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Case Study 2: Skillet Handle
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Temperature Analysis of Cast Iron Skillet Handle

1. Introduction

Within this experiment, the temperature distribution of a cast iron skillet is analyzed in the scenario of the skillet used to cook some items. The distribution was examined first experimentally and then compared to the theoretical model and results. The basic experimental design is that the skillet had been cooking some items at a high temperature, near 100 degrees centigrade; the item has been cooking for a long time. This allows the handle to be treated as if it is in a steady state scenario. The objective of the study is to analyze how hot the skillet handle will reach and whether it will harm any user who is trying to move the skillet. If the skillet is a low enough temperature such that it will harm the user, this study will act as a confirmation. Otherwise, a design change may be suggested so as to ensure the safety of the user.

With regards to analysis, the skillet handle is treated as a fin given that it is subject to radial and axial conduction within the handle and that it dissipates heat into the environment via natural convection and radiation. Also, the handle itself is characterized by a rectangular cross section, However, a hydraulic diameter was obtained from the perimeter and cross-sectional area of the handle so as to be able to model this handle as a fin. Throughout the analytical phase of this study, estimations were made so as to make the more possible, most notably normalizing the thickness of the handle and be able to get a constant hydraulic diameter at all axial positions in the skillet. Given these estimations were made, upper bound and lower bound analysis was done so as to provide context to these estimates. The upper bound assumes the largest thickness measures is the constant thickness. The lower bound assumes the smallest thickness, which occurs at two divots in the surface is the constant thickness. Lastly, a weighted thickness is calculated using the cross sectional area and perimeter. The analysis is done in the context of these three different thicknesses.

With regards to daily life, cast iron skillets are commonly used in many household kitchens and sometimes are a necessity for recipes given their ability to retain heat. Consequently, this ability to retain heat is also what makes their handles dangerous to users. A baseline analysis of the steady state temperature of the handle will aid therefore in understanding how dangerous these handles may be (do they only get hot or can they burn), as well as informing design choices. Though not the focus of this case study, an understanding of the temperature distribution in pans as a whole will provide context for the use of insulation in other kitchenware of the importance of such insulation.

2. Experimental Design

For the purpose of this experiment, the hardware needed was a cast iron skillet, an electric hot plate, two type-K thermocouples, and lastly a DAQ board. A small Flir thermographic camera was used for a qualitative method of representing the temperature distribution, but it was not used for analysis. With regards to software, LabView was the main avenue of data collection, but Matlab was used for analysis. The thermocouples were coated in a thermally conductive material and then adhered onto the skillet handle at two positions. A thermally conductive material was coated onto the thermocouples so as to decrease the thermal gradient between the thermocouple and the skillet, giving the most accurate reading. The first position is the root of the skillet handle, or at the location where the handle connects with the skillet itself. The position of the second thermocouple was placed at the very tip of the skillet handle. This is expected position where the user would grab the handle. The distance between these two locations was measured to be 7 inches. After the hardware had been set up, the skillet was heated via the electric hot plate until it reached a steady state temperature. This steady temperature was found by observing the continuous measurements being taken by the thermocouples. The measurements taken for this case study began when the steady state temperature was reached. It is important to note that the skillet was not filled with any fluid, and therefore all heat from the electric plate is dissipating into the skillet itself. This was done so as to reduce noise associated with an open system mass transfer given that water (the likely fluid) would boil away.

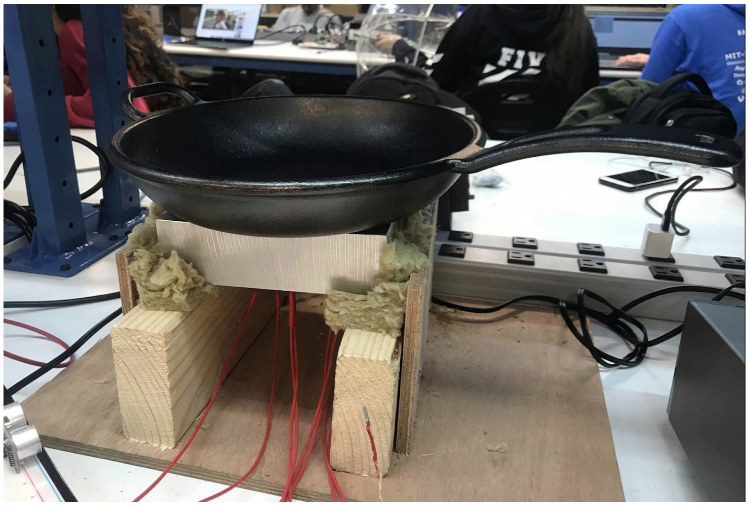

Figure 2.1: The picture above shows the experimental set up for this case study. As can be seen, the cast iron skillet is placed on top of the electric hot plate.

Throughout this experiment, there are different sources of potential error that may affect the experimental results. The most significant source of error is the method of attachment between the thermocouples and the skillet. For context, the thermocouples are of the form of a cylinder that is designed to be inserted into a hole within the specimen. A combination of no holes in the skillet handle, the handle being too thin to even make a hole, as well as a limited amount of time that could be dedicated to adjusting the handle, the thermocouple was not mounted in the ideal form. In this experiment, the thermocouples were simply taped onto the skillet. Ideally, the thermocouples would be patches that are designed to be adhered onto flat surfaces but these were not available for the experiment. Overall, this method of attachment means that the thermocouple was not in solid conduction with the skillet handle along its surface area, and therefore it may not represent a fully accurate reading.

With regards to experimental data, shown below is the data from the two thermocouples. Given the small change in temperature over the long time scale of around 13 minutes, this temperature was taken to be the steady state temperature.

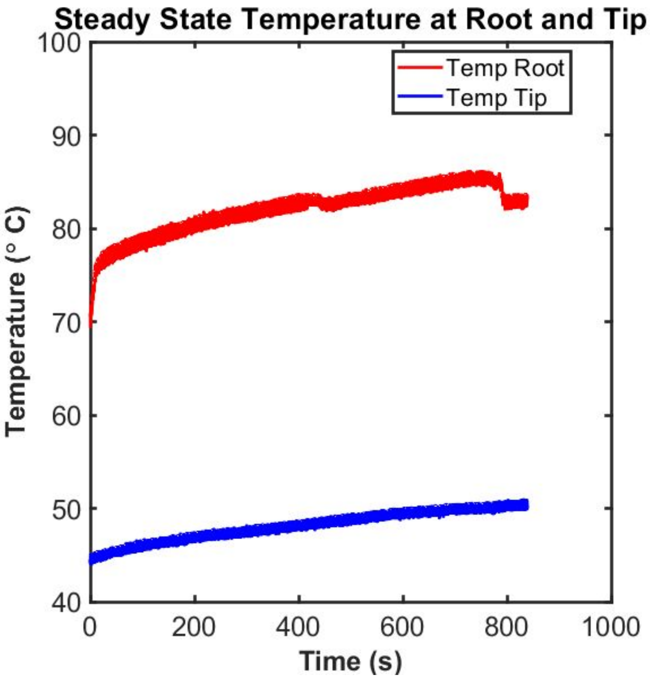

Figure 2.2: Shown above the temperature reading through time at two different positions on the skillet. The red line shows the temperature of the root of the handle while the blue line shows the tip temperature, which is the temperature of interest.

The experiment yielded a steady state root temperature of 84 degrees Celsius and a tip temperature of 49 degrees C.

3. Analysis

For this case study, the skillet handle was modeled as a cylindrical fin at study state that is subject to natural convection as well as radiation. As mentioned above, the diameter of the imposed cylinder is based off of an upper bound, lower bound, and weighted thickness. This imposed uniform thickness is done so as to simplify the overall geometry of the handle. Within the actual skillet handle, there are actually 3 indentations along the length of the skillet handle. However, these indentations are all next to each such that the inner thickness of the skillet handle actually remains uniform while the rim thickness also remains uniform. This cross section can be easily seen in Figure 3.1 and 3.2.

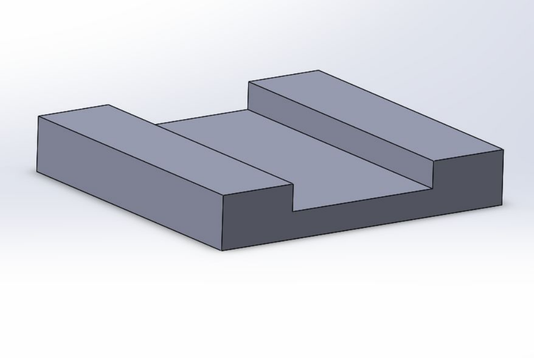

Figure 3.1

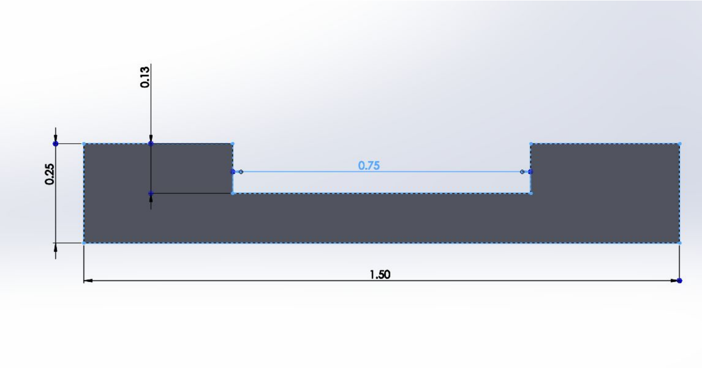

Figure 3.2

The measured geometric properties of the skillet handle are the following:

Total Length (in)	Total Width (in)	Indentation Width(in)	Inner Thickness(in)	Rim Thickness(in)
7	1.5	0.75	0.125	0.25

The upper bound thickness is simply the the rim thickness, the lower bound thickness is the inner thickness, and the weighted thickness directly uses the cross sectional area and perimeter of Figure 3.2 for calculating hydraulic diameter using equation (1). For the upper bound and lower bound, the area and perimeter were found using equations (2) and (3)

$$D_H = 4 * \frac{A}{P} \quad \textbf{(1)}$$

$$A_{rect} = Width * Thickness \quad \textbf{(2)}$$

$$Perimeter_{Rect} = 2 * Width + 2 * Thickness \quad \textbf{(3)}$$

Using this method, the hydraulic diameter for the three cases are:

Lower Bound (m)	Weighted Thickness (m)	Upper Bound (m)
0.0061	0.0095	0.0117

After these diameters have been found, the nusselt and rayleigh correlations can be used for the horizontal cylinder as in the normal case. The equations for these correlations are shown in equation (4) and (5) respectively. The nusselt correlation can be used to therefore find the heat transfer coefficient for natural convection by equation (6)

$$Nu_D = 0.36 + 0.518 * Ra_D^{.25} * (1 + (\frac{0.559}{Pr})^{9/16})^{-4/9} \quad \textbf{(4)}$$

$$Ra_D = (g * \beta * D_h^{3})/(\alpha * \nu) * (T_{root} - T_{inf}) \quad \textbf{(5)}$$

$$h_{conv} = D_h * Nu_d/k_{air} \ \textbf{(6)}$$

With regards to radiation, the heat transfer coefficient can be found more simply by an average of the absolute upper bound radiation and absolute lower bound radiation. Given the absolute upper bound radiation would happen at the hottest temperature within this experiment, the temperature of the root of the handle is used. Conversely for the absolute lowest bound, the lowest temperature in this setup would be the ambient room temperature. Equations (7), (8), and (9) show the averaging to show the most accurate heat transfer coefficient.

$$h_{rad,\,UB} = 4\sigma\varepsilon(T_{root})^3 \ \textbf{(7)}$$

$$h_{rad,\,LB} = 4\sigma\varepsilon * (T_{inf})^3 \ \textbf{(8)}$$

$$h_{rad,\,average} = (h_{rad,\,LB} + h_{rad,\,UB})/2 = 2\sigma\varepsilon(T_{root}^{3} + T_{inf}^{3}) \ \textbf{(9)}$$

The following table shows the given thermophysical parameters necessary for this case study.

T_{inf}	T_{root}	β	g	σ
294	357.15	0.003401	9.81	5.67E-8

The following table shows the properties of air and the solid skillet.

k_{air}	α_{air}	ν_{air}	Pr	k_{solid}	ε

0.02821	2.616E-5	1.851E-5	0.71	52	0.82

Using these given properties, the heat transfer coefficient for radiation is found using equation (9) and yields $h_{rad} = 6.6\ W/m^2K$. For natural convection, the following table describes the heat transfer coefficient for each of the three thickness cases.

Lower Bound (W/m^2K)	Weighted Thickness (W/m^2K)	Upper Bound (W/m^2K)
0.653	1.8062	1.234

For each case, $h_{total} = h_{conv} + h_{rad}$. This total heat transfer coefficient is used within the fin formula. In order to understand which case is to be used in the fin, the Biot number and other calculations must be done so as to identify the fin type. Checkings the insulated tip condition as well as biot number, the following numbers are calculated. As can be seen, the fin can be treated as an insulated tip in all three cases.

	Lower Bound	Weighted Thickness	Upper Bound
$Bi = hL/K \ll 1$	0.0008	0.0014	0.0019
$PL/A \gg 1$	117	75	61

The insulated tip condition is described equation (10) and (11).

$$m_{fin} = \sqrt{(h_{total} * P)/(k_{handle} * A)} \quad \textbf{(10)}$$

$$T(x) = T_{inf} + (T_{root} - T_{inf}) * cosh(L - x)/(cosh(m_{fin} * (L)) \quad \textbf{(11)}$$

Upon calculations of the temperature 7 inches away from the root of the handle, the temperature for each condition can be analytically found. These values are shown in the table below, as well as the experimental temperature.

Experimental	Lower Bound	Weighted Thickness	Upper Bound
322.15 K	316.7 K	323.1 K	325.7 K

As can be seen, the experimental temperature and weighted thickness model are within 1% of each other and therefore the weighted thickness model is the most accurate. However, the upper bound limit may serve useful as a safety factor of sorts. Shown below is a graphical representation of the experimental and analytical temperatures. In terms of Celsius, the experimental temperature found was to be 49 degrees C while the model was 49.9 degrees C.

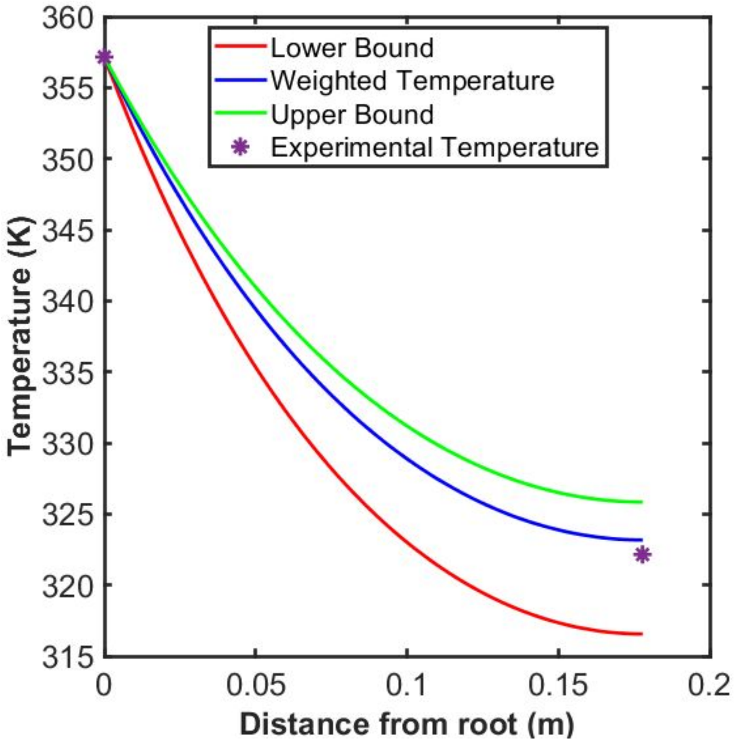

Figure 3.3

4. Design Considerations

Given that our model is shown to be accurate to the experiment, I used the model to predict the tip temperature at varying root temperatures, for which the model predictions is shown below. Given that 60 degrees C is considered the temperature that causes burns for short term handling, the handle tip should not exceed 60 degrees C in any case.

Root Temp (C)	100	110	120
Tip Temp Prediction (C)	55.56	58.66	61.48

Potential ways to decrease the tip temperature is to look at the main driving factors. As can be seen, a lower hydraulic diameter leads to a lower predicted temperature. Therefore minimizing cross sectional area or maximizing wetted perimeter will lead to a decrease in hydraulic diameter. This can be done and is done with the experimental skiller using indentation and holes in the handle. These design changes will lead to a lower tip temperature. Other potential solutions include some form of insulation such as a rubber handle cover or otherwise a longer handle. A rubber handle would insulate the heated tip temperature from contacting the users hand. A longer handle would allow more convective and radiative heat transfer between the root and tip. For reference, increasing the handle length from 7 inches to 10 inches, in the case of the root temperature being 120 degree C, would lead to a tip temperature of 42.54 degrees C. This is nearly a 19 degree C decrease in tip temperature.