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Invisibility Cloaks and Hot Reactions: Applying Infrared Thermography in the Chemistry Education Laboratory

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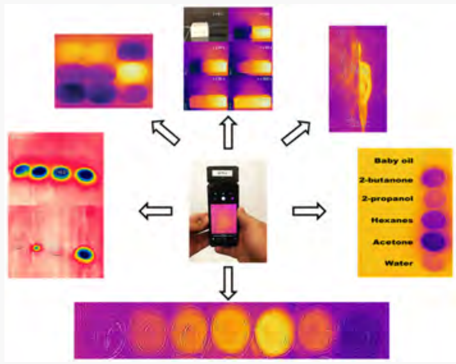

ABSTRACT: Infrared (IR) thermography renders invisible infrared radiation with intuitive coloration in images and videos taken of objects, reactions, and processes. Educators can take advantage of this technology to extend students' sensory perception of chemical reactions or processes that absorb or release heat in rich detail. In theory, IR thermography can be applied essentially universally for such analysis given that any change in thermal energy must result in, or from, the change of potential energy due to the interactions among atoms, molecules, and photons. Through the use of IR thermography, students can visualize otherwise invisible evidence of what is occurring on the molecular level in a variety of chemical process such as evaporative cooling, phase change, dissolution, titration, and enzymatic reactions. While not new, IR cameras are rapidly becoming affordable with models that connect easily with smartphones and tablets. The price decrease has opened the door for large-scale implementation in the chemistry education laboratory. We report here several laboratory activities and best practices that will facilitate the exploration of specific chemistry concepts through the use of infrared thermography, as well as integration of this technique into existing general chemistry laboratory courses.

KEYWORDS: *First-Year Undergraduate/General, Laboratory Instruction, Inquiry-Based/Discovery Learning, Laboratory Equipment/Apparatus*

INTRODUCTION

Chemical Indicators in Chemistry

Indicators are fundamental tools in chemistry because they provide a visible response to an otherwise invisible chemical or physical process.[1] Among the earliest recorded proponents of indicators was Robert Boyle, who is most widely known for his work on the relationship between the pressure and volume of gases. Robert Boyle also systematically employed indicators including color-changing (pH-sensitive) vegetable juices in a seminal classification of substances that we now understand to be acidic, neutral, or alkaline.[2,3] The role that indicators played in the work of a founding figure in modern chemistry underscores their importance in the scientific approach to study chemical and physical phenomena.[4] Scientists now rely on indicators that have been developed to respond to myriad processes, exemplifying their ongoing role in scientific inquiry. While there is considerable diversity among indicators in use, the general properties of good indicators include reacting quickly and stoichiometrically to produce a visible (or physically measurable) entity in response to the chemical or physical process of interest. Current indicators usually rely on visualization of products or reactants, often through a color change associated with either generation of products or loss of reactants.

An alternative to monitoring chromophore-based indicators as a proxy for reaction progress involves detecting heat transfer inherent to the reaction itself. The essence of this idea led to the development of calorimetry and related enthalpimetric techniques that rely on precise measurement of the heat evolved or absorbed by a system during the reaction or process of interest itself. Heat, either absorbed or released, is after all a stoichiometric product of chemical reactions and physical processes themselves. Therefore, monitoring heat represents a quantitative and versatile strategy to track the progress of reactions given that the total heat from any reaction or process is a product of the molar enthalpy change of the reaction and the number of moles produced

$$q = n_p \Delta H_r \tag{1}$$

where q is heat, n_p is the moles of product generated, and ΔH_r is the molar enthalpy of the reaction (i.e., this implies the reaction or process occurs under conditions of constant pressure).[5,6]

Monitoring heat is appealing because it involves detection of an inherent, and essentially universal, component of any reaction. In principle, reactions can be analyzed without

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requiring the use of exogenous indicators, which could also notably be applied to optically-dense mixtures or other samples that are not amenable to traditional indicator modalities.[5]

There is, however, an ironic disadvantage with utilizing "heat" as an indicator. The greatest strength of this strategy is also a potential weakness: Any and every reaction that involves a change (transfer) in energy will contribute to the measured change in temperature. Thus, it is important to account for every reaction that is occurring, which, for example, may not only include secondary or "side reactions", but also sample evaporation, heat dissipation to the surroundings, heats of dilution, etc.[5] A more restrictive problem is that the instrumentation required for monitoring changes in enthalpy during a reaction is typically dedicated to a single sample, which has tempered enthusiasm because of the inherently low throughput. An important challenge then is to be able to accurately and simultaneously record heat transfer occurring in multiple samples undergoing reactions or physical processes of experimental interest.

Infrared Thermography: An Increasingly Accessible Laboratory Tool

Infrared thermography is a form of imaging based on detection of infrared radiation, typically in the ∼7000−14,000 nm wavelength range. The resulting images, called thermograms, are false-colored to represent the IR radiation as thermal radiation, for which the peak emission occurs with an energy that depends on the temperature of the object.[7] While IR thermography is not new, the available technology has undergone rapid price drops with expanding availability in recent years. Multiple vendors now offer affordable (<$200) hand-held or smartphone-compatible devices suitable for IR thermography.

Importantly, IR thermograms can be used to estimate the temperatures of multiple objects in the field of view. For example, the FLIR One Pro used in this study captures IR thermogram images with a resolution of 160 × 120 pixels, meaning the rendered thermogram contains information from 19,200 microsensors. IR thermography has been applied in numerous contexts including materials analysis,[8,9] various medical evaluation procedures,[7,10] crop phenotyping,[11] and detection of bacteria,[12] and in strategies for low-cost, high-throughput enthalpimetric analyses.[13−16] The flexible application of IR thermography brings to light several key features that, as we have discussed in prior work,[17] represent unique affordances with the potential to enhance learning of fundamental chemistry concepts by students: (i) accelerated data collection arising from the ability to capture the temperatures of multiple objects in real time, (ii) visual feedback for the user rendered with intuitive coloration, and (iii) capture of thermal data that are correlated over time and space (i.e., the ability to visualize temperature gradients across samples and their changes over time that would be difficult to record with single-point thermometers).[17] IR thermography has been used in educational settings, especially in physics coursework, as an introduction to light−matter interactions and heat transfer.[18−22] Notably, a recently published article also describes the use of IR thermography to explore various reactions and processes in support of chemistry education.[23] Here, we discuss expanding on both these modules and our previous work[17] to create more quantitative chemistry lab-focused activities that can be easily integrated into a traditional lab curriculum.

The following examples demonstrate versatile applications of IR thermography to study different chemistry phenomena through visualization of heat transfer during the salient reaction or process. These examples are meant to illustrate how IR thermography could be applied as a standard tool in the chemistry laboratory, including using the IR camera for investigations of colligative properties, phase change, enthalpies of solution, evaporative cooling, titration, and enzyme kinetics. We expect visualization of heat transfer in these contexts to have the same positive influence on student learning as visualization-supported inquiry activities with simulations that have been shown to improve student outcomes on standard conceptual chemistry exams.[24]

Opportunities in Chemistry Education

The primary opportunity to impact education and inquiry will be realized by exploiting the unique affordances of IR thermography to complement existing chemistry lab curricula. In particular, IR thermography "...significantly lowers the technical barrier of experimental skills..."[17] for analysis of experimental subjects, simply by providing the user with an intuitively colored image that is rich with evidence of how heat is being transferred across an object and through time. Imaging multiple objects in the same field of view accelerates data collection and provides the means to distinguish subtle variations in side-by-side comparisons. Furthermore, IR thermography is ideally suited to analyze temperature gradients or "thermally heterogenous" samples as exemplified by the simple case of heat transfer between two aluminum blocks depicted in Figure 1 (details of the experimental setup,

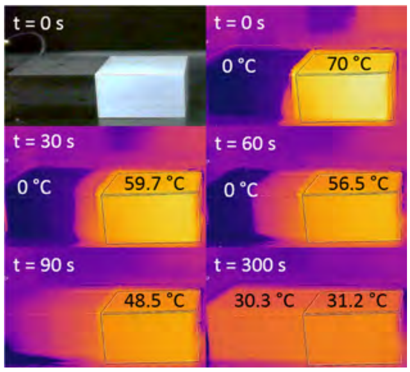

Figure 1. Two aluminum blocks depicted in the top-left visible-light image were cooled to 0 °C (black/left block) and heated to 70 °C (white/right block), respectively. The blocks were placed in contact and imaged every 30 s for 5 min to visualize transfer of heat between the two blocks.

procedures, and considerations for this and all following activities can be found in the Supporting Information). The time-lapsed thermograms clearly depict the entropy-driven "thermal diffusion" that governs heat transfer from one mass to another with detail that could not be replicated using one, or even many, single-point thermometers or sensors.

In light of the ease with which a user can obtain information-rich thermographic data, IR imaging is well-suited to instructional strategies that emphasize iterative, student-based inquiry. With a simple side-by-side comparison of "experimental" and "control" samples, IR thermography can expose the user to subtle processes that are otherwise invisible, and thus commonly overlooked. IR thermography facilitates both initial inquiry and engagement, as well experimental follow-through due to the ease of data acquisition, a notion recognized previously and referred to as "instant inquiry".[25] With low technical and logistical barriers for experimental analysis, IR thermography is thus well-suited to iterative cycles of observation, modeling, and experimentation,[26] which underlie several pedagogies including the model−observe−reflect−explain (MORE) thinking frame[27] and the predict observe explain (POE) teaching sequence.[28] In the following sections, we present experimental design considerations and introduce diverse examples of activities that address several fundamental concepts in chemistry education.

■ IR IMAGING DEVICE AND EXPERIMENTAL CONSIDERATIONS

The thermograms presented in this work were captured using a FLIR One Pro, which is a smartphone plug-in device available for use with both iOS and Android platforms (available from the manufacturer's Web site for $400 at the time of publication). These devices require an app to generate images and temperature measurements. We used both a free app produced by FLIR called "FLIR One", as well as a $10 app produced by Vernier called "Thermal Analysis Plus". Both apps have the ability to record the temperatures at several user-defined points or averaged regions in the field of view. Video recordings of an experiment allow the user to change the position of the on-screen thermometers ad hoc, which affords great flexibility in data collection and subsequent analysis. One advantage of the Vernier app is that it also produces an on-screen plot of the temperature vs time data recorded for user-defined points (or averaged regions), and the data can be easily exported by e-mail in .csv format.

How Is Temperature Measured?

IR imaging devices measure IR radiation emitted by objects in the field of view in order to estimate temperature. This idea is based on the principle of black body radiation that posits that objects emit electromagnetic radiation according to their temperature (objects at temperatures below 500 K mainly emit in the infrared regime).[7] The devices are calibrated to estimate the temperature of objects in the field of view based on the IR signal and, in the case of the FLIR One Pro, are accurate to ±3 °C according to the manufacturer's specifications. One of the factors that can affect accurate temperature estimation is dependent on an object's emissivity, which is a parameter that describes how effectively an object emits infrared radiation. Perfect blackbody emitters (flat, nonreflective surfaces) have an emissivity of 1.0, whereas the opposite extreme includes perfect reflectors (emissivity of 0.0). Importantly, objects characterized by low emissivity (e.g., shiny or reflective surfaces) exhibit weaker IR emission, and their temperatures are therefore *underestimated* by IR imaging devices. This phenomenon is well-illustrated by a "Leslie cube" (Figure 2[29]), which is a hollow aluminum block prepared with painted (high emissivity) or polished (low emissivity) sides. When the temperature of the Leslie cube is measured using IR imaging, the different surfaces of the cube falsely appear to be different temperatures due to differences in their respective emissivities. When analyzing samples using these cameras, the user should be cognizant that different surface or material properties will affect the apparent temperatures reported by IR imaging devices. Perspective angles should also be taken into consideration, e.g., to avoid shallow angles subject to undesirable specular reflection. The emissivity values for many materials and substances can easily be found tabulated on the Internet and used to adjust emissivity settings in the FLIR and Vernier apps if desired.

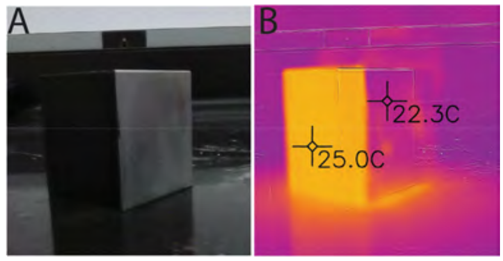

Figure 2. (A) A Leslie cube is a hollow aluminum block filled with heated water to ensure uniform temperature. (B) When imaged using an IR camera, the matte black painted surface *appears* warmer than the adjacent shiny (unpainted) surfaces.

What Can Be Imaged with IR Imaging Devices?

IR imaging cameras are easy to use for imaging a wide array of objects. However, one other caveat arises from the fact that these cameras are sensitive to infrared radiation in a limited range (a 7,000−14,000 nm range reported for the IR cameras used here). As a result, certain IR imaging devices cannot "see" through most glass or many types of plastic, which means we had to think creatively about the use of containers or sample holders in our experiments. Interestingly, common "grocery bags" (typically high-density polyethylene), or even thin trash bags are largely transparent to IR radiation and can be effectively used as IR-transparent "windows".

It is also important to consider the immediate environment when measuring the temperature of objects over a period of time. The IR imaging cameras we used are sensitive enough to demand attention be given to factors such as air currents that can alter cooling or warming of samples (e.g., from unchecked building HVAC system airflow) and also reflection of the operator's body heat onto samples. We often used a matte cardboard trifold poster board situated under a shelf (to limit air currents) in order to create a uniform background for imaging experiments. Inexpensive smartphone tripods work well to support and orient the IR camera during experiments (Figure 3).

Device Performance

The IR imaging cameras we used did exhibit some accuracy and precision performance issues. We compared the accuracy and "stability" of the temperature readings reported by two FLIR

Figure 3. A matte cardboard trifold poster board was used (left) to create a uniform background for imaging experiments using the FLIR One Pro and a smartphone tripod (right).

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One Pro cameras (iOS and Android models) with a contactless IR thermometer (Figure 4). Both instruments were used to record the temperature of a digitally controlled aluminum heat block set to 30.0 °C (an independent thermocouple reported the actual temperature was 29.5 °C). Over a 10 min period, the FLIR One Pro exhibited greater fluctuation in the reported temperature of the aluminum heat block that appeared to coincide with automated temperature (re)calibrations that the device underwent internally. The temperature accuracy reported by the FLIR One Pro cameras was within 1−2 °C of the verified temperature setting, which is within the device tolerance specifications. More advanced thermography equipment or future iterations of these inexpensive devices may not be affected as much by these issues. Regardless, while these particular IR imaging devices are likely not the best choice for highly accurate or precise temperature measurements, they do excel at revealing subtle differences in temperature between objects in the same field of view, which indicates an important experimental design consideration to keep in mind.

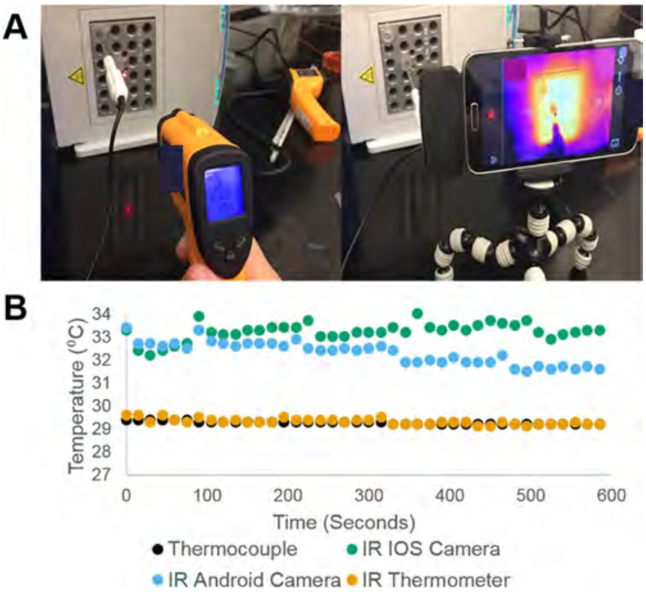

Figure 4. (A) Two FLIR One Pro cameras (iOS and Android models; right) were compared with a contactless IR thermometer (left) for temperature reading accuracy and "stability". Both instruments were focused on a digitally controlled aluminum heat block analyzed over a period of 10 min. (B) Compared to the contactless IR thermometer, the FLIR One Pro exhibited slightly greater fluctuation in the reported temperature. Accuracy for both the FLIR One cameras was also reported systematically higher, but within the device tolerance.

EXAMPLE LABORATORY ACTIVITIES

"Lab 0"

While operation of the FLIR One Pro cameras is fairly intuitive, we developed a guided exploration we refer to as "Lab 0" wherein students use the cameras to investigate a variety of objects and materials (Supporting Information). The "Lab 0" activity includes walk-throughs on how the app that is used with the camera works, and all of the ways the IR images can be annotated after being collected. This includes the addition and relocation of on-screen thermometers to extract quantitative data from thermograms as well as ways to adjust the image color palette, temperature scale, and the use of the "MSX" mode to include helpful outlines of objects overlaid onto the thermal image. In addition to the discussion of how the camera functions, students are also guided to explore the limitations of the cameras through the "IR Myth-buster", "Heat Hunters", "Reflections", and "Invisibility Cloak" activities.

Glass, mirrors, plastic whiteboards, wood, metal, plastic bags, and IR-reflective emergency-rescue thermal blankets are provided to students along with a handout to guide their investigation with practical tips for imaging these materials, e.g., demonstrations of their respective differences in reflectivity and emissivity (Figure 5). One of the goals of "Lab 0" is to teach students how to interpret what they are seeing through the camera. For example, students observe examples of how interference from reflections they may encounter can affect their results, and they also observe different materials that are transparent or opaque to IR light. This can be important if students attempt to image objects through a material that is visually transparent (e.g., plexiglass), but happens to be opaque to IR light (e.g., attempting to visualize an object behind a hood sash that *appears* clear (visible light), but is actually opaque to IR imaging (Figure 5D). Students visualize materials that reflect IR light (an "IR mirror"), and observe differences in the transmission of IR light through plastic bags compared with emergency-rescue thermal blankets with an IR-reflective coating.

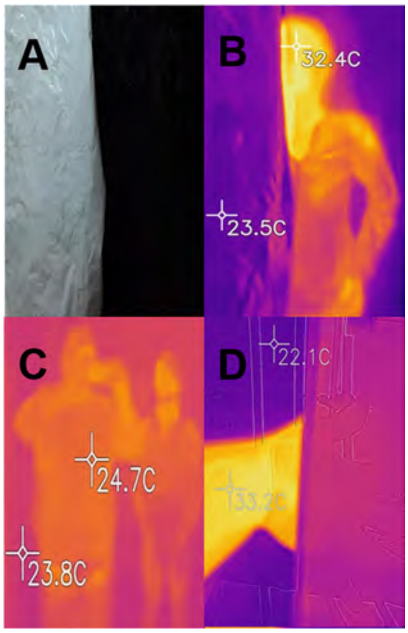

Figure 5. (A) Visible image of a human behind a reflective thermal blanket (white, left) and a trash bag (black, right). (B) IR thermogram of a human behind the same reflective thermal blanket (left) and the trash bag (right). (C) IR thermogram of heat reflection of two humans off the surface of a classroom white board. (D) IR thermogram of a hand behind a plastic hood sash showing that not all materials are IR-transparent.

Thermochemistry

An early topic that chemistry students are introduced to is thermochemistry, which includes concepts related to quantifying changes in temperature for different substances as a function of how much heat energy they absorb. Thermochemistry incorporates concepts of thermal conductivity, convection, radiation, thermal mass, specific heat, heat capacity, and

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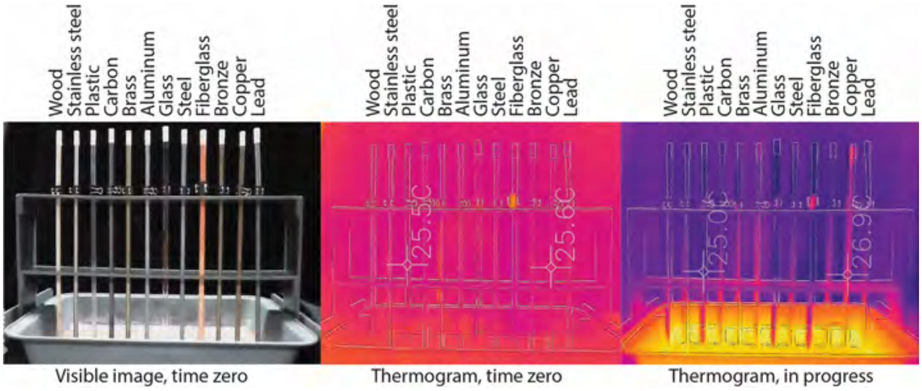


Figure 6. Multiple rods of different compositions were upended in a tray of hot water (visible image at left). An IR thermogram was collected from the rods before adding the hot water to assess differences in emissivity of the various materials (middle image). The rods were imaged again after several minutes in order to visualize the variations in the temperature distributions along the rods due to differences in the thermal conductivities of each material (right image).

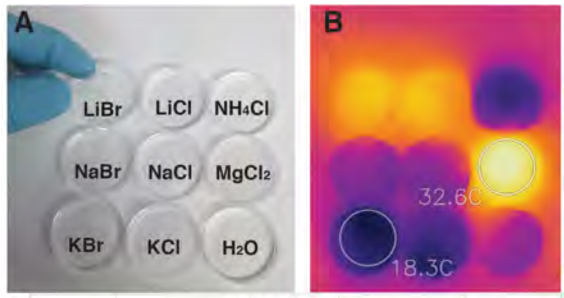
enthalpy. IR thermography offers the opportunity to "see" different temperature regions of objects and can support a more holistic view of the movement of thermal energy during an experiment. Figure 1 depicts heat transfer through time between two aluminum blocks prepared at two different initial temperatures. This simple activity could be rapidly repeated according to student inquiry about the effects of different masses (combinations of aluminum blocks differing in masses), different initial temperatures, or objects with different compositions to explore the effects of altering specific heat or heat capacity. We also captured thermograms comparing thin rods made of different materials that were placed in a warm water bath (Figure 6). The efficient heat transfer along the aluminum and copper rods, for example, reveals the reason why computer heat sinks are made of these metals, rather than fiberglass or plastic.[30]

Heats of Solution

Enthalpies of solution represents another facet of thermochemistry for which IR imaging is suited to compare or rank changes associated with dissolving ionic solids. For example, the dissolution of different alkali cations paired with bromide or chloride anions can be used in discussions of lattice energy, heats of solvation, enthalpy of solution (ΔH_{soln}), and Hess's law. Figure 7 depicts the temperature changes associated with combining 0.01 mol of eight salts with 4.0 mL of distilled water compared with a sample of water alone as a baseline (Figure 7A). The differences in temperatures that result from dissolving the eight salts are readily apparent in the IR thermogram and correspond to the enthalpies of solution reported for these ionic compounds (Figure 7 B,C).[31,32] By making the approximation that the specific heat of the solutions match that of water (4.179 J g^{-1} deg C^{-1}) and also accepting that the solutions are far from infinite dilution, one can estimate the change in temperature that each solution should undergo by calculating the heat (q) using eq 1, and solving for the expected temperature change of the solution according to eq 2:

$$\Delta T_{\text{solution}} = \frac{q}{\text{specific heat}_{H_2O} \times m} \tag{2}$$

where m is mass of the solution (approximated as 4.0 g in this case). Figure 7C shows the predicted temperature changes estimated in this way compared to the actual temperature changes measured by IR thermography. This simplified procedure does not attempt to account for heat loss to the experimental surroundings, evaporative cooling, use of concentrated solute solutions, or changes in solution heat capacity that result from ion solvation.[33,34] However, the temperature changes estimated in this way for the eight different solutions nevertheless predict the sign and relative magnitudes of the reported enthalpies of solution in all but one case. Sodium bromide is an exception; the predicted temperature change and literature ΔH_{soln} indicate the dissolved salt solution should have increased slightly in temperature, whereas a 0.4 °C decrease in temperature was observed, likely due to "heat contamination" from neighboring samples. This application of infrared thermography can help students visualize and compare



C

Substance	Temperature (°C)	Reported ΔH_{soln} (kJ/mol)	Measured ΔT vs. water (°C)	Theoretical ΔT (°C)
H_2O	22.1	0.00	0.0	0.0
LiBr	27.6	-48.80	+5.5	+29.2
LiCl	26.9	-37.00	+4.8	+22.1
NH_4Cl	19.5	+14.78	-2.6	-8.8
NaBr	21.6	-0.60	-0.5	0.4
NaCl	21.7	+3.90	-0.4	-2.3
$MgCl_2$	32.6	-160	+10.3	+95.7
KBr	18.3	+19.90	-3.9	-11.9
KCl	19.2	+17.20	-2.9	-10.3

Figure 7. (A) Shallow Petri dishes were used to dissolve 0.01 mol of eight different salts with addition of 4 mL of water to each (one dish contained water alone for comparison). (B) The thermogram of the dissolved electrolytes is consistent with the reported enthalpies of solution for the ionic solids. Note the temperature-averaged circles that were used to measure the temperature for each solution (only two examples are displayed in the thermogram for clarity). (C) Table of reported ΔH_{soln} values with measured and theoretical temperature changes for the dissolution of the various ionic solids.

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enthalpies of solution in terms of differences in magnitude (extent of color change) vs the sign of ΔH_{soln} (direction of temperature change). A recent study published by Samuelsson *et al.* discussed a related example, the deliquescence of sodium hydroxide pellets exposed to air, and reported specific affordances associated with the use of IR imaging that positively impacted students' abilities to understand and explain the phenomenon they were observing.[35] Concepts underlying enthalpy changes for these and related processes can be difficult for students to grasp. The use of IR thermography to augment sensory perception and direct attention has potential to strengthen understanding based on how students learn the topic and measures of their learning thereof.[35,36]

Evaporative Cooling

Figure 8 shows dishes filled with liquids including baby oil (a good control because it does not undergo significant evaporation), various volatile organic compounds, and water. The dishes were placed near a hood to increase the effects of evaporation, but they were initially covered and allowed to equilibrate uniformly to room temperature. Once equilibrated, the dishes were uncovered. The thermograms in Figure 8 were captured shortly after uncovering the dishes (left) and after several minutes to allow evaporative cooling to occur (right). The differences in the "initial" temperatures between the compounds may be due to slight differences in emissivity, or likely the tendency for acetone to efficiently cool due to evaporation. Regardless, after several minutes, the baby oil essentially remains unchanged in temperature, while the acetone has cooled approximately 8 °C below ambient temperature. The other compounds cooled as well to varying extents. The choice of the liquids can be made strategically to examine differences in the nature of intermolecular interactions and forces that exist in the bulk liquid, as well as the overall molecular mass of the compounds. In addition to addressing concepts of vapor pressure and boiling point, introducing solutes in the liquids would support discussions of colligative properties (i.e., altering the vapor pressure and degree of evaporative cooling as a function of solute concentration) and Raoult's law.

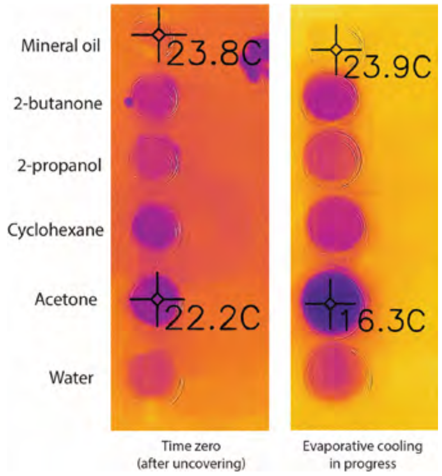

Figure 8. Glass petri dishes were filled with equal amounts of six different liquids. The dishes were covered to allow them to equilibrate to room temperature. The lids were removed and quickly imaged with an IR camera (left panel). A second IR thermogram was captured after several minutes to document the temperatures of the solutions obtained by evaporative cooling. Temperature readings embedded in the image by the FLIR One app were darkened manually for clarity (original images in Supporting Information).

Freezing Point Depression

Figure 9 shows identical trays of water that were frozen and compared by IR thermography as sodium chloride was sprinkled on the surface of one tray. The sudden drop in temperature for the tray with added salt was clearly visible according to the effect expected from adding a solute that depresses the freezing point of the water. The value of this activity is that it can lead to the cognitive conflict arising from the (incorrect) expectation that adding salt to ice favors melting due to an *increase* in temperature. Students must grapple with the striking visual evidence of a *decrease* in temperature following addition of salt to the ice on their way to constructing a more robust explanation involving freezing point depression, entropy-driven/endothermic reactions, etc. This activity can also be modified easily to illustrate related concepts including: phase transitions, examples of processes that are both spontaneous and endothermic, or the effects of adding different solutes characterized by different van't Hoff factors.

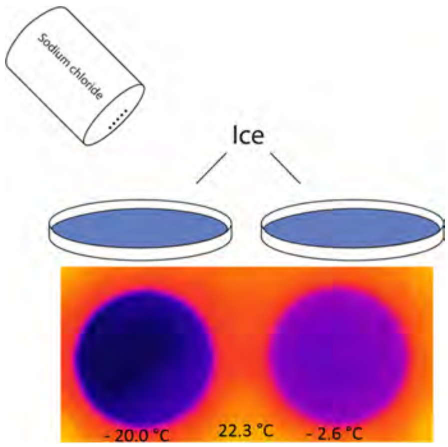

Figure 9. Sodium chloride was sprinkled on to the surface of one of two shallow trays containing ice. The resulting drop in temperature (left tray) was easily observed by IR thermography.

Phase Change

A final activity related to intermolecular forces is an extension of the freezing point depression experiment and is used to explore concepts related to phase change and estimating (or ranking) melting points based on molecular structure. Figure 10 shows four Petri dishes filled with different compounds: canola oil, olive oils of differing purities, and oleic acid that were frozen and allowed to warm while being imaged with an IR camera. Temperature data were easily extracted from videos recorded with the FLIR One app (discussed above) and plotted (Figure 10). Plateaus in the warming trends corresponded to the phase transitions (melting temperatures), which can be related to the molecular structures of the compounds. The differences in plateau time can be used to initiate discussions regarding their purity (e.g., oleic acid is a uniform small molecule whereas olive oil comprises a heterogeneous composition, mainly triglyceride esters of oleic acid, palmitic acid, and other fatty acids). In addition, molecular mass, molecular structure, and molecular packing can be related to the warming behavior of these four samples, since the plateau temperature corresponds to the melting point (e.g., −4 °C for olive oil and +13 °C for oleic acid).

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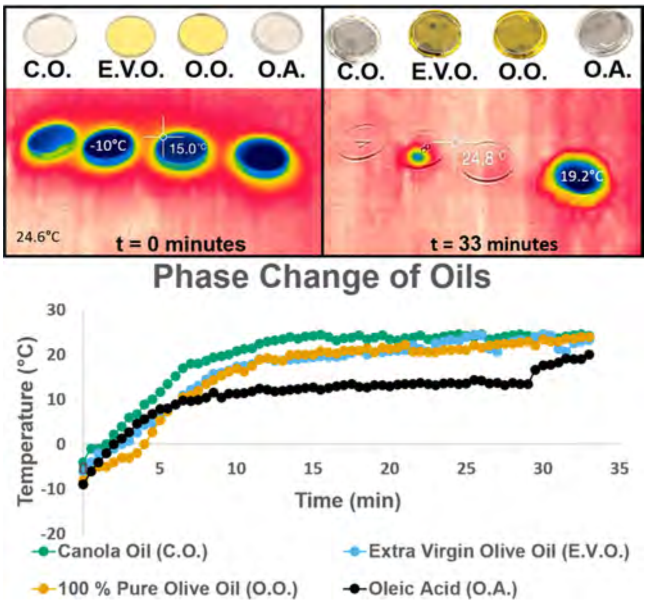

Figure 10. Four Petri dishes were filled with different oils: canola oil (C.O.), extra-virgin olive oil (E.V.O.), olive oil (O.O.), and oleic acid (O.A.) and frozen at −20 °C. The dishes were moved to the room temperature benchtop and monitored by IR thermography immediately after removal (top left) and again after approximately 15 min). The temperatures of each tray over time were plotted in Excel (lower panel).

Reactions between Acids and Bases

One of the fundamental reactions that students are exposed to is the reaction of acids and bases.[37] Acid−base neutralization is famously used in analytical titrations of unknown solutions to find the equivalence point, and these reactions traditionally use a color-changing pH indicator similar to those espoused by Boyle. As an alternative strategy for titrating acids and bases, Figure 11 shows that a thermogram taken of a series of reactions between a known base with an unknown acid solution can reveal an equivalence point. The final volume was kept the same in all reactions; however, the volumetric ratios of known base and unknown acid were systematically varied. The greatest temperature change (increase) is expected when the molar ratios of known base and unknown acid added together are equivalent (i.e., maximum number of neutralization events). Therefore, knowing the concentration and volume of known titrant added to the reaction with the greatest increase in temperature can be used to determine the number of moles of the unknown acid present. This approach touches on concepts of acid/base neutralization, equivalence points, stoichiometry, molar enthalpy of neutralization, and heats of dilution.

Enzyme Kinetics

A final example that highlights the novel capabilities of IR thermography is one where the technique was applied to track the catalytic activity of an enzyme. Catalase is a widespread enzyme in nature that accelerates the degradation of hydrogen peroxide into molecular oxygen and water.[38] The enzymatic activity of catalase was tracked as the enzyme acted on hydrogen peroxide in increasing concentrations in a buffered solution (pH 7) placed in Petri dishes. The same amount of catalase was added into each Petri dish, and the average temperature increase vs time was plotted for each reaction with increasing H_2O_2 concentrations using the Vernier app (Figure 12). A clear trend in both the magnitude of reaction temperature change, as well as the rate of temperature change, is observed and corresponds to the increase in enzyme substrate (H_2O_2) concentration. This experimental activity pertains to biological catalysis, enzyme activity, and enzyme kinetics.

■ CONCLUSIONS AND FUTURE DIRECTIONS

IR imaging provides a platform for rendering invisible and abstract concepts with intuitive visualization that has the potential to engage students with traditionally difficult material related to heat transfer, physical processes, thermodynamics, intermolecular interactions, and chemical reactions. Experiments and demonstrations can be easily implemented using a single IR thermography device to render heat as a versatile indicator. This strategy is amenable to short, modified iterations allowing the investigator to quickly and efficiently test hypotheses. IR imaging technology is rapidly becoming

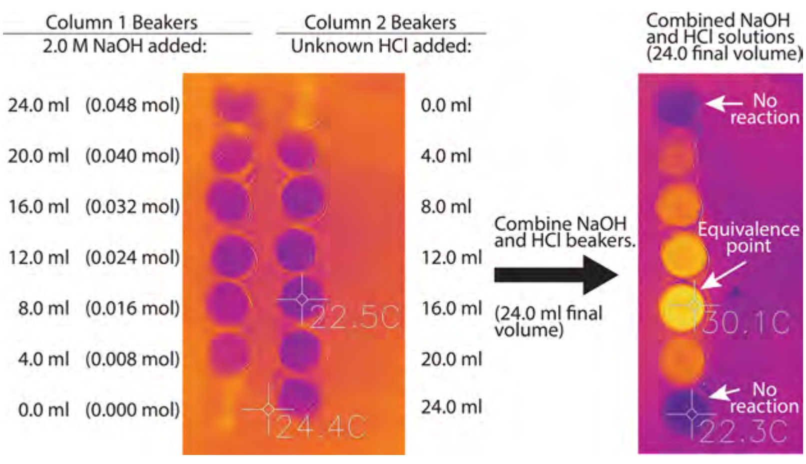

Figure 11. Two columns of beakers were prepared. Column 1 (left) shows beakers with decreasing volumes of the known titrant, 2.0 M NaOH, ranging from 24 to 0 mL. Column 2 shows beakers with increasing volumes of an HCl solution of unknown concentration ranging from 0 to 24 mL. The contents of each pair of corresponding beakers were combined (column 3, right thermogram) such that the combined volume of the known titrant and unknown sample would equal 24 mL in all cases, but with different molar ratios. The greatest heat of reaction was observed when the molar ratio of combined NaOH and HCl was 1:1, which allowed for the determination of the unknown HCl concentration given its added volume and the quantity of known NaOH titrant with which it was combined.

https://dx.doi.org/10.1021/acs.jchemed.9b00789
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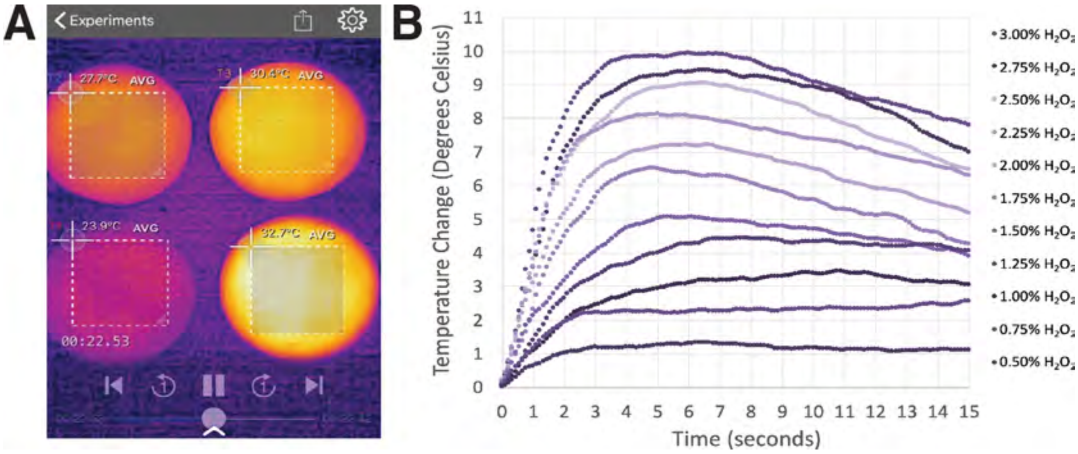

Figure 12. Petri dishes were prepared with increasing concentrations of H_2O_2 ranging from 0.50% to 3.00% (v/v). An equal volume of catalase (250 μL of 2.0 mg/mL catalase, 25 mM sodium phosphate buffer pH 7.0) was added to each dish, and the change in temperature of the solution was recorded using the Vernier Thermal Analysis Plus app. (A) Screenshot of Vernier app showing 4 dishes that contained different concentrations of H_2O_2 after addition of catalase and user-defined boxes used to collect average temperature for each dish (dashed boxes). (B) Data recorded for multiple H_2O_2 concentrations were normalized to plot temperature change vs time for each substrate concentration to monitor enzyme activity as a function of substrate concentration.

affordable to the point that these devices could become more common as a tool in the chemist's or educator's repertoire for scientific inquiry. Ongoing improvements in accuracy, precision, time response, and cost will further advance the vision and potential benefits of this important visualization tool.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.9b00789.

Example brief descriptions with file formats indicated are shown below; customize for your material. "Lab0" guided inquiry activity to acclimate students to the use of smartphone plug-in IR imaging cameras (PDF, DOCX)

Brief methods descriptions for activities described above (PDF, DOCX)

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Notes

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