (b) The jar was wrapped with aluminum foil. (c) A warm area emerged after a hot water jar was placed. (d) The warm area became insignificant after the hot water jar was wrapped. (e) A cool area emerged after a cold water jar was placed. (f) The cool area became insignificant after the cold water jar was wrapped.

Depending on the experimental conditions (e.g., humidity, room temperature, etc.), the temperature of the area could rise more than 1°C [Fig. 4(b)]. To make sure that this effect is not an artifact from the IR camera, we confirmed the result using a fast-response surface temperature sensor from Vernier, which measured at least 0.6°C of increase consistently under the same experimental conditions as those for Fig. 4 results.

Our theory is that this phenomenon is caused by the condensation of water vapor from the cup onto the underside of the paper. When the water molecules in the vapor condense, they release heat. The heat is quickly conducted through the thin paper and shows up on the other side. The amount of water molecules condensed on the paper is so tiny that we can hardly feel any moisture, but it is enough to result in a temperature increase that is picked up by the IR camera.

This heating mechanism can be confirmed by leaving the paper above the cup for a minute until it reaches thermal equilibrium with the environment [Fig. 4(c)]—in which case the temperature becomes the same as the ambient temperature—and then removing it. IR imaging of the paper shows that the temperature of the originally heated circular zone fell below the ambient temperature immediately after the removal [Fig. 4(d)]. This can only be explained by the fact that the water molecules that had condensed to the underside of the paper began to evaporate, resulting in the quick cooling of the paper. If we leave the paper on the cup for a while and then shift it a little bit, Fig. 4(e) is what we would see. The image shows the condensation and evaporation occurred at the same time in different parts of the paper, resulting in warmer and cooler zones with an overlap area that was still in thermal equilibrium. The heating stops [Fig. 4(c)] because water molecules have to evaporate from the condensate layer as well, and when the evaporation from that layer and condensation onto that layer reach dynamic equilibrium, no net heat is released anymore. Furthermore, it seems that the water molecules condensed to the paper had not been able to permeate through the paper; otherwise, we would have observed evaporative cooling on the other side of the paper. Approximately how thick was the condensed layer of water? The following Fermi calculation will give us some clue.

The thermal energy needed to raise 1°C for an area of the size of a cup on the paper is:

$$\Delta Q = \rho_{\text{paper}} \pi R^2 c_{\text{paper}}$$
$$= 80 \times 3.14 \times 0.05^2 \times 1.336 \text{ J}$$
$$= 0.84 \text{ J}.$$

The area density of typical printer paper is 80 g/m^2. The specific heat of

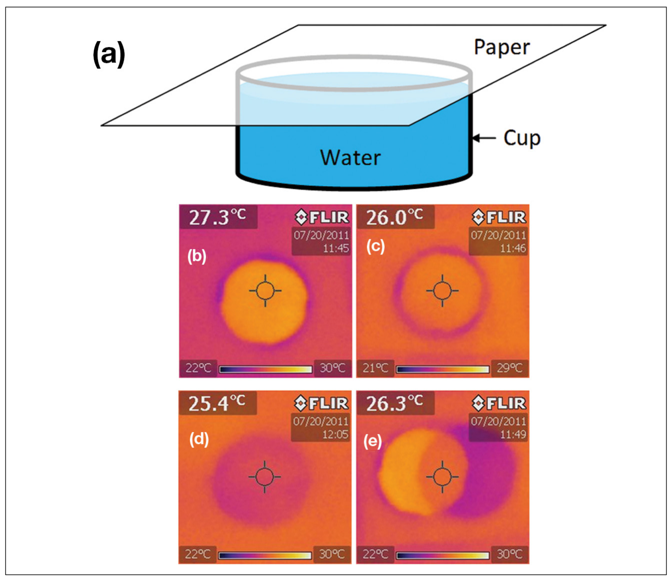

Fig. 4. Visualizing latent heats of condensation and evaporation. (a) The experimental setup is as simple as placing a piece of paper above a cup of water. (b) Shortly after a piece of paper was placed on top of the cup, the part of the paper above water warmed up. (c) A minute later, the temperature of the paper became the same everywhere. (d) The paper was removed from the cup and the area immediately cooled down. (e) IR imaging shows that part of the paper warmed up and part of it cooled down when it was shifted. All four IR images were shot from the top. The perimeter appeared to be cooler due to the heat conduction through the edge of the cup when the paper was on top of it (because water in an open cup is always slightly cooler than room temperature due to the evaporative cooling effect).

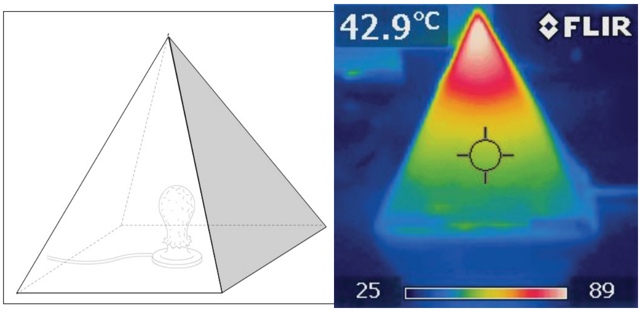

Fig. 5. An experiment that shows a possible "heat concentration" effect in a pyramid when a heater (a 40W light bulb) was placed on the floor inside to heat it up.

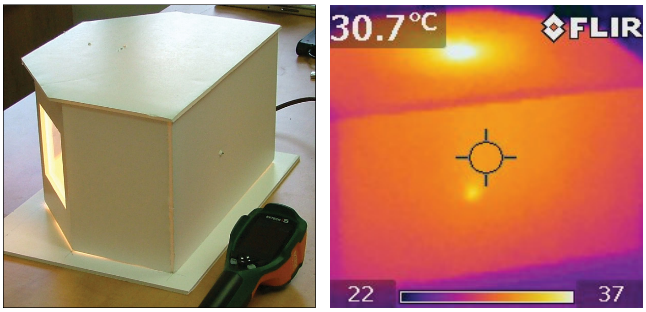

Fig. 6. Demonstration of thermal bridging. A short nail was inserted into the back wall of a heated scale model house, shown on the left, to create a thermal bridge. The IR image on the right shows heat loss through it (the lower bright spot).

water is 1.336 J/(g×°C). Assume that the diameter of the cup is 10 cm (the area is not important in the calculation of the thickness as it will cancel out later—in theory, this phenomena has nothing to do with the diameter of the cup).

The latent heat of condensation of water at 25°C is estimated using the following empirical cubic function[4]: $L(T) = -0.0000614342 \times T^3 + 0.00158927 \times T^2 - 2.36418 \times T + 2500.79 \approx 2442$ J/g. Suppose all the latent heat is used to heat up the paper. The water condensed to the paper is, therefore, estimated to be $0.84/2442 = 3.44 \times 10^{-4}$ g. This seems about right—a cup of water evaporates approximately 6 g per day, or 7×10^{-5} g per second, in a typical office in Northeastern U.S. in winter. Since 1 g of water occupies 10^{-6} m^3 of volume, this means the total volume of water condensed to the paper is 3.44×10^{-10} m^3.

The molar mass of water is 18 g/mol. So the average volume of a single water molecule is $18/6.02\times10^{23}\approx3\times10^{-29}$ m^3, which corresponds to about 3.1×10^{-10} m wide assuming all the directions are equivalent. For a circular area with a diameter 10 cm, the volume of a monolayer of water is: $3.1\times10^{-10} \times 3.14 \times 0.05^2$ $m^3 \approx 2.43\times10^{-12}$ m^3. Hence, the total number of monolayers is $3.44 \times10^{-10}/(2.43\times10^{-12}) \approx 140$, which is to say that the condensate is about 40 nm thick. Considering all the heat is not released at once, the rate of vapor deposition is probably a few nanometers per second. Behind what the IR camera captured in this experiment could actually be a nanoscale process, similar to the atomic layer deposition technique widely used to grow thin films and nanostructures.

Of course, this estimation does not take into account the roughness and porosity of the paper surface, which could result in complicated adsorption and permeation of water molecules that may affect the deposition process.

•Could thermal energy be concentrated? This experiment poses an interesting question: could thermal energy be "focused?" Some argue that thermal energy cannot be "concentrated" due to its diffusivity. We investigated the natural convection pattern in a pyramid, as shown in Fig. 5. When heated by a 40W light bulb from the inside for 10 minutes, the temperature at the tip can reach higher than 100°C—enough to boil water.

The IR image in Fig. 5 shows that the top of the pyramid recorded the highest temperature. One can argue that this is purely due to the natural convection effect—hot air keeps rising to the top to keep it the hottest. At the same time, the tip is losing thermal energy to the outside. Two factors related to the particular geometry of the pyramid suggest that there might be some kind of "heat concentration" in it. First, from the inside, the gradually narrower space towards the top of the pyramid provides a mechanism to "select" the hottest air molecules to rise to the tip. Second, from the outside, the gradually reduced surface area towards the top of the pyramid decreases the heat loss area. We theorize that due to the combination of these two effects, the temperature at the tip of the pyramid could reach a high value, suggesting a possibility of "focusing heat" using a particular shape.

Engineering projects

IR imaging could be a great problem-solving tool for engineering design. A good activity is to have students construct model houses that can be used as laboratories for conducting various heat transfer experiments and relate them to real building applications. In this section, we will present a few projects that can be used in the engineering classroom.

•Insulation and thermal bridges Insulation of a house can be compromised by some constructional components in the structure of a building known as thermal bridges. A simple type of thermal bridge is formed when a conductive material connects an otherwise insulated house to the environment (e.g., a metal stud), reducing the effectiveness of the insulation.[5]

Figure 6 shows an experiment that demonstrates the concept of this type of thermal bridging. A light bulb is placed inside a model house to heat it up. On one of its walls, push a nail or screw through the wall from the inside. After running the experiment for a few minutes, an IR camera easily catches the thermal bridge.

•The difference between the weather shell and the thermal envelope In building science, weather shell and thermal envelope are two different concepts students often have troubles with, because they are not always the same. Their differences can be shown by comparing the IR images of the very same model house with and without a ceiling. When

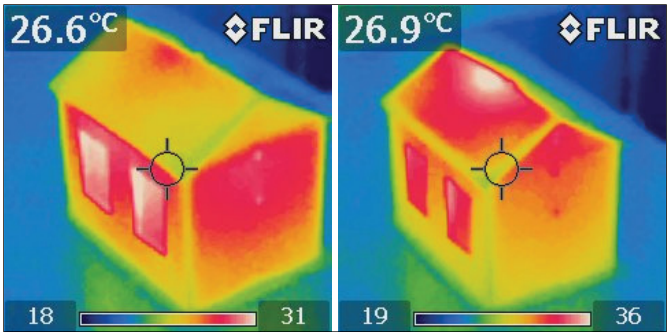

Fig. 7. Using an IR camera to reveal the thermal signature of a simple model house heated by a light bulb inside it. Left: a model house with a ceiling. Right: a model house without a ceiling.

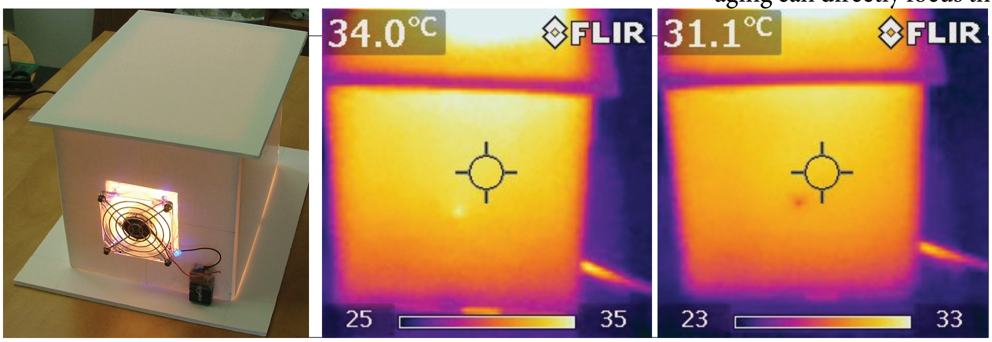

Fig. 8. A blower-door test for a model house. Left: a computer fan was fit into a square opening on the wall of a model house heated by a light bulb inside. On the opposite wall, a small hole was punched to simulate a crack. Center: an IR image taken when the fan was off reveals exfiltration. Right: an IR image taken when the fan was on reveals infiltration.

there is no ceiling, the IR image shows the weather shell is the thermal envelope (the right image in Fig. 7). When there is a ceiling, the IR image shows the weather shell is larger than the thermal envelope (the left image in Fig. 7).

•Infiltration, , and a blower-door test

In building science, infiltration is the introduction of outside air into a building through small holes and cracks in the building envelope. The opposite process, the leakage of inside air to the outside environment, is called exfiltration. To achieve energy efficiency, both need to be controlled.

Small holes and cracks cannot be easily found by visual inspection. But a standard energy inspection procedure called the blower-door test can reveal them. A blower door consists of a fan that blows air out of a house and thus creates a negative pressure inside the house. Air from the outside will then be sucked into the house through small holes and cracks. If the outdoor temperature is lower than indoor temperature, the defects will show up as cooler in an IR view. By scanning the house using an IR camera, an inspector can identify all the leakages.

Figure 8 shows an experiment of a blower-door test using a model house and a computer fan. The IR images show the air leakage spot. The fan can be connected to a dimmer switch to control its speed, thus allowing students to investigate practical questions such as how much the pressure difference should be set in order for the hole to show up clearly in the IR image.

Summary

This paper shows that IR imaging can be used to demystify all the mechanisms related to heat transfer and provide rich learning and exploration opportunities for students that would otherwise be infeasible or cost too much time. An IR image provides a lot of information about an experiment that can be rapidly recognized and absorbed by the human brain. Salient, real-time thermal visualizations of invisible heat flow make the underlying concepts "speak for themselves" and can potentially offer superb laboratory experiences to students. What an IR camera can show and tell in no time would take students hours using traditional tools such as thermometers or sensors. By liberating students from laborious work, IR imaging can directly focus them on core science.

The application of IR imaging is not limited to the examples given in this paper. If the heat flow is driven by some underlying physical, chemical, or biological process, IR visualization may help uncover it.[6] In a way, the universality of heat lends itself to the versatility of IR imaging. By providing students with real-time visualizations of real-world processes, IR imaging opens a new avenue for science and engineering education.

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