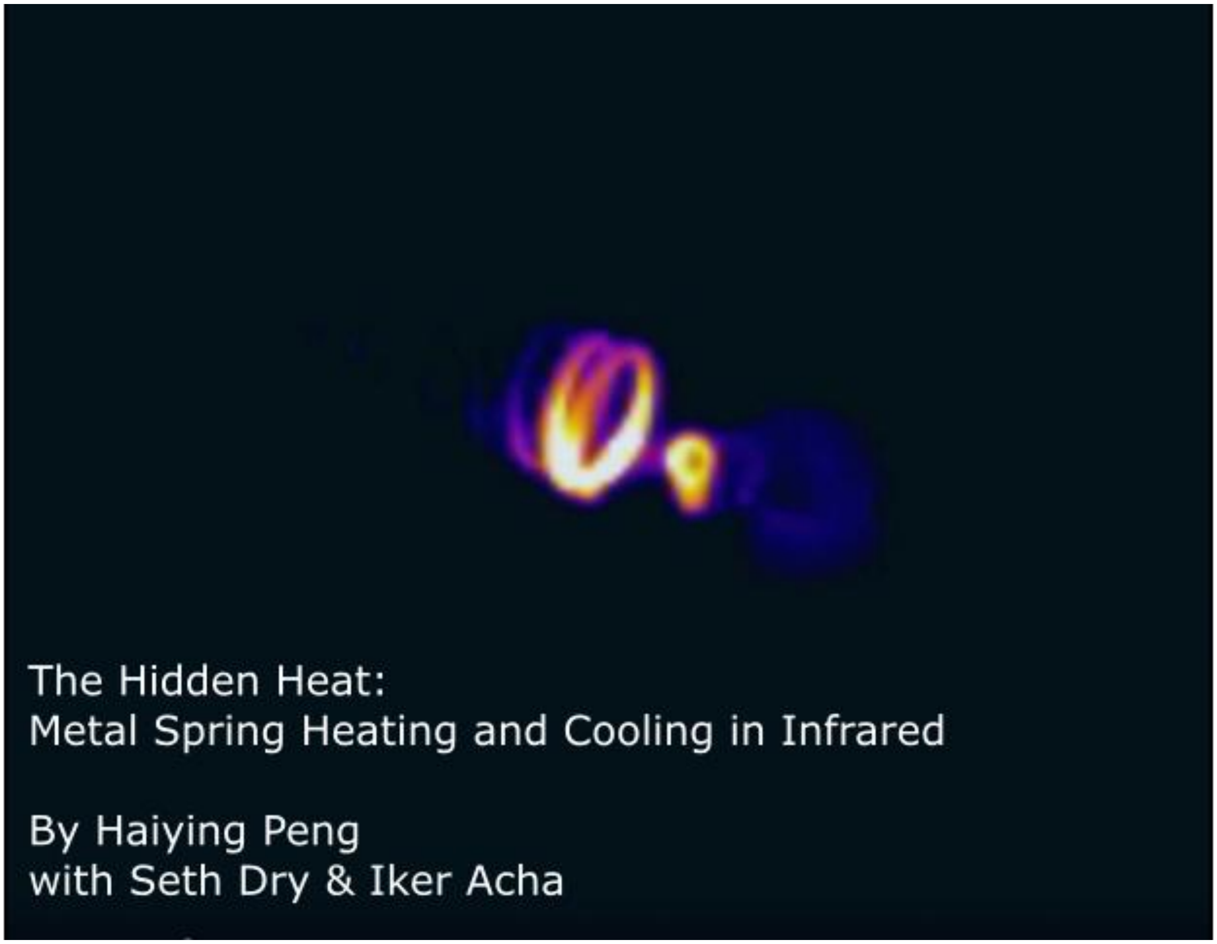

Team third report: The Hidden Heat – Metal Spring Heating and Cooling in Infrared

Haiying Peng

MCEN 5151-002 Flow visualization

11/19/2025

1 Introduction

The purpose of this report is to describe and discuss the video on the cover. High-resolution versions of the video are available on flowvis.org, along with many other inspiring flow images and videos. This video was created for the Team First assignment in the MCEN 5151 Flow Visualization course in Fall 2025, with help from my teammates, Seth Dry and Iker Acha. Seth proposed the idea of observing heat flow during the process of heating metal with a torch and recording it with a thermal imaging camera. We all worked together to design and set up the experiment and to assist one another with our projects.

This video is intended to show how heat moves along a metal spring over time. It records a metal coil being heated at one end with a torch while a thermal imaging camera captures how the temperature changes along the spring as it warms and then cools.

A wide temperature range was used on the thermal camera so that both the hot area near the torch and the cooler surroundings appear in the same frame. This makes the movement of heat along the coils visible through smooth color changes. The spring is placed slightly above the visual center of the frame so that it becomes the main focus, while the cooler background and the torch remain less noticeable. This helps viewers focus on the heat flow rather than on the equipment.

This report documents and analyzes the heat transfer seen in the video, including how fast the heated region spreads along the spring and how the spring returns to room temperature after the torch is removed. The goals were to visualize heat conduction in a simple metal structure, to show how the temperature changes over time using infrared imaging.

2 Methodology

2.1 Test setup

The experiment was conducted in one of the experimental physics classrooms in the basement of the Duane Physical Laboratories Building on the main campus. The setup is shown in Figure 1. The thermal camera used was a FLIR E6 Pro. Although it is an advanced thermal camera, it cannot record video on its own and can only capture still images. Therefore, it had to be connected to a computer running FLIR Tools software, which was used to display and record the video.

The flow apparatus includes a vertical metal coil spring hanging in still room air, a handheld torch used to heat the bottom 0.5 in (1.27×10^{-2} m) of the spring, and a thermal imaging camera placed 1.5 ft (0.457 m) away. The spring has a wire diameter of 1/8 in (3.18×10^{-3} m) and a coil diameter of 1.5 in (3.81×10^{-2} m).

After the torch is turned on, the hot end of the spring reaches an estimated surface temperature of about 410 °F (≈ 210 °C, 483 K) quickly, while the ambient air is at 20 °C (293 K). This gives a temperature difference of roughly ΔT = 190 K. The thermal camera was set to a wide temperature range so that both the hot region and the cooler coils remain within the colormap. This setting makes the temperature gradients along the spring easy to see.

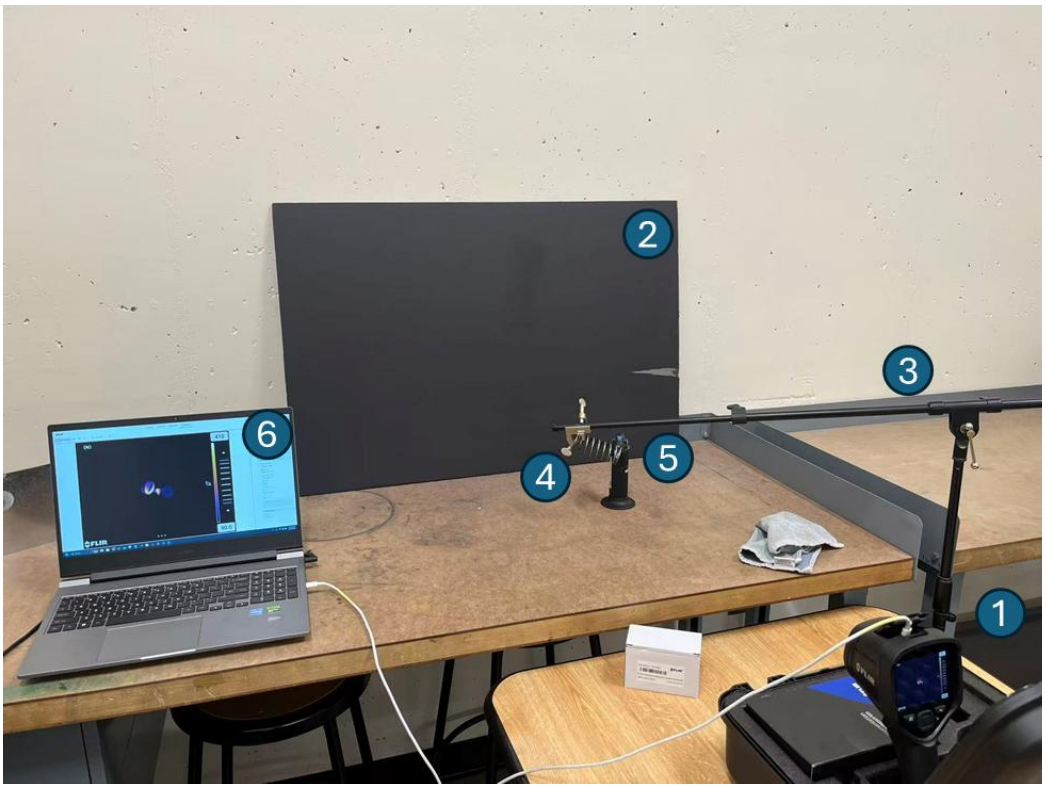

Figure 1. Experimental setup: 1. Thermal imaging camera; 2. Poster board (used to provide a uniform background temperature in the image); 3. Metal stand; 4. Tested metal spring; 5. Torch; 6. Laptop (running the official FLIR software for real-time display and video recording).

2.2 Flow discussion

The temperature pattern on the spring is controlled by three main processes: conduction in the metal, natural convection in the air around it, and thermal radiation to the surroundings. When the torch heats the bottom of the spring, a strong local heat source creates a steep temperature gradient along the wire, and heat conducts upward through the metal. At the same time, the air next to the hot coils warms, expands, and becomes less dense than the cooler air nearby. Gravity acting on this density difference creates an upward buoyancy force, which drives a rising plume of warm air along the heated part of the spring. Viscous forces in the air oppose this motion.

The visible “motion” in the thermal image, the growth and spreading of the bright hot region and its slow return when the torch is removed, comes from both heat conduction in the spring and buoyancy-driven natural convection removing heat from the coils. As the spring cools toward room temperature, the temperature gradients in the metal weaken, the buoyancy forces decrease, and the color field becomes more uniform. Infrared thermography turns these temperature differences into color patterns, so the apparent “motion” in the video is the changing temperature field caused by conduction in the solid and convection in the air.[1]

2.2.1 Nondimensional analysis

Dimensionless parameters are used to identify the flow regime and to compare it with classical theory.

1. Grashof number (Gr) and Rayleigh number(Ra)

To quantify the relative importance of buoyancy and viscous forces in the surrounding air, we estimate the Grashof number (Gr) using the heated length as the characteristic vertical scale.

$L = 0.5$ in $= 1.27 \times 10^{-2}$ m

Taking a film temperature near 115 °C (the average of 20 °C and 210 °C), the thermal expansion coefficient of air is approximately $\beta = 1/T_f = 2.6\times10^{-3}K^{-1}$, and the kinematic viscosity is $\nu = 2.3 \times 10^{-5}$ m^2/s.

$$Gr_L = \frac{g\beta\Delta T L^3}{\nu^2} = \frac{9.8 \times 2.6 \times 10^{-3} \times 190 \times (1.27 \times 10^{-2})^3}{(2.3 \times 10^{-5})^2} = 1.9 \times 10^4$$

For air, the Prandtl number (Pr) is about 0.7, so the Rayleigh number is:

$$Ra\_L = Gr \times Pr = 1.9 \times 10^4 \times 0.7 = 1.3 \times 10^4$$

For natural convection in air, the flow is usually laminar when $Gr \lesssim 10^{8\text{–}9}$and becomes turbulent only at higher values. Thus $Gr = 1.9 \times 10^4$ therefore indicates laminar natural convection along the spring. This corresponds to a smooth rising thermal plume, which matches the thermal image where no small, chaotic structures appear. It also places the flow in the laminar natural-convection regime for a horizontal cylinder. This range is consistent with classical free-convection correlations, such as the Churchill–Chu correlation, which predict laminar boundary layers and smooth thermal plumes for $Ra_D \sim 10^4$–10^8.

2. Fourier number (Fo) and Biot number (Bi)

Inside the spring wire, the main process is transient heat conduction along a slender steel cylinder. The wire loses heat to the surrounding air through natural convection and radiation. A useful way to describe this behavior is by using the Biot number and the Fourier number. These numbers compare internal conduction to external convection and to the time scale of heat diffusion.

For a long cylinder cooled by convection, the characteristic length is:

$$L_c = \frac{V}{A_s} = \frac{R}{2} = 7.94 \times 10^{-4} m$$

where R is the wire radius. The wire diameter is 1/8 in = 3.175×10^{-3} m.

Using a representative convective–radiative heat transfer coefficient $h = 20$ W/m^{2}K for a small hot wire in still air, and a typical thermal conductivity for carbon steel $k = 45$ W/mK, the Biot number is:

$$\mathrm{Bi} = \frac{hL_c}{k} = \frac{20 \times 7.94 \times 10^{-4}}{45} = 3.53 \times 10^{-4}.$$

This Biot number is much smaller than 0.1 , which is the common limit for using the lumped-capacitance approximation [2]. When $\mathrm{Bi} \ll 0.1$, means the internal conduction resistance is very small compared with the external convection resistance. This means the wire's temperature is almost uniform across each cross-section. In other words, the spring acts like a series of "lumped" thermal nodes along its length: the temperature changes mainly along the wire, not across its radius. This supports treating each small segment of the spring as having a uniform temperature that cools according to Newton's law of cooling.

The Fourier number characterizes how much diffusion has occurred over a given time. For heat conduction it is defined as:

$$\mathrm{Fo} = \frac{\alpha t}{L^2}$$

where α is the thermal diffusivity, t is time, and L is the characteristic length in the direction of interest. For steel, a typical thermal diffusivity is $\alpha \approx 1.3 \times 10^{-5}$ m^2/s.

As for Axial diffusion along the heated length, the heated segment is about 0.5 in = 0.0127 m, so a representative axial length scale is $L = 0.0127/2 = 6.35 \times 10^{-3}$ m. From the original video, the spring cools from its hot state back to near ambient in 7 min 16 s, giving a total cooling time of t = 436s.

$$\mathrm{Fo} = \frac{\alpha t}{L^2} \approx 1.41 \times 10^2.$$

A Fourier number of order 10^2 along the spring length means that conduction has had substantial time to redistribute heat over the entire heated region, by the end of the cooling period the axial temperature profile is close to its quasi-steady exponential form governed by the balance of conduction and convection.

The Biot number of 3.5×10^{-4}shows that the wire is "thermally thin", meaning it has almost no internal resistance and its temperature is nearly uniform across each cross-section. The large Fourier numbers (about 10^2–10^4) show that conduction has had enough time to smooth out temperature differences both across the wire and along its length during the cooling period.

Because Bi $\ll 0.1$, the transient cooling of each small segment of wire can be modeled by a lumped time constant:

$$\tau = \frac{\rho c_p L_c}{h}$$

With $\rho \approx 7.8 \times 10^3$ kg/m^{3}and $c_p \approx 5.0 \times 10^2$ J/kg·K. This gives:

$$\tau \approx 1.55 \times 10^2 \text{ s.}$$

The measured cooling time to "near ambient" is about 436 s, which is roughly $t = 2.8\tau$. For a lumped system, the dimensionless temperature:

$$\Theta(t) = \frac{T(t) - T_\infty}{T_0 - T_\infty} = \exp(-\frac{t}{\tau})$$

t = 436s, $\Theta(t)$ would then be:

$$\Theta(436\text{ s}) = \exp\,(-2.8) \approx 6.0 \times 10^{-2}.$$

This means that after 7 min 16 s the spring ends up only about 6% above ambient temperature, which matches the observation that the thermal image has largely faded back to the background color by the end of the video.

3 Visualization techniques

The visualization was performed using a FLIR E6 Pro thermal imaging camera, which detects infrared radiation and converts it into a false-color temperature field. Although the E6 Pro is an advanced thermal camera, it can only capture still images and cannot record video by itself. To obtain continuous thermal footage, the camera was connected to a computer running FLIR Tools software, which provided real-time display and allowed external video recording of the thermal stream. This setup made it possible to document the full heating and cooling process of the spring as a continuous sequence rather than as separate frames.

Because infrared imaging records emitted thermal radiation instead of reflected visible light, the visualization does not depend on external lighting. For this reason, lighting arrangements were not relevant for this experiment. The key visual information comes entirely from temperature differences shown through the thermal colormap.

A wide temperature range was selected to prevent saturation near the hot end of the spring and to keep contrast across the cooler upper coils. The camera was placed about 1.5 ft away at a nearly horizontal angle, giving a clear and undistorted view of the full spring. With the FLIR E6 Pro's 640 × 480 pixels spatial resolution and the 10.13 frame/second capture rate available through FLIR Tools, this setup produced a clear and continuous visualization of transient heat conduction in the wire and natural convection in the surrounding air.

4 Photographic techniques

A FLIR E6 Pro thermal imaging camera was used for the visualization. The camera has a field of view of 33° × 25°, and the video was recorded at a frame rate of 10.13 frames per second. The camera was placed 1.5 ft from the metal spring.

The raw thermal footage was post-processed using Movavi video-editing software to improve clarity and presentation. The original recording was 13 minutes and 50 seconds long and captured the full heating and cooling cycle of the spring. For visual conciseness, the video was sped up and shortened to 17 seconds so that the overall temperature change could be viewed efficiently while still showing the main heat-flow behavior.

Parts of the original frame were cropped to remove distracting background elements that did not help show the thermal physics. This kept the viewer's attention on the spring and the temperature patterns along its coils. The spring was placed slightly above the center of the frame, leaving space at the bottom for the heat source and creating a natural vertical path in the composition. This framing guides the viewer's eye upward along the spring, matching the physical upward movement of heat and the rising warm air. Together, these adjustments improved the clarity, readability, and visual quality of the final thermal visualization.

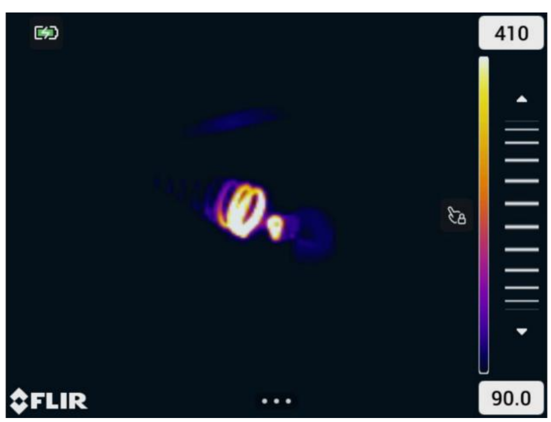

Figure 2. snapshot from original video

5 Conclusion

This video shows the transient thermal behavior of a metal spring as it undergoes rapid heating and gradual cooling. The thermal imagery makes it clear how heat introduced at one end of the spring moves along the coils through transient conduction in the wire, while the surrounding air responds through laminar natural convection. This rising warm air forms a smooth thermal plume. The growth of the bright, high-temperature region and its later decay illustrate both the directional nature of heat conduction in the solid and the buoyancy-driven motion of the heated air.

Visually, the video is effective. The wide temperature range prevents saturation and captures the full gradient from hot to cool in a single frame. I especially like the curved shape of the chosen spring, which makes the heat spreading along the coil length easier to see and also adds aesthetic appeal to the composition.

There are also some limitations. Because the thermal imaging camera has relatively low pixel resolution, the overall image is not very sharp, and post-processing cannot greatly improve the quality. This reduces the clarity of the final video.

Overall, the intent of the visualization was achieved. The video clearly shows how heat spreads along a metal structure, making the physical mechanisms easy to understand even for viewers without prior knowledge of thermal-fluid science.

References:

[1] Usamentiaga, Rubén, et al. "Infrared thermography for temperature measurement and non-destructive testing." Sensors 14.7 (2014): 12305-12348.

[2] M. Bahrami. “Transient Heat Conduction.” https://www.sfu.ca/~mbahrami/ENSC%20388/Notes/Transient%20Heat%20Conduction.pdf