Heat Sink Model Validation

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Final Lab Design Project

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ABSTRACT

This Heat Sink Model Validation design project was conducted in order to better understand the phenomenon of conductive and convective heat transfer across a heat sink through conduction and natural convection. This experiment also aimed to complete numerical simulations and compare their results to the experimental results collected. The main data collected in this experiment was the temperature across the fins and at the base of the heat sink. Several other data points were collected, mainly those pertaining to the conditions in which the experiment was conducted. This experiment was set up so that the forced convection from the surrounding atmosphere would be limited by a box around the heat sink and heat plate. When the heat sink was brought to a steady-state temperature by the heat plate, the data points from the thermocouples were retrieved. These data points were compared to simulations from the use of MATLAB and ANSYS, where the results found that experimental analysis does line up accurately with both the MATLAB and ANSYS simulation models. The convective heat transfer coefficient (h) was the primary data value being tested, since the other values are known for these conditions. This h-value will differ depending on the position of the fin and where it is at on the heat sink. Using MATLAB and ANSYS, it was found that the temperature distribution from the experimental data lines up very closely with the simulation results with some error involved. There are some varying temperature differences between the experimental and simulation data. For example, the fin edge temperatures are higher in the simulation than in the experiment by about 5-10 K. This is most likely due to the uncertainty in the experimental analysis. The uncertainty of this experiment comes largely from the thermocouples, as well as from the initial set up. The thermocouples have their own instrumentation error to be calculated and included. The thermocouples may also be in the way of the heat transfer through the fins due to the amount of material being placed in the narrow passages of the heat sink. This added material can interfere with the overall flow of heat in the heat sink. The box around the experiment may also cause some minor change in the values that were found because this may induce channel flow, such that of a chimney. While this was meant to get rid of forced convection, it may also have added another factor into the overall error of the experiment.

INTRODUCTION

For the final design project, group G2 delves into the application of heat transfer analysis to provide validation for simulative models. For a chosen heat sink, the team uses both ANSYS and Matlab programs to render the heat dispersion gradient for similar lab testing base plate temperature and boundary conditions. The heat sink is used for data collection in the lab, in which a provided heat plate brings the heat sink to a steady temperature. The surface temperature in various areas along the heat sink is collected using the design setup. This temperature measurement data is collected using a series of K-type thermocouples relayed through a DAQ system that includes the use of the LabVIEW program as well as a NI-9213 module. The primary objective of the experiment is to use the collected temperature measurements taken across the heat sink and apply derivations to validate both the ANSYS and Matlab models. The simulated results will then be compared and iterated to match the experimental results as closely as possible.

In order to make the proper derivation assumptions, the heat sink was tested behind a barrier to allow for the reduction of forced convection conditions from the surrounding air and its movement in the lab room facility. This barrier was made tall enough to assume that most of the forced convection employed by this movement could be ignored in the development of results. Furthermore, the heat plate is measured at steady state from the allowance of the heat sink to reach a preset temperature before data is collected. The idea was to diverge from transient conditions, to allow for the validation calculations and modeling process to be more accurate for scope of the project. The heat sink chosen for the experiment is made of 6063 aluminum alloy, whose heat transfer coefficient is between 201-218 W/m*K [1]. For modeling, the assumption was made to keep the value of (k) at 200 W/m*K between the two simulations.

Our team investigated possible Nusselt number correlations that could fit the heat sink geometry and assumed conditions described. After exploring channel correlations and that for extruded fins, it was determined that localized plate Nusselt derivations could be used. This assumption was made based on the individual fin surfaces being the correct geometry of individual vertically oriented rectangular plates. The flow across these fins is assumed to be parallel to the surface as the outer air is moved along the fins to the center due to the temperature gradient that occurs.

The phenomenon associated with the heat sink experiment is the ability for cooling of a heated surface to take place due to the spreading resistance of the finned geometry. This is tested in the experiment throughout several factors, the primary being the simulative modeling that employs the correct conditions to visualize the temperature gradient created along the heat sink fins. Furthermore, the in-lab tests conducted with the design enabled for the temperature differences to be seen using the collected surface temperature data. Between the developed model simulation results and collected temperature data, the experiment will validate the characteristics relating to the heat dispersion of the sampled geometry used. This in turn will help understand how well the heat sink is using heat transfer correlations relating to the material, geometry, and fluid surrounding air to allow for the temperature gradient to take shape.

The following equations were used to derive the local Nusselt number for the individual fins along the heat sink geometry [2]. The Nusselt number correlation used for premade assumptions of the parallel fluid flow across each side of the fins. Both the local Reynolds number, (Re_x), and Prandtl number, (Pr), are found using equations 1 and 2. These two dimensionless numbers are used in defining the flow characteristics of the heat sink during the experimentation.

$$Re_x = \frac{\rho * U_\infty * L_x}{\mu} \tag{1}$$

The local Reynolds number, defined in equation # above, is found using the density of the fluid (ρ), free steam velocity running across the 'plate' (U_∞), dynamic viscosity (μ) and the location for the area of interest (L_x).

$$Pr = \frac{\mu * C_p}{k_f} \tag{2}$$

The Prandtl number derivation shown above uses the same dynamic viscosity (μ) of the fluid air but also the kinematic viscosity of the fluid (k_f) and specific heat capacity (C_p).

$$Nu_x = \frac{h_x * x}{k} = 0.332 Re_x^{\frac{1}{2}} * Pr^{\frac{1}{3}} \tag{3}$$

$$h_x = \left(\frac{1}{x}\right) * k * 0.332 Re_x^{\frac{1}{2}} * Pr^{\frac{1}{3}} \tag{4}$$

Using both results from equation 1 and 2 above, the derived local Nusselt number shown in equation 3 can then be solved for the local heat transfer coefficient (h_x). This allows for the changing value of (h) along the fins to be found and inputted and verified to the simulated models created. The calculations will enable the accuracy of the models to be comparative to the collected experimental temperature values of the heat sink.

DESIGN

The experimental setup consists of five main components: a heat plate, heat sink, 11 K-type thermocouples, a NI-9213 module, and adhesive. The design includes the placement of the thermocouples across various areas of the heat sink to help gain an even temperature distribution of collected data. To start the design process, first the individual placement positions of the thermocouples along the heat sink was determined. Figure 1 below shows the mapped-out placement points on the developed CAD model of the chosen heat sink for the experimentation. As shown, four thermocouples are to be adhered to the top center of the fins (denoted by the red markings). Four more are to be placed on the bottom corners of the heat sink fins closest to the outside of the geometry. Two are to be placed on the underside of the heat sink, on opposing sides to gain an average surface contact temperature between the heat sink and the heat plate. Figure 1 shows that the thermocouples will be placed on one fourth of the heat sink due to the assumption of even temperature distribution amongst the four quadrants due to even geometry.

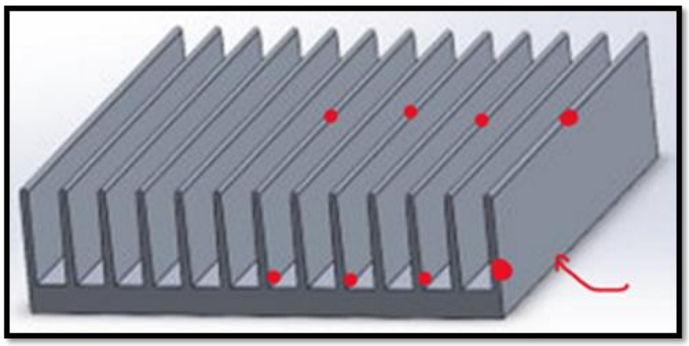

Figure 1: Thermocouple Placement on the Heat sink Geometry

The top center and bottom corner placement decisions were made to capture the change of temperature from the bottom to the top of the fins, and the separation made to gain an even spread along the fins. The center bottom of the fins was found to be difficult to allow for placement of the thermocouple wires without disrupting the center top and inner walls of the experiment. The tradeoff for this possible problem was to attach these thermocouples along the bottom corners of the fins near the exterior side as shown. The last thermocouple was set off to the exterior of the experiment to capture the ambient air temperature conditions of the room.

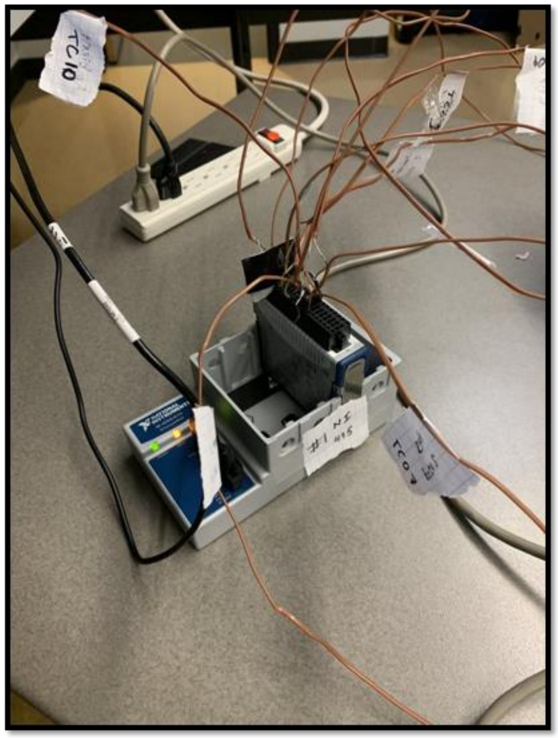

Figure 2: NI-9213 Module and K-Type Thermocouple Wire

Figure 2 above shows one of the primary components of the DAQ system setup used during the experiment to facilitate the data collection process. The NI-9213 module shown is hooked up to the lab computer (outside of the schematic) and the thermocouple wire leads are shown (brown wires). The tags on the thermocouple wire were to mark the heat sink temperature collection positions on the heat sink as shown in figure 1. This device has a connection to the lab computer to allow for the measurements to be taken in LabVIEW and recorded in an Excel workbook.

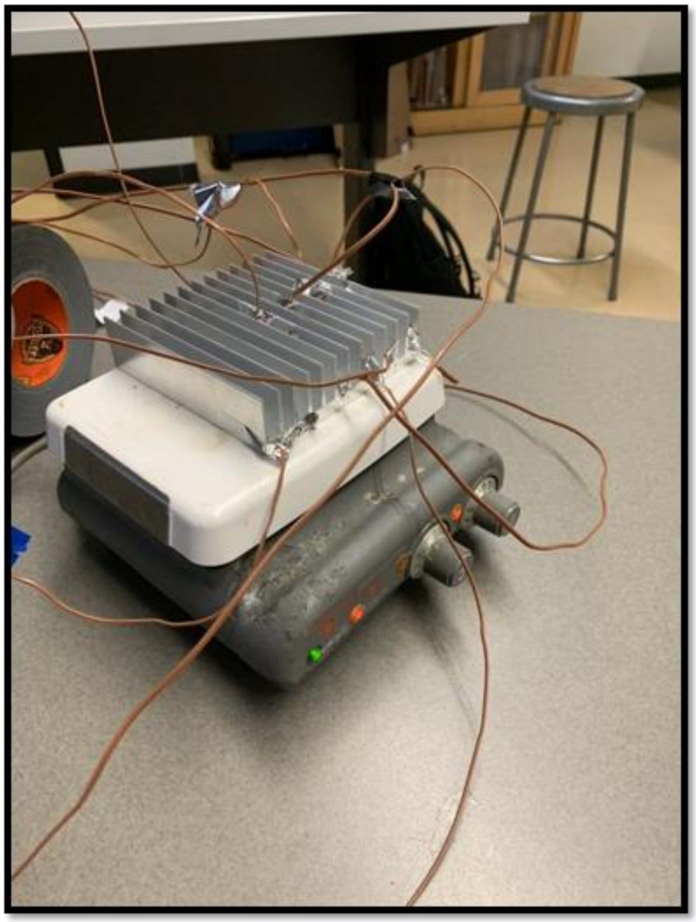

Figure 3: Heat sink, Heat plate and Thermocouples

On the other end of the design is a heat sink that is resting on a heat plate to provide the necessary heating source element. Figure 3 shows the heat sink geometry and the thermocouples placed onto it using grooves cut into the heat sink along with aluminum tape adhesive.

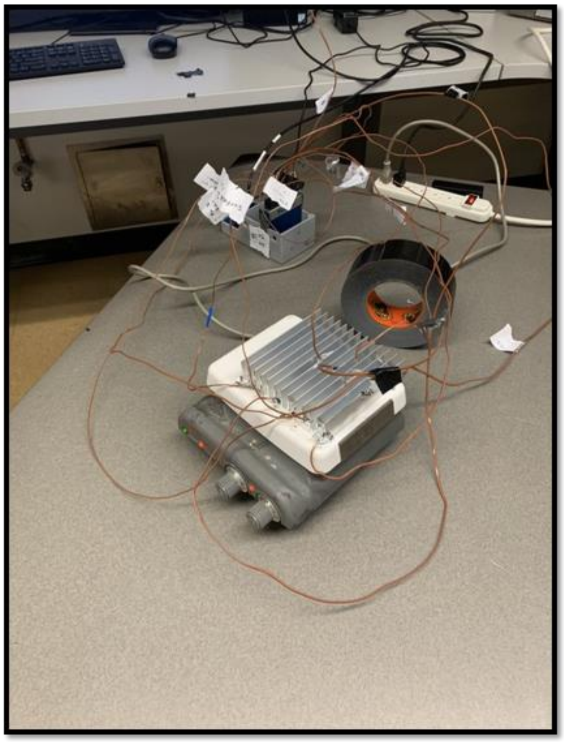

Figure 4: Full Design used for Experimentation

Figure 4 above shows the full design for the heat sink temperature collection process. In the back left is the lab computer used to run the LabVIEW system. The heat sink and thermocouples leading into the NI-9213 device are also included. A power strip in the back right is seen to allow for the design to sit further form the lab room counter to avoid crowding during the data collection procedure.

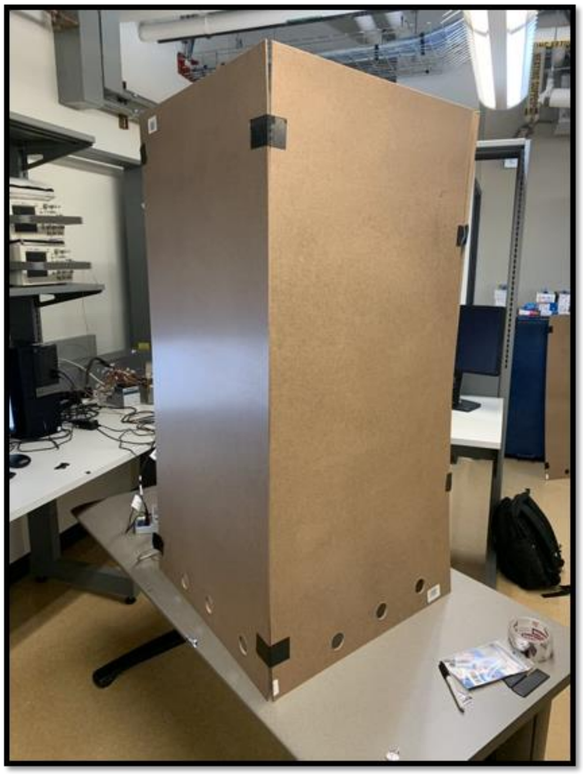

Figure 5: Board Walls Around the Design

Figure 5 shows the entirety of the design used for the experimentation procedure. The items shown in figure 3 were enclosed in a chimney structure composed of cut particle board. The board walls helped to reduce the forced convection of the lab room conditions while collecting data. However, after a meeting with the instructor it was determined that the chimney walls may cause unwanted flow patterns. This was noted but the experiment design had already been completed and was deemed acceptable for the scope of this project. The thermocouples were led outside of the structure to the NI-9213 device through holes shown in figure 5 along the bottom of the walls.

Table 1: Design Components BOM

Qty	Item	Est. Cost
1	Heat sink	$12.00 /ea.
11	K-type thermocouples	$0.00
1	Roll of aluminum tape (or similar)	$8.00 /ea.
1	4’x8’x3/8” sheet particle board	$15.00 /ea.
1	NI-9213 Module	$0.00
1	Variable Heat Plate	$0.00
	Total Est. Cost	$35.00

Table 1 shows all the components sourced to complete the shown design and associated overall cost. All items with no associated cost were borrowed from the Lab 111 room. Initially, a heat resistant glue was chosen to adhere the thermocouples to the heat sink but upon building the design this proved to be difficult due to the stresses the wire lengths induced on the attachment points. Instead, while in the lab the thermocouples were attached using individual pieces of aluminum foil tape, which can be seen in figure 3 detail.

METHODS

For this lab, the instruments used were like that of the Heat Fin Lab 7 [3]. The instrumentation consists of a heat plate, thermocouples, and the NI-9213 module that connects to the LabView program. The thermocouples were calibrated by taking a regression line between the expected temperatures and the temperature read by the thermocouples. This data will allow us to properly calibrate the system and will be considered during the analysis portion of the lab. The thermocouple calibration curve can be seen in the figure below. Expected temperature values were taken from an ice bath and boiling water.

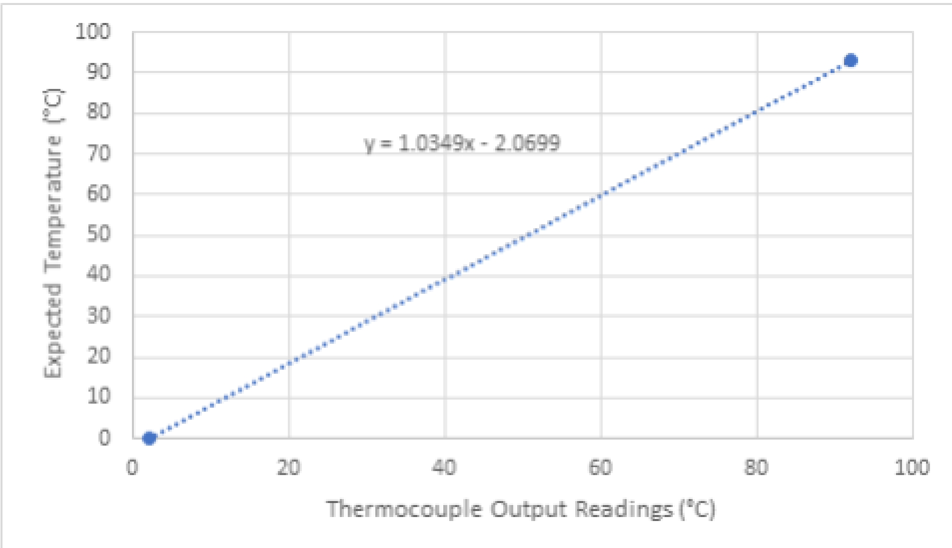

Figure 6: Thermocouple Calibration Chart

The LabVIEW system was set up using the manipulation of the preexisting program given for lab 7, this was very minor and only required renaming the thermocouple positions and deleting some of the remaining unnecessary placeholders [3]. All the necessary editing of the program was done under the DAQ feature icon in the diagram tab of LabVIEW. The NI-9213 module thermocouple wire port positions are labeled based on the LabVIEW program. This included stating the various surface positions on the heat sink that the thermocouples would be adhered to during the experimental process, such as 'middle fin center.' The thermocouples were placed onto the heat sink in the positions described above in figure 1 and shown executed in figure 3. The thermocouples could each be individually attached to the heat sink with the use of premade grooves into the heat sink surface and pieces of aluminum tape. Small pieces of the tape worked best in attempt to not interfere with the geometry and mass of the fin surfaces too much, while still maintaining proper adhesion. Once the 10 thermocouples are in the correct locations and one ambient suspended nearby, the heat sink had to be moved delicately to avoid breaking the thermocouple surface bonds established. The heat sink was placed on a hot plate to bring it to a steady state temperature. Without needing to reach a specific temperature value, the heating element dial was turned until a temperature was reached within the range of the LabVIEW program digital thermometer display. Waiting roughly 10 minutes allowed for the heat plate and heat sink to reach a consistent surface contact temperature. This can be identified by starting the LabVIEW program and watching the thermocouple temperature input data climb to a temperature, eventually becoming steady across the heat sink positions with only minor less than 0.1°C variations.

When the entire heat sink reaches a steady state temperature, the values of the thermocouples were recorded using the LabView program. The wooden walls are placed around the heat sink and NI-9213 device as shown in figure 5 above. Then, the ‘start’ bottom in LabVIEW is clicked to allow for the data to begin collecting; note that the button illuminates. The ‘start’ button is clicked again to stop the data recording. This was done for a total of 24 seconds at a frequency of 10 Hertz. This gives a total of 240 values to minimize the error and maximize the sample size for averaging the surface temperature data. This process was conducted three different times at about 5 minutes between trials to allow for time to assure proper thermocouple connections to the heat sink surface. It is important to check these surface connections between data collection trials, as well as ensuring the data properly imports to Excel Workbook form the LabVIEW program. This should happen automatically as the setting exists in the system once data collection is started.

During the experiment process, there are some points to note that could add onto the uncertainty within the data that was collected and analyzed. The fins of this heat sink are very close together and when putting thermocouples in between them, more material is being placed between the fins. This extra material can affect the heating of the heat sink and thus could result in an error in the temperatures. Another aspect of the thermocouples is the adhesive. A heat-resistant tape was used to adhere them onto the heat sink. This added material could also affect the values of the temperature output. Another part of this experiment that could affect the uncertainty is the box that was put around the heat plate. This box (figure 5 above) was used to reduce the amount of forced convection from the surrounding air, but it could also introduce a channel flow onto the experiment. This could change the h-values of the experiment and in turn would also affect the Nusselt number.

The K-type thermocouples used during experimentation have associated error in the temperature readings collected during this experimental procedure. With reference to the specific Omega TT-K-20-500 type thermocouple wire datasheet, the specified manufacture error is measured as a deviation of 0.8°F of a total read 392.0°F measurement [4]. Due to the DAQ system allowing for a digitalized reading achieved via the voltage potential signal for each wire thus no associated resolution uncertainty, the total design stage uncertainty for the thermocouple temperature measurements is found to be 0.2%.

RESULTS

Experimental Data

The experimental results consist of temperature readings from 11 different thermocouples (TC) distributed across the heat sink. 2 TCs were placed on the bottom of the heat sink, 1 TC collected the ambient temperature and the other 8 TCs were placed on the fins of the heat sink. The 8 TCs placed on the fins were separated into two groups: center and edge. 4 TCs were placed on the center of the fins, and the other 4 were placed at the edge of the fins. The raw data for this section can be found in Appendix 1. Below in Table 2 are the steady state temperatures of the TCs.

Table 2: Average Experimental Thermocouple Results

Ambient:	20.1			
	Fin 1	**Fin 2**	**Fin 3**	**Fin 4**
Center	93.6	85.2	88.7	88.6
Edge	84.4	86.5	84.8	70.9
Base 1	91.6		**Base 2**	93.2

There are a few important things to note when looking at the data in Table 2. First is that the thermocouple reading for the edge of fin 4 is very low compared to the center of fin 4. This massive difference in temperature is not expected, and because it deviates so much from the rest of the data, we have decided to throw out its data. Another thing to note is that the center of fin 2 is cooler than that of fin 3 or 4 by a few degrees, which isn't expected either. This might be due to poor contact with the heat sink, but the deviation is not large enough to justify throwing out its data. Next, we will show the temperature readings over time to show that the temperatures in Table 2 are indeed steady state temperatures. This graph can be seen below in Figure 7.

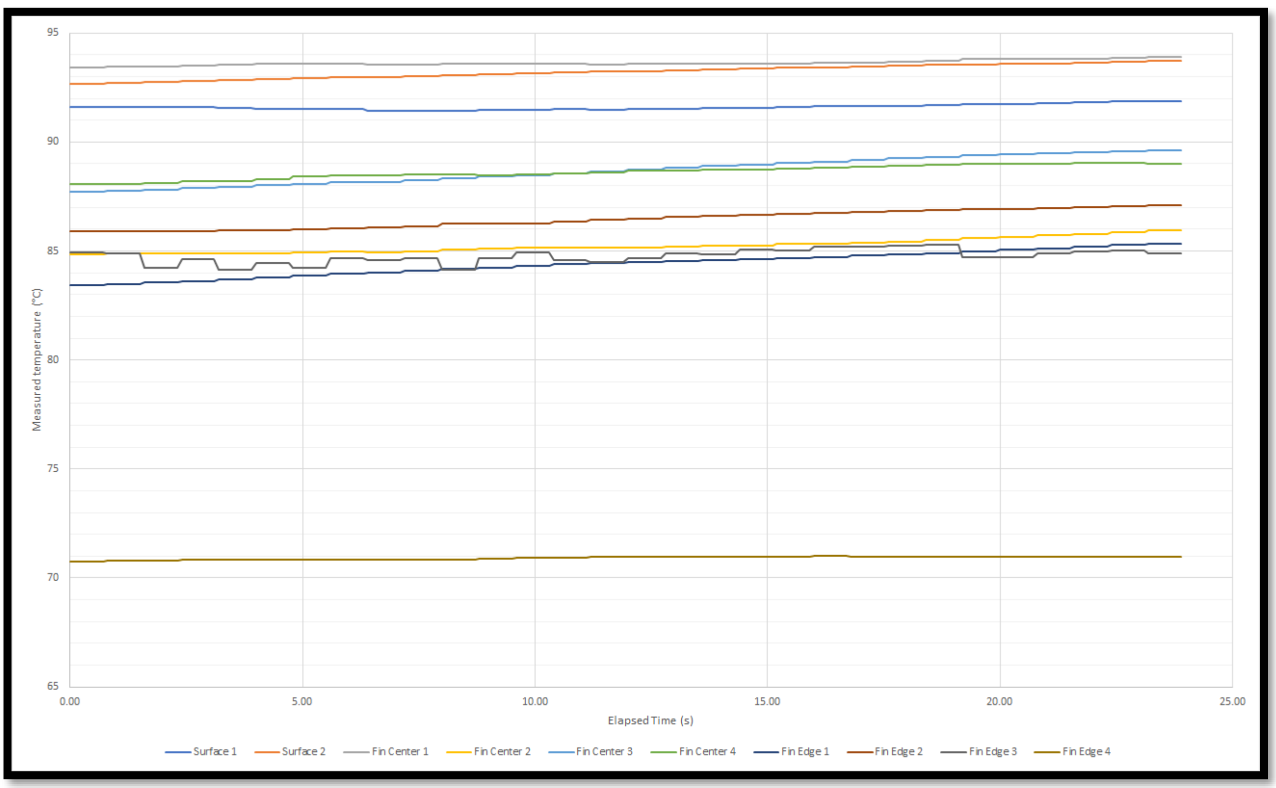

Figure 7: Temperature readings over time

As we can see from Figure 7, the temperatures from the thermocouples do not change significantly over time, so it can be assumed that the heat sink had reached steady state by the end of data collection. Overall, we can see that there isn't very much temperature variation between the center of fin 1 and the center of fin 4. This would suggest that because there was not much air flow over the heat sink, the temperature of the heat sink should be relatively isothermal. Although there is still enough convection to give up to 9 degrees difference between the hottest and coldest regions.

MATLAB SIMULATION

The heat sink geometry is created in SolidWorks and exported as an STL file. This file can then be imported into MATLAB for simulation using the PDE Toolbox [5]. The geometry is meshed with a maximum edge length of 5 mm.

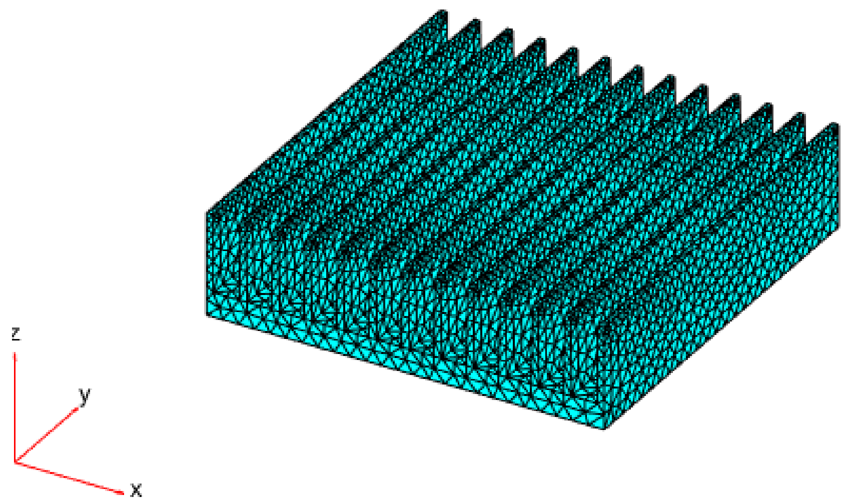

Figure 8: Heat sink geometry mesh from MATLAB simulation

Boundary Conditions

The model is assigned a thermal conductivity k of 200 $\frac{\mathrm{W}}{\mathrm{mK}}$, approximately equal to that of the heat sink used in the experimental procedures [6, 7]. Ambient air is assumed to have a temperature of about 293 K, Prandtl number *Pr* of 0.69, k of 0.03 $\frac{\mathrm{W}}{\mathrm{mK}}$, and kinematic viscosity v of $24 \times 10^{-6} \frac{m^2}{s}$ [2, p. 911]. The bottom surface of the heat sink is assumed to be isothermal and about 365 K.

Prediction of Heat Transfer Coefficient *h*

The above boundary condition values are known to a relatively high degree of certainty. However, calculation of heat transfer through convection relies on identifying the convective heat transfer coefficient h of the various heat sink surfaces. This is a nontrivial process as there are several complicating factors. Firstly, the high thermal conductivity of the heat sink compared to the low thermal conductivity of the surrounding air suggests that the temperature gradient over the heat sink should be small. This is corroborated by experimental results, showing a maximum temperature difference of under 10 K. As such, simulations are expected to be sensitive to even small changes in h. Secondly, air moving between heat sink fins does not follow a simple, straight path. Consider the simple control volume shown below:

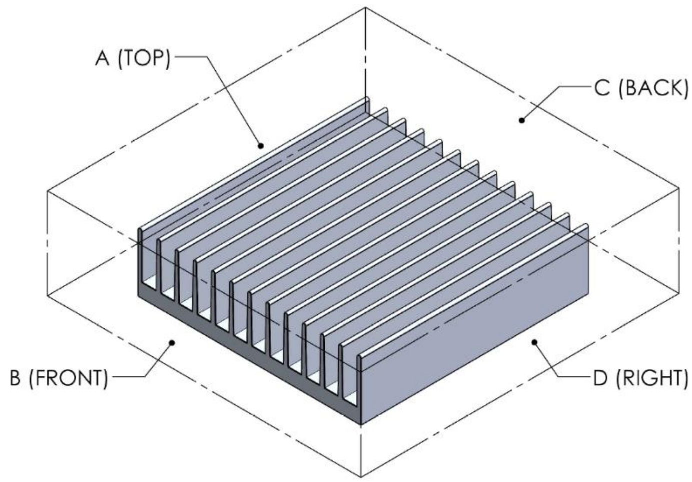

Figure 9: Control volume drawn around heat sink

As air between fins is heated, it will exit the control volume vertically through surface A due to advection. Maintaining conservation of mass requires that additional air must be drawn into the gaps between fins. The majority of this air is assumed to enter through surfaces B and C, as air moving parallel to the fins experiences less resistance to flow compared to air moving perpendicularly to the fins (as would be the case for air entering through surface D). This air, then, is drawn into the control volume horizontally, gets heated by the heat sink, and exits the control volume vertically. The diagram below shows the approximate expected path followed by the air as it undergoes this process.

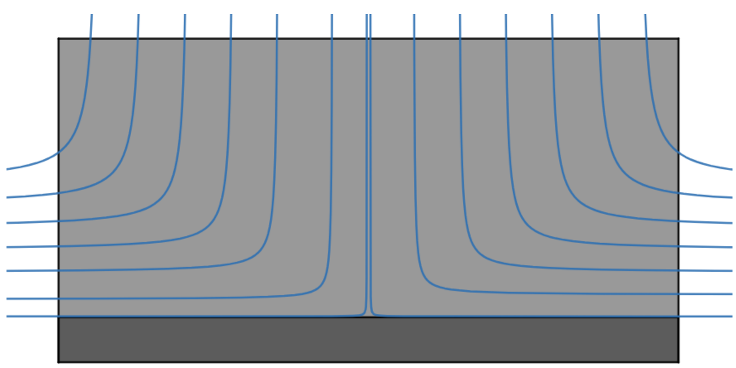

Figure 10: Anticipated streamlines of air moving between fins

Nusselt number correlations have been derived for many simple geometries [2], but none explored over the course of this experiment appear to fully encapsulate the expected airflow shown above. As such, calculating values of *h* for simulation is necessarily imprecise. Approximating the airflow as parallel flow over a flat plate appears to be the simplest appropriate correlation and will be used for the remainder of this discussion. Further work regarding this experiment would include a more detailed analysis of appropriate *Nu* correlations to quantitatively assess their accuracy to experimental conditions.

The value of *h* for the outermost faces of the geometry is assumed to be approximately 20 $\frac{\mathrm{W}}{\mathrm{m^2K}}$, while the bottom surface is assumed to have negligible heat transfer by convection. The inner faces of the fins experience varying values of *h* depending on the assumed distance it must travel to reach a given location (according to the streamlines shown in Figure 10). This distance is used in the calculation of Reynold's number *Re* which is then used to compute *h* according to Equation 3. Additionally, fins farther from the center of the heat sink are expected to experience improved heat transfer characteristics due to greater available airflow. Quantifying this effect likely requires flow simulations of the experimental setup, but this was unable to be completed in the timeframe of this report. Instead, this will be approximated by assuming increased flow velocity near the center fins.

Incorporating the varying flow velocity and characteristic length into Equation 3, values of *h* were computed over each fin surface. Results are shown below. Note that isosurfaces are shown extending through the gaps between fins as well as within the fins themselves purely for ease of visualization—values of *h* are used only for calculation of heat transfer by convection at the surfaces of the fins.

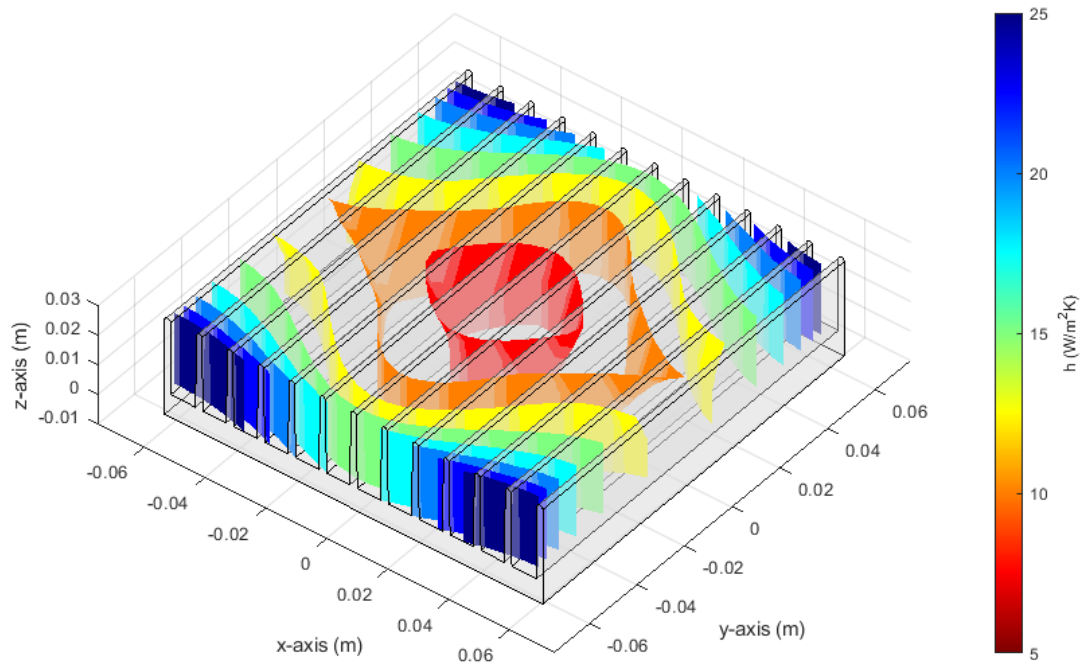

Figure 11: Isosurfaces of calculated h *values*

This variation in *h* is qualitatively as anticipated. As mentioned previously, more thorough analysis would be needed to assess how closely these results model experimental behavior. This discussion will continue under the assumption that these results adequately describe the approximate heat transfer characteristics of the heat sink geometry.

Simulation

With all boundary conditions assigned to the model, the steady-state simulation results may be calculated. The resulting temperature plot is shown below.

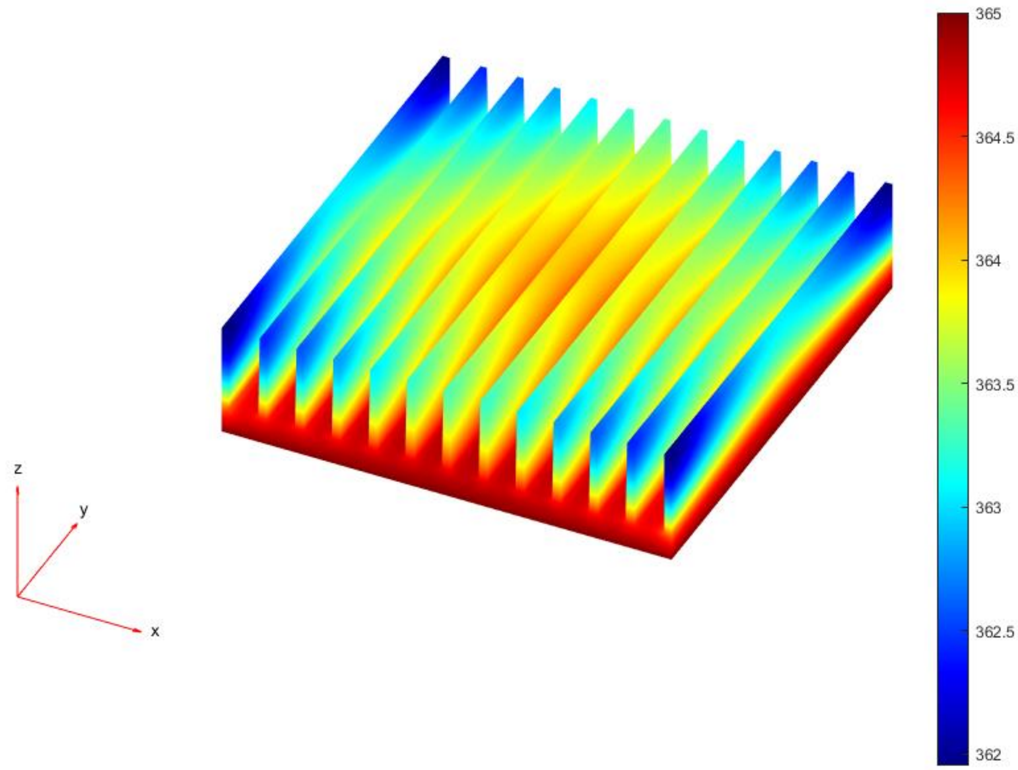

Figure 12: MATLAB simulation results (temperatures in Kelvin)

The resulting temperature distribution follows the general trends expected for the geometry and those shown by the experimental results. However, the simulated results differ from experimental results in a few areas. The simulated values for fin edge temperatures are higher than experimental values by about 5-10 K. Fin center temperatures are also generally overestimated by the simulation, with the exception of fin 1 which has a simulated temperature about 2 K lower than the experimental value.

Overall, while the simulated results differ noticeably from experimental results, the results are still quite informative of real-world behavior. The primary limitation is the large uncertainty associated with the results. Reducing this uncertainty would require more information regarding local flow velocity, identifying a more accurate *Nu* correlation, and more precise control over thermocouple adhesion and location. Given these improvements, simulation results may be achieved within about 1 K of experimental values. This error should be negligible for nearly any practical application of such a simulation. Even without such improvements, the results produced above deviate from experimental results by a maximum of about 6% which is also typically sufficient for most applications.

ANSYS SIMULATION

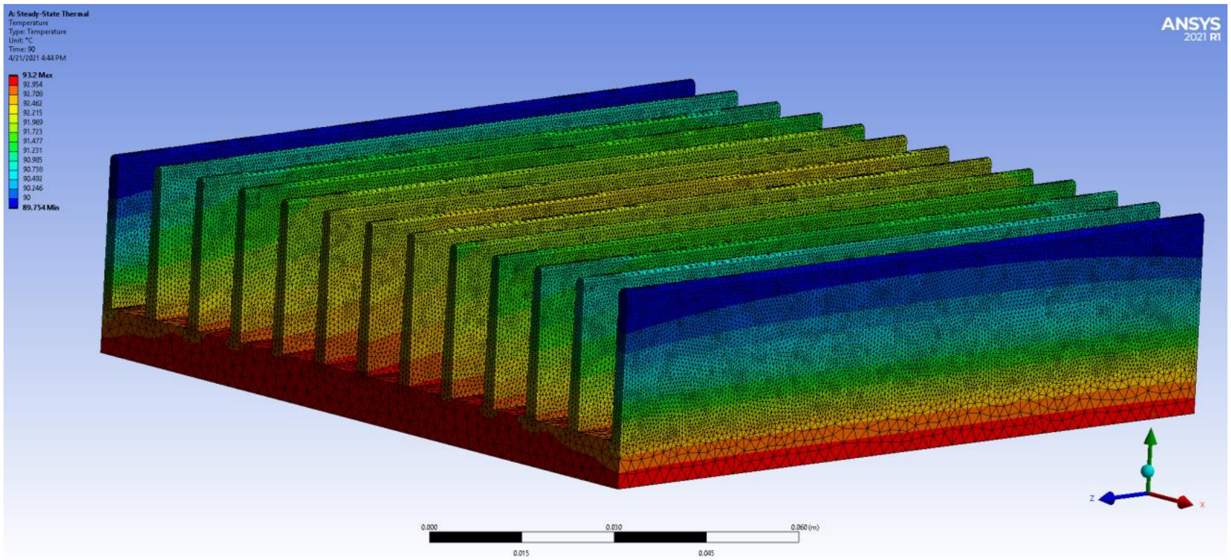

Figure 13: ANSYS Heat sink Heat Map

Above in figure 13 is the initial simulation results from ANSYS. This simulation uses a convective coefficient of 25 W/m^2K at the outer surfaces and decreases by 2.5 all the way to the inner most fins where the convective coefficient is 5 W/m^2K. This scenario represents what we would assume our experimental tests results to be like. Unfortunately, this model makes several assumptions about the boundary conditions around the heat sink, and so does not accurately represent the experimental data. Below in figure 14 are the results after we varied the convective coefficients of the surfaces along the heat sink to better match the results seen in the experimental data.

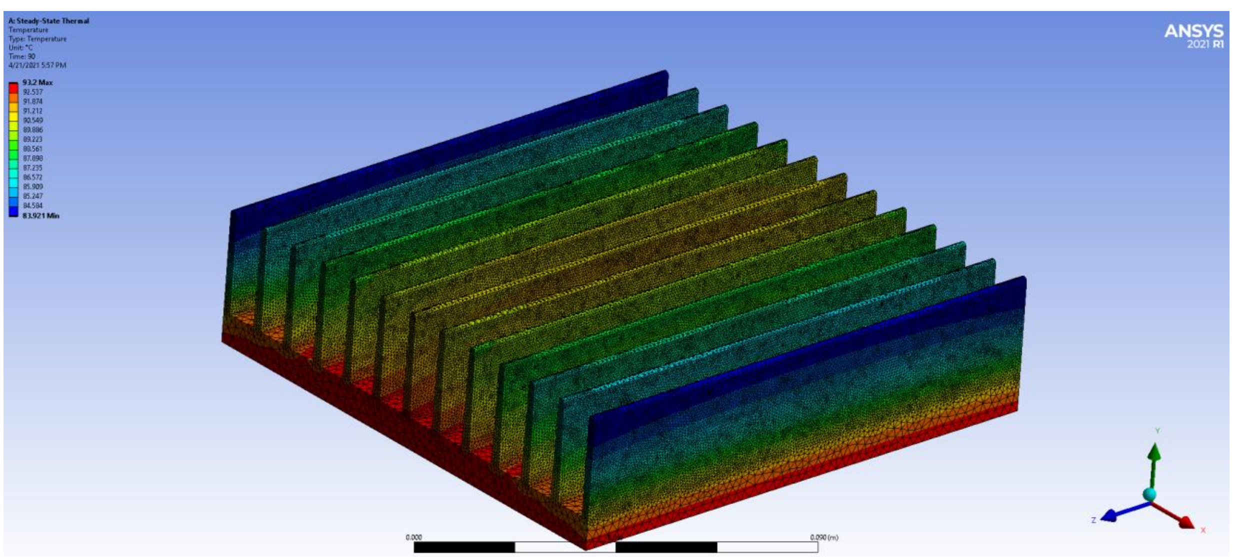

Figure 14: ANSYS Heat sink Heat Map Modified h Values

This modified heat map required greatly different convective coefficient values compared to the initial heat map. For the modified simulation, we had h values of 65 W/m^{2}K at the outer surfaces and a minimum h value of 10 at the inner most fins. This gives us around 84 degrees Celsius at the far edges with the very center being close to 92 degrees. This would suggest that there was much more airfoil in and around our test setup than previously thought. In this case, we had to ignore one of our thermocouples that was set at the very edge of the farthest fin because it was reading a value of 70 degrees, which was much too low considering the neighboring thermocouple readings were in the low 80s.

ERROR AND UNCERTAINTY

Within this experiment there are two major known sources of error. These sources of error include the thermocouples and the measurements of conditions within the room in which the experiment was conducted. The thermocouples themselves have a known uncertainty associated with them. However, there is also the issue of knowing the conditions of the room. The ambient temperature is known using a thermocouple, but the humidity of the air, speed of the air around the heat sink, and the measurement of the characteristic length of the heat sink surfaces all have some associated uncertainty as well. These sources of error are most apparent in the calculation of the convective coefficients. Because we could not measure the speed of the air near the heat sink, we are assuming anywhere from 1 (m/s) to 2 (m/s) for the air foil, with an uncertainty of 50%. We are also assuming the characteristic length to have an uncertainty of 10%. This uncertainty propagates through the calculation of the Reynolds number, and therefore through the equation for convective coefficients. Assuming an air speed of 1.5 (m/s), a characteristic length of .087 (m), air density of 1.221 (kg/m^3) and a dynamic viscosity of 1.7894E-5, we found the Reynolds number to be 8,907 ± 4,542. The uncertainty associated with this Reynolds number is large, but that is to be expected when the uncertainty of the air flow is 50%. When propagating this towards the calculation of h, we find a similarly high uncertainty. We find h to be 9.547 ± 4.962 (W/m^{2}K) with Re = 8,907 ± 4,542, Pr = .69, L = .087 (m) and k = .03 (W/mK).

DISCUSSION

The main goal of this experiment was to compare and analyze the differences between the experimental data and the results of the simulations. When comparing the data and results, we find some significant differences between both the data and the simulation results. First, it is important to analyze the experimental results and make sure that they make sense given the conditions found in the problem. The largest anomaly can be found with the thermocouple at the edge of the 4th fin. This thermocouple was reading a temperature of around 70 degrees, about 14 degrees cooler than the middle of the fin. This large drop in temperature does not make sense given the context of the problem and is likely due to a faulty thermocouple. Therefore, we have decided to throw out that thermocouples data from this thermocouple. There were some smaller anomalies as well, with the center of the 1st fin being cooler than both the 2nd and 3rd fin centers. Logically we would assume the center of fin 1 to be warmer than the other fins. This discrepancy could likely be due to the physical contact between the thermocouple and the heat sink. These differences are not large enough though to throw out the thermocouple data, so we will use all of the remaining thermocouple data.

With the experimental data and its discrepancies accounted for, we can compare them to the results found with the simulations. For both MATLAB and ANSYS, an initial simulation was done with convective coefficient values (h values) that were assumed due to the low air speed inside the experiment room. Then, a second simulation was done which would try to approximate the experimental results as closely as possible by changing the h values. For the ANSYS simulations, the initial simulation was found to be lacking when compared to the experimental results. The minimum temperature on the heat sink in the initial simulation was found to be 90 degrees, much warmer than the 84 degrees seen in the experimental results. However, when trying to account for this difference in temperature in the modified simulation, we find that we can get close to the actual results. With this modified simulation, we find a minimum temperature of 83.9 degrees. We also find agreement along the fin edges when compared to the experimental results. This simulation is not perfect though, and the temperature differences between the experimental data and the simulation vary most at the centers of the fins, with the simulation typically being cooler around the center of the fins than the actual data. This difference likely comes from the lack of ability to vary the h value along the fin, like that can be done with the MATLAB simulation. Unfortunately, the h values for the modified simulation needed to change drastically compared with the initial simulation. The h value at the outer surfaces for the modified simulation were 65 W/m^2K, compared to the 25 W/m^2K used in the initial simulation. This would suggest that there was much more air flow through the heat sink than previously thought. This could possibly be explained by induced channel flow around the heat sink due to the cardboard panels next to it. Although one of the 4 panels was left out to try and combat this, it’s possible that the other 3 panels could still have affected the surrounding air currents.

CONCLUSIONS

This Heat Sink Model Validation experiment was carried out in order to both validate numerical simulations of a heat sink, as well as help to better understand conduction and natural convection in terms of heat dissipation across a heat sink. This experiment used an aluminum alloy heat sink 5 inches long and wide, with 13 fins protruding from the base of the heat sink about an inch and a half into the air. A hot plate was also used to provide an isothermal surface. 11 thermocouples were then attached to the base of the heat sink, as well as to the edge and centers of 4 fins to collect temperature readings in real time. These thermocouples were then attached to a LabVIEW instrument which fed the temperature data to a data sheet. Two simulation software’s were then used to generate a replica of the heat sink and its environment: ANSYS and MATLAB. Each software would be used to create an initial guess as to what the convective coefficients would be around the heat sink, and then a modified simulation would be done that tried to replicate the experimental results as close as possible. The significant findings of this report were that because the air flow in the room was low, the heat sink behaved more like an isothermal object because it was not able to advect away enough heat. There was still some air flow and therefore some convection at the surfaces of the heat sink however, leading to a temperature differential of around 9 degrees Celsius. We also found that our initial guess within ANSYS produced an inaccurate result with reference to the experimental data. The convective coefficients were much lower than was actually the case, so the modified simulation needed convective coefficient values about 3 times that in the initial guess. Another interesting find was that within MATLAB, one could vary the convective coefficient values across the length of a surface, and not just create a single value for each surface. ANSYS was only able to apply a constant convective coefficient value to each surface. This would theoretically give the MATLAB model much more control and therefore more accurate results. Overall, we found that these steady state thermal simulations were very sensitive to conditions such as the airflow in the room, which are not easily measured. This means that in order to get an accurate picture using a numerical simulation, the exact conditions surrounding the heat sink must be known to a high level of certainty.

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APPENDIX I: TABLES

Time	Time	Time (s)	Surface 1	Surface 2	Fin Center 1	Fin Center 2	Fin Center 3	Fin Center 4	Fin Edge 1	Fin Edge 2	Fin Edge 3	Fin Edge 4	Ambient
4/9/2021 11:57:14.046	0.00	0.00	91.59823	92.66336	93.417172	84.837352	87.729456	88.062345	83.449019	85.889579	84.922023	70.751559	20.103965
4/9/2021 11:57:14.146	0.10	0.10	91.59823	92.66336	93.417172	84.837352	87.729456	88.062345	83.449019	85.889579	84.922023	70.751559	20.103965
4/9/2021 11:57:14.246	0.20	0.20	91.59823	92.66336	93.417172	84.837352	87.729456	88.062345	83.449019	85.889579	84.922023	70.751559	20.103965
4/9/2021 11:57:14.346	0.30	0.30	91.59823	92.66336	93.417172	84.837352	87.729456	88.062345	83.449019	85.889579	84.922023	70.751559	20.103965
4/9/2021 11:57:14.446	0.40	0.40	91.59823	92.66336	93.417172	84.837352	87.729456	88.062345	83.449019	85.889579	84.922023	70.751559	20.103965
4/9/2021 11:57:14.546	0.50	0.50	91.59823	92.66336	93.417172	84.837352	87.729456	88.062345	83.449019	85.889579	84.922023	70.751559	20.103965
4/9/2021 11:57:14.646	0.60	0.60	91.59823	92.66336	93.417172	84.837352	87.729456	88.062345	83.449019	85.889579	84.922023	70.751559	20.103965
4/9/2021 11:57:14.746	0.70	0.70	91.59823	92.66336	93.417172	84.837352	87.729456	88.062345	83.449019	85.889579	84.922023	70.751559	20.103965
4/9/2021 11:57:14.846	0.80	0.80	91.59286	92.713	93.445492	84.88643	87.774086	88.086803	83.491364	85.897443	84.875454	70.796791	20.101209
4/9/2021 11:57:14.946	0.90	0.90	91.59286	92.713	93.445492	84.88643	87.774086	88.086803	83.491364	85.897443	84.875454	70.796791	20.101209
4/9/2021 11:57:15.046	1.00	1.00	91.59286	92.713	93.445492	84.88643	87.774086	88.086803	83.491364	85.897443	84.875454	70.796791	20.101209
4/9/2021 11:57:15.146	1.10	1.10	91.59286	92.713	93.445492	84.88643	87.774086	88.086803	83.491364	85.897443	84.875454	70.796791	20.101209
4/9/2021 11:57:15.246	1.20	1.20	91.59286	92.713	93.445492	84.88643	87.774086	88.086803	83.491364	85.897443	84.875454	70.796791	20.101209
4/9/2021 11:57:15.346	1.30	1.30	91.59286	92.713	93.445492	84.88643	87.774086	88.086803	83.491364	85.897443	84.875454	70.796791	20.101209

4/9/2021 11:57:15.446	1.40	1.40	91.59286	92.713	93.445492	84.88643	87.774086	88.086803	83.491364	85.897443	84.875454	70.796791	20.101209
4/9/2021 11:57:15.546	1.50	1.50	91.59286	92.713	93.445492	84.88643	87.774086	88.086803	83.491364	85.897443	84.875454	70.796791	20.101209
4/9/2021 11:57:15.646	1.60	1.60	91.61663	92.74912	93.471968	84.904325	87.810151	88.117715	83.54889	85.905709	84.204611	70.814447	20.09933
4/9/2021 11:57:15.746	1.70	1.70	91.61663	92.74912	93.471968	84.904325	87.810151	88.117715	83.54889	85.905709	84.204611	70.814447	20.09933
4/9/2021 11:57:15.846	1.80	1.80	91.61663	92.74912	93.471968	84.904325	87.810151	88.117715	83.54889	85.905709	84.204611	70.814447	20.09933
4/9/2021 11:57:15.946	1.90	1.90	91.61663	92.74912	93.471968	84.904325	87.810151	88.117715	83.54889	85.905709	84.204611	70.814447	20.09933
4/9/2021 11:57:16.046	2.00	2.00	91.61663	92.74912	93.471968	84.904325	87.810151	88.117715	83.54889	85.905709	84.204611	70.814447	20.09933
4/9/2021 11:57:16.146	2.10	2.10	91.61663	92.74912	93.471968	84.904325	87.810151	88.117715	83.54889	85.905709	84.204611	70.814447	20.09933
4/9/2021 11:57:16.246	2.20	2.20	91.61663	92.74912	93.471968	84.904325	87.810151	88.117715	83.54889	85.905709	84.204611	70.814447	20.09933
4/9/2021 11:57:16.346	2.30	2.30	91.61663	92.74912	93.471968	84.904325	87.810151	88.117715	83.54889	85.905709	84.204611	70.814447	20.09933
4/9/2021 11:57:16.446	2.40	2.40	91.61081	92.79023	93.51556	84.887771	87.87944	88.203376	83.587877	85.918053	84.60308	70.826778	20.145683
4/9/2021 11:57:16.546	2.50	2.50	91.61081	92.79023	93.51556	84.887771	87.87944	88.203376	83.587877	85.918053	84.60308	70.826778	20.145683
4/9/2021 11:57:16.646	2.60	2.60	91.61081	92.79023	93.51556	84.887771	87.87944	88.203376	83.587877	85.918053	84.60308	70.826778	20.145683
4/9/2021 11:57:16.746	2.70	2.70	91.61081	92.79023	93.51556	84.887771	87.87944	88.203376	83.587877	85.918053	84.60308	70.826778	20.145683
4/9/2021 11:57:16.846	2.80	2.80	91.61081	92.79023	93.51556	84.887771	87.87944	88.203376	83.587877	85.918053	84.60308	70.826778	20.145683

4/9/2021 11:57:16.946	2.90	2.90	91.61081	92.79023	93.51556	84.887771	87.87944	88.203376	83.587877	85.918053	84.60308	70.826778	20.145683
4/9/2021 11:57:17.046	3.00	3.00	91.61081	92.79023	93.51556	84.887771	87.87944	88.203376	83.587877	85.918053	84.60308	70.826778	20.145683
4/9/2021 11:57:17.146	3.10	3.10	91.61081	92.79023	93.51556	84.887771	87.87944	88.203376	83.587877	85.918053	84.60308	70.826778	20.145683
4/9/2021 11:57:17.246	3.20	3.20	91.57292	92.83091	93.549733	84.896541	87.946725	88.209015	83.691594	85.934219	84.128296	70.821889	20.121395
4/9/2021 11:57:17.346	3.30	3.30	91.57292	92.83091	93.549733	84.896541	87.946725	88.209015	83.691594	85.934219	84.128296	70.821889	20.121395
4/9/2021 11:57:17.446	3.40	3.40	91.57292	92.83091	93.549733	84.896541	87.946725	88.209015	83.691594	85.934219	84.128296	70.821889	20.121395
4/9/2021 11:57:17.546	3.50	3.50	91.57292	92.83091	93.549733	84.896541	87.946725	88.209015	83.691594	85.934219	84.128296	70.821889	20.121395
4/9/2021 11:57:17.646	3.60	3.60	91.57292	92.83091	93.549733	84.896541	87.946725	88.209015	83.691594	85.934219	84.128296	70.821889	20.121395
4/9/2021 11:57:17.746	3.70	3.70	91.57292	92.83091	93.549733	84.896541	87.946725	88.209015	83.691594	85.934219	84.128296	70.821889	20.121395
4/9/2021 11:57:17.846	3.80	3.80	91.57292	92.83091	93.549733	84.896541	87.946725	88.209015	83.691594	85.934219	84.128296	70.821889	20.121395
4/9/2021 11:57:17.946	3.90	3.90	91.57292	92.83091	93.549733	84.896541	87.946725	88.209015	83.691594	85.934219	84.128296	70.821889	20.121395
4/9/2021 11:57:18.046	4.00	4.00	91.53623	92.86516	93.583989	84.909202	88.013422	88.270112	83.784648	85.952261	84.443759	70.83163	20.119895
4/9/2021 11:57:18.146	4.10	4.10	91.53623	92.86516	93.583989	84.909202	88.013422	88.270112	83.784648	85.952261	84.443759	70.83163	20.119895
4/9/2021 11:57:18.246	4.20	4.20	91.53623	92.86516	93.583989	84.909202	88.013422	88.270112	83.784648	85.952261	84.443759	70.83163	20.119895
4/9/2021 11:57:18.346	4.30	4.30	91.53623	92.86516	93.583989	84.909202	88.013422	88.270112	83.784648	85.952261	84.443759	70.83163	20.119895

4/9/2021 11:57:18.446	4.40	4.40	91.53623	92.86516	93.583989	84.909202	88.013422	88.270112	83.784648	85.952261	84.443759	70.83163	20.119895
4/9/2021 11:57:18.546	4.50	4.50	91.53623	92.86516	93.583989	84.909202	88.013422	88.270112	83.784648	85.952261	84.443759	70.83163	20.119895
4/9/2021 11:57:18.646	4.60	4.60	91.53623	92.86516	93.583989	84.909202	88.013422	88.270112	83.784648	85.952261	84.443759	70.83163	20.119895
4/9/2021 11:57:18.746	4.70	4.70	91.53623	92.86516	93.583989	84.909202	88.013422	88.270112	83.784648	85.952261	84.443759	70.83163	20.119895
4/9/2021 11:57:18.846	4.80	4.80	91.52362	92.92169	93.605951	84.94141	88.090491	88.410635	83.860965	85.989405	84.238779	70.841877	20.159457
4/9/2021 11:57:18.946	4.90	4.90	91.52362	92.92169	93.605951	84.94141	88.090491	88.410635	83.860965	85.989405	84.238779	70.841877	20.159457
4/9/2021 11:57:19.046	5.00	5.00	91.52362	92.92169	93.605951	84.94141	88.090491	88.410635	83.860965	85.989405	84.238779	70.841877	20.159457
4/9/2021 11:57:19.146	5.10	5.10	91.52362	92.92169	93.605951	84.94141	88.090491	88.410635	83.860965	85.989405	84.238779	70.841877	20.159457
4/9/2021 11:57:19.246	5.20	5.20	91.52362	92.92169	93.605951	84.94141	88.090491	88.410635	83.860965	85.989405	84.238779	70.841877	20.159457
4/9/2021 11:57:19.346	5.30	5.30	91.52362	92.92169	93.605951	84.94141	88.090491	88.410635	83.860965	85.989405	84.238779	70.841877	20.159457
4/9/2021 11:57:19.446	5.40	5.40	91.52362	92.92169	93.605951	84.94141	88.090491	88.410635	83.860965	85.989405	84.238779	70.841877	20.159457
4/9/2021 11:57:19.546	5.50	5.50	91.52362	92.92169	93.605951	84.94141	88.090491	88.410635	83.860965	85.989405	84.238779	70.841877	20.159457
4/9/2021 11:57:19.646	5.60	5.60	91.49844	92.9751	93.590192	84.955485	88.148517	88.482792	83.952971	86.0353	84.65108	70.834007	20.160114
4/9/2021 11:57:19.746	5.70	5.70	91.49844	92.9751	93.590192	84.955485	88.148517	88.482792	83.952971	86.0353	84.65108	70.834007	20.160114
4/9/2021 11:57:19.846	5.80	5.80	91.49844	92.9751	93.590192	84.955485	88.148517	88.482792	83.952971	86.0353	84.65108	70.834007	20.160114

4/9/2021 11:57:19.946	5.90	5.90	91.49844	92.9751	93.590192	84.955485	88.148517	88.482792	83.952971	86.0353	84.65108	70.834007	20.160114
4/9/2021 11:57:20.046	6.00	6.00	91.49844	92.9751	93.590192	84.955485	88.148517	88.482792	83.952971	86.0353	84.65108	70.834007	20.160114
4/9/2021 11:57:20.146	6.10	6.10	91.49844	92.9751	93.590192	84.955485	88.148517	88.482792	83.952971	86.0353	84.65108	70.834007	20.160114
4/9/2021 11:57:20.246	6.20	6.20	91.49844	92.9751	93.590192	84.955485	88.148517	88.482792	83.952971	86.0353	84.65108	70.834007	20.160114
4/9/2021 11:57:20.346	6.30	6.30	91.49844	92.9751	93.590192	84.955485	88.148517	88.482792	83.952971	86.0353	84.65108	70.834007	20.160114
4/9/2021 11:57:20.446	6.40	6.40	91.44747	92.99393	93.56097	84.951205	88.180327	88.478731	84.010727	86.065075	84.55967	70.825254	20.130206
4/9/2021 11:57:20.546	6.50	6.50	91.44747	92.99393	93.56097	84.951205	88.180327	88.478731	84.010727	86.065075	84.55967	70.825254	20.130206
4/9/2021 11:57:20.646	6.60	6.60	91.44747	92.99393	93.56097	84.951205	88.180327	88.478731	84.010727	86.065075	84.55967	70.825254	20.130206
4/9/2021 11:57:20.746	6.70	6.70	91.44747	92.99393	93.56097	84.951205	88.180327	88.478731	84.010727	86.065075	84.55967	70.825254	20.130206
4/9/2021 11:57:20.846	6.80	6.80	91.44747	92.99393	93.56097	84.951205	88.180327	88.478731	84.010727	86.065075	84.55967	70.825254	20.130206
4/9/2021 11:57:20.946	6.90	6.90	91.44747	92.99393	93.56097	84.951205	88.180327	88.478731	84.010727	86.065075	84.55967	70.825254	20.130206
4/9/2021 11:57:21.046	7.00	7.00	91.44747	92.99393	93.56097	84.951205	88.180327	88.478731	84.010727	86.065075	84.55967	70.825254	20.130206
4/9/2021 11:57:21.146	7.10	7.10	91.44747	92.99393	93.56097	84.951205	88.180327	88.478731	84.010727	86.065075	84.55967	70.825254	20.130206
4/9/2021 11:57:21.246	7.20	7.20	91.42918	93.03962	93.565343	84.995438	88.255984	88.516952	84.091232	86.144722	84.676471	70.850873	20.131242
4/9/2021 11:57:21.346	7.30	7.30	91.42918	93.03962	93.565343	84.995438	88.255984	88.516952	84.091232	86.144722	84.676471	70.850873	20.131242

4/9/2021 11:57:21.446	7.40	7.40	91.42918	93.03962	93.565343	84.995438	88.255984	88.516952	84.091232	86.144722	84.676471	70.850873	20.131242
4/9/2021 11:57:21.546	7.50	7.50	91.42918	93.03962	93.565343	84.995438	88.255984	88.516952	84.091232	86.144722	84.676471	70.850873	20.131242
4/9/2021 11:57:21.646	7.60	7.60	91.42918	93.03962	93.565343	84.995438	88.255984	88.516952	84.091232	86.144722	84.676471	70.850873	20.131242
4/9/2021 11:57:21.746	7.70	7.70	91.42918	93.03962	93.565343	84.995438	88.255984	88.516952	84.091232	86.144722	84.676471	70.850873	20.131242
4/9/2021 11:57:21.846	7.80	7.80	91.42918	93.03962	93.565343	84.995438	88.255984	88.516952	84.091232	86.144722	84.676471	70.850873	20.131242
4/9/2021 11:57:21.946	7.90	7.90	91.42918	93.03962	93.565343	84.995438	88.255984	88.516952	84.091232	86.144722	84.676471	70.850873	20.131242
4/9/2021 11:57:22.046	8.00	8.00	91.44791	93.08396	93.588358	85.050873	88.331867	88.515937	84.167484	86.239384	84.127395	70.855231	20.164245
4/9/2021 11:57:22.146	8.10	8.10	91.44791	93.08396	93.588358	85.050873	88.331867	88.515937	84.167484	86.239384	84.127395	70.855231	20.164245
4/9/2021 11:57:22.246	8.20	8.20	91.44791	93.08396	93.588358	85.050873	88.331867	88.515937	84.167484	86.239384	84.127395	70.855231	20.164245
4/9/2021 11:57:22.346	8.30	8.30	91.44791	93.08396	93.588358	85.050873	88.331867	88.515937	84.167484	86.239384	84.127395	70.855231	20.164245
4/9/2021 11:57:22.446	8.40	8.40	91.44791	93.08396	93.588358	85.050873	88.331867	88.515937	84.167484	86.239384	84.127395	70.855231	20.164245
4/9/2021 11:57:22.546	8.50	8.50	91.44791	93.08396	93.588358	85.050873	88.331867	88.515937	84.167484	86.239384	84.127395	70.855231	20.164245
4/9/2021 11:57:22.646	8.60	8.60	91.44791	93.08396	93.588358	85.050873	88.331867	88.515937	84.167484	86.239384	84.127395	70.855231	20.164245
4/9/2021 11:57:22.746	8.70	8.70	91.44791	93.08396	93.588358	85.050873	88.331867	88.515937	84.167484	86.239384	84.127395	70.855231	20.164245
4/9/2021 11:57:22.846	8.80	8.80	91.46748	93.11388	93.598511	85.105576	88.401863	88.489751	84.231808	86.250185	84.681103	70.876539	20.125376

4/9/2021 11:57:22.946	8.90	8.90	91.46748	93.11388	93.598511	85.105576	88.401863	88.489751	84.231808	86.250185	84.681103	70.876539	20.125376
4/9/2021 11:57:23.046	9.00	9.00	91.46748	93.11388	93.598511	85.105576	88.401863	88.489751	84.231808	86.250185	84.681103	70.876539	20.125376
4/9/2021 11:57:23.146	9.10	9.10	91.46748	93.11388	93.598511	85.105576	88.401863	88.489751	84.231808	86.250185	84.681103	70.876539	20.125376
4/9/2021 11:57:23.246	9.20	9.20	91.46748	93.11388	93.598511	85.105576	88.401863	88.489751	84.231808	86.250185	84.681103	70.876539	20.125376
4/9/2021 11:57:23.346	9.30	9.30	91.46748	93.11388	93.598511	85.105576	88.401863	88.489751	84.231808	86.250185	84.681103	70.876539	20.125376
4/9/2021 11:57:23.446	9.40	9.40	91.46748	93.11388	93.598511	85.105576	88.401863	88.489751	84.231808	86.250185	84.681103	70.876539	20.125376
4/9/2021 11:57:23.546	9.50	9.50	91.46748	93.11388	93.598511	85.105576	88.401863	88.489751	84.231808	86.250185	84.681103	70.876539	20.125376
4/9/2021 11:57:23.646	9.60	9.60	91.47427	93.1548	93.587564	85.164773	88.479272	88.515593	84.300176	86.280269	84.94592	70.908154	20.113159
4/9/2021 11:57:23.746	9.70	9.70	91.47427	93.1548	93.587564	85.164773	88.479272	88.515593	84.300176	86.280269	84.94592	70.908154	20.113159
4/9/2021 11:57:23.846	9.80	9.80	91.47427	93.1548	93.587564	85.164773	88.479272	88.515593	84.300176	86.280269	84.94592	70.908154	20.113159
4/9/2021 11:57:23.946	9.90	9.90	91.47427	93.1548	93.587564	85.164773	88.479272	88.515593	84.300176	86.280269	84.94592	70.908154	20.113159
4/9/2021 11:57:24.046	10.00	10.00	91.47427	93.1548	93.587564	85.164773	88.479272	88.515593	84.300176	86.280269	84.94592	70.908154	20.113159
4/9/2021 11:57:24.146	10.10	10.10	91.47427	93.1548	93.587564	85.164773	88.479272	88.515593	84.300176	86.280269	84.94592	70.908154	20.113159
4/9/2021 11:57:24.246	10.20	10.20	91.47427	93.1548	93.587564	85.164773	88.479272	88.515593	84.300176	86.280269	84.94592	70.908154	20.113159
4/9/2021 11:57:24.346	10.30	10.30	91.47427	93.1548	93.587564	85.164773	88.479272	88.515593	84.300176	86.280269	84.94592	70.908154	20.113159

4/9/2021 11:57:24.446	10.40	10.40	91.49565	93.19618	93.580211	85.173568	88.566995	88.559372	84.382879	86.349566	84.562956	70.934845	20.141017
4/9/2021 11:57:24.546	10.50	10.50	91.49565	93.19618	93.580211	85.173568	88.566995	88.559372	84.382879	86.349566	84.562956	70.934845	20.141017
4/9/2021 11:57:24.646	10.60	10.60	91.49565	93.19618	93.580211	85.173568	88.566995	88.559372	84.382879	86.349566	84.562956	70.934845	20.141017
4/9/2021 11:57:24.746	10.70	10.70	91.49565	93.19618	93.580211	85.173568	88.566995	88.559372	84.382879	86.349566	84.562956	70.934845	20.141017
4/9/2021 11:57:24.846	10.80	10.80	91.49565	93.19618	93.580211	85.173568	88.566995	88.559372	84.382879	86.349566	84.562956	70.934845	20.141017
4/9/2021 11:57:24.946	10.90	10.90	91.49565	93.19618	93.580211	85.173568	88.566995	88.559372	84.382879	86.349566	84.562956	70.934845	20.141017
4/9/2021 11:57:25.046	11.00	11.00	91.49565	93.19618	93.580211	85.173568	88.566995	88.559372	84.382879	86.349566	84.562956	70.934845	20.141017
4/9/2021 11:57:25.146	11.10	11.10	91.49565	93.19618	93.580211	85.173568	88.566995	88.559372	84.382879	86.349566	84.562956	70.934845	20.141017
4/9/2021 11:57:25.246	11.20	11.20	91.4913	93.23001	93.571144	85.167885	88.649423	88.59606	84.443493	86.457264	84.481569	70.95289	20.132824
4/9/2021 11:57:25.346	11.30	11.30	91.4913	93.23001	93.571144	85.167885	88.649423	88.59606	84.443493	86.457264	84.481569	70.95289	20.132824
4/9/2021 11:57:25.446	11.40	11.40	91.4913	93.23001	93.571144	85.167885	88.649423	88.59606	84.443493	86.457264	84.481569	70.95289	20.132824
4/9/2021 11:57:25.546	11.50	11.50	91.4913	93.23001	93.571144	85.167885	88.649423	88.59606	84.443493	86.457264	84.481569	70.95289	20.132824
4/9/2021 11:57:25.646	11.60	11.60	91.4913	93.23001	93.571144	85.167885	88.649423	88.59606	84.443493	86.457264	84.481569	70.95289	20.132824
4/9/2021 11:57:25.746	11.70	11.70	91.4913	93.23001	93.571144	85.167885	88.649423	88.59606	84.443493	86.457264	84.481569	70.95289	20.132824
4/9/2021 11:57:25.846	11.80	11.80	91.4913	93.23001	93.571144	85.167885	88.649423	88.59606	84.443493	86.457264	84.481569	70.95289	20.132824

4/9/2021 11:57:25.946	11.90	11.90	91.4913	93.23001	93.571144	85.167885	88.649423	88.59606	84.443493	86.457264	84.481569	70.95289	20.132824
4/9/2021 11:57:26.046	12.00	12.00	91.49933	93.24276	93.571545	85.175004	88.721798	88.6709	84.493391	86.501136	84.652866	70.955975	20.121191
4/9/2021 11:57:26.146	12.10	12.10	91.49933	93.24276	93.571545	85.175004	88.721798	88.6709	84.493391	86.501136	84.652866	70.955975	20.121191
4/9/2021 11:57:26.246	12.20	12.20	91.49933	93.24276	93.571545	85.175004	88.721798	88.6709	84.493391	86.501136	84.652866	70.955975	20.121191
4/9/2021 11:57:26.346	12.30	12.30	91.49933	93.24276	93.571545	85.175004	88.721798	88.6709	84.493391	86.501136	84.652866	70.955975	20.121191
4/9/2021 11:57:26.446	12.40	12.40	91.49933	93.24276	93.571545	85.175004	88.721798	88.6709	84.493391	86.501136	84.652866	70.955975	20.121191
4/9/2021 11:57:26.546	12.50	12.50	91.49933	93.24276	93.571545	85.175004	88.721798	88.6709	84.493391	86.501136	84.652866	70.955975	20.121191
4/9/2021 11:57:26.646	12.60	12.60	91.49933	93.24276	93.571545	85.175004	88.721798	88.6709	84.493391	86.501136	84.652866	70.955975	20.121191
4/9/2021 11:57:26.746	12.70	12.70	91.49933	93.24276	93.571545	85.175004	88.721798	88.6709	84.493391	86.501136	84.652866	70.955975	20.121191
4/9/2021 11:57:26.846	12.80	12.80	91.51853	93.26466	93.581095	85.188339	88.807793	88.690973	84.540096	86.54607	84.875853	70.955197	20.110888
4/9/2021 11:57:26.946	12.90	12.90	91.51853	93.26466	93.581095	85.188339	88.807793	88.690973	84.540096	86.54607	84.875853	70.955197	20.110888
4/9/2021 11:57:27.046	13.00	13.00	91.51853	93.26466	93.581095	85.188339	88.807793	88.690973	84.540096	86.54607	84.875853	70.955197	20.110888
4/9/2021 11:57:27.146	13.10	13.10	91.51853	93.26466	93.581095	85.188339	88.807793	88.690973	84.540096	86.54607	84.875853	70.955197	20.110888
4/9/2021 11:57:27.246	13.20	13.20	91.51853	93.26466	93.581095	85.188339	88.807793	88.690973	84.540096	86.54607	84.875853	70.955197	20.110888
4/9/2021 11:57:27.346	13.30	13.30	91.51853	93.26466	93.581095	85.188339	88.807793	88.690973	84.540096	86.54607	84.875853	70.955197	20.110888

4/9/2021 11:57:27.446	13.40	13.40	91.51853	93.26466	93.581095	85.188339	88.807793	88.690973	84.540096	86.54607	84.875853	70.955197	20.110888
4/9/2021 11:57:27.546	13.50	13.50	91.51853	93.26466	93.581095	85.188339	88.807793	88.690973	84.540096	86.54607	84.875853	70.955197	20.110888
4/9/2021 11:57:27.646	13.60	13.60	91.55738	93.31881	93.5919	85.220844	88.889661	88.721715	84.587828	86.595169	84.842054	70.969096	20.125507
4/9/2021 11:57:27.746	13.70	13.70	91.55738	93.31881	93.5919	85.220844	88.889661	88.721715	84.587828	86.595169	84.842054	70.969096	20.125507
4/9/2021 11:57:27.846	13.80	13.80	91.55738	93.31881	93.5919	85.220844	88.889661	88.721715	84.587828	86.595169	84.842054	70.969096	20.125507
4/9/2021 11:57:27.946	13.90	13.90	91.55738	93.31881	93.5919	85.220844	88.889661	88.721715	84.587828	86.595169	84.842054	70.969096	20.125507
4/9/2021 11:57:28.046	14.00	14.00	91.55738	93.31881	93.5919	85.220844	88.889661	88.721715	84.587828	86.595169	84.842054	70.969096	20.125507
4/9/2021 11:57:28.146	14.10	14.10	91.55738	93.31881	93.5919	85.220844	88.889661	88.721715	84.587828	86.595169	84.842054	70.969096	20.125507
4/9/2021 11:57:28.246	14.20	14.20	91.55738	93.31881	93.5919	85.220844	88.889661	88.721715	84.587828	86.595169	84.842054	70.969096	20.125507
4/9/2021 11:57:28.346	14.30	14.30	91.55738	93.31881	93.5919	85.220844	88.889661	88.721715	84.587828	86.595169	84.842054	70.969096	20.125507
4/9/2021 11:57:28.446	14.40	14.40	91.56926	93.36438	93.600197	85.263394	88.967907	88.736725	84.640227	86.650058	85.04364	70.990121	20.119007
4/9/2021 11:57:28.546	14.50	14.50	91.56926	93.36438	93.600197	85.263394	88.967907	88.736725	84.640227	86.650058	85.04364	70.990121	20.119007
4/9/2021 11:57:28.646	14.60	14.60	91.56926	93.36438	93.600197	85.263394	88.967907	88.736725	84.640227	86.650058	85.04364	70.990121	20.119007
4/9/2021 11:57:28.746	14.70	14.70	91.56926	93.36438	93.600197	85.263394	88.967907	88.736725	84.640227	86.650058	85.04364	70.990121	20.119007
4/9/2021 11:57:28.846	14.80	14.80	91.56926	93.36438	93.600197	85.263394	88.967907	88.736725	84.640227	86.650058	85.04364	70.990121	20.119007

4/9/2021 11:57:28.946	14.90	14.90	91.56926	93.36438	93.600197	85.263394	88.967907	88.736725	84.640227	86.650058	85.04364	70.990121	20.119007
4/9/2021 11:57:29.046	15.00	15.00	91.56926	93.36438	93.600197	85.263394	88.967907	88.736725	84.640227	86.650058	85.04364	70.990121	20.119007
4/9/2021 11:57:29.146	15.10	15.10	91.56926	93.36438	93.600197	85.263394	88.967907	88.736725	84.640227	86.650058	85.04364	70.990121	20.119007
4/9/2021 11:57:29.246	15.20	15.20	91.6055	93.40289	93.602773	85.318384	89.044927	88.767549	84.689833	86.705291	85.025601	70.990227	20.129309
4/9/2021 11:57:29.346	15.30	15.30	91.6055	93.40289	93.602773	85.318384	89.044927	88.767549	84.689833	86.705291	85.025601	70.990227	20.129309
4/9/2021 11:57:29.446	15.40	15.40	91.6055	93.40289	93.602773	85.318384	89.044927	88.767549	84.689833	86.705291	85.025601	70.990227	20.129309
4/9/2021 11:57:29.546	15.50	15.50	91.6055	93.40289	93.602773	85.318384	89.044927	88.767549	84.689833	86.705291	85.025601	70.990227	20.129309
4/9/2021 11:57:29.646	15.60	15.60	91.6055	93.40289	93.602773	85.318384	89.044927	88.767549	84.689833	86.705291	85.025601	70.990227	20.129309
4/9/2021 11:57:29.746	15.70	15.70	91.6055	93.40289	93.602773	85.318384	89.044927	88.767549	84.689833	86.705291	85.025601	70.990227	20.129309
4/9/2021 11:57:29.846	15.80	15.80	91.6055	93.40289	93.602773	85.318384	89.044927	88.767549	84.689833	86.705291	85.025601	70.990227	20.129309
4/9/2021 11:57:29.946	15.90	15.90	91.6055	93.40289	93.602773	85.318384	89.044927	88.767549	84.689833	86.705291	85.025601	70.990227	20.129309
4/9/2021 11:57:30.046	16.00	16.00	91.63341	93.4261	93.624642	85.34714	89.106228	88.806422	84.731353	86.757363	85.216314	70.996799	20.117579
4/9/2021 11:57:30.146	16.10	16.10	91.63341	93.4261	93.624642	85.34714	89.106228	88.806422	84.731353	86.757363	85.216314	70.996799	20.117579
4/9/2021 11:57:30.246	16.20	16.20	91.63341	93.4261	93.624642	85.34714	89.106228	88.806422	84.731353	86.757363	85.216314	70.996799	20.117579
4/9/2021 11:57:30.346	16.30	16.30	91.63341	93.4261	93.624642	85.34714	89.106228	88.806422	84.731353	86.757363	85.216314	70.996799	20.117579

4/9/2021 11:57:30.446	16.40	16.40	91.63341	93.4261	93.624642	85.34714	89.106228	88.806422	84.731353	86.757363	85.216314	70.996799	20.117579
4/9/2021 11:57:30.546	16.50	16.50	91.63341	93.4261	93.624642	85.34714	89.106228	88.806422	84.731353	86.757363	85.216314	70.996799	20.117579
4/9/2021 11:57:30.646	16.60	16.60	91.63341	93.4261	93.624642	85.34714	89.106228	88.806422	84.731353	86.757363	85.216314	70.996799	20.117579
4/9/2021 11:57:30.746	16.70	16.70	91.63341	93.4261	93.624642	85.34714	89.106228	88.806422	84.731353	86.757363	85.216314	70.996799	20.117579
4/9/2021 11:57:30.846	16.80	16.80	91.64786	93.4583	93.648307	85.386426	89.176949	88.872876	84.789	86.777838	85.218636	70.979648	20.121371
4/9/2021 11:57:30.946	16.90	16.90	91.64786	93.4583	93.648307	85.386426	89.176949	88.872876	84.789	86.777838	85.218636	70.979648	20.121371
4/9/2021 11:57:31.046	17.00	17.00	91.64786	93.4583	93.648307	85.386426	89.176949	88.872876	84.789	86.777838	85.218636	70.979648	20.121371
4/9/2021 11:57:31.146	17.10	17.10	91.64786	93.4583	93.648307	85.386426	89.176949	88.872876	84.789	86.777838	85.218636	70.979648	20.121371
4/9/2021 11:57:31.246	17.20	17.20	91.64786	93.4583	93.648307	85.386426	89.176949	88.872876	84.789	86.777838	85.218636	70.979648	20.121371
4/9/2021 11:57:31.346	17.30	17.30	91.64786	93.4583	93.648307	85.386426	89.176949	88.872876	84.789	86.777838	85.218636	70.979648	20.121371
4/9/2021 11:57:31.446	17.40	17.40	91.64786	93.4583	93.648307	85.386426	89.176949	88.872876	84.789	86.777838	85.218636	70.979648	20.121371
4/9/2021 11:57:31.546	17.50	17.50	91.64786	93.4583	93.648307	85.386426	89.176949	88.872876	84.789	86.777838	85.218636	70.979648	20.121371
4/9/2021 11:57:31.646	17.60	17.60	91.66717	93.49739	93.684031	85.434827	89.256123	88.898451	84.84389	86.817292	85.250234	70.970707	20.123468
4/9/2021 11:57:31.746	17.70	17.70	91.66717	93.49739	93.684031	85.434827	89.256123	88.898451	84.84389	86.817292	85.250234	70.970707	20.123468
4/9/2021 11:57:31.846	17.80	17.80	91.66717	93.49739	93.684031	85.434827	89.256123	88.898451	84.84389	86.817292	85.250234	70.970707	20.123468

4/9/2021 11:57:31.946	17.90	17.90	91.66717	93.49739	93.684031	85.434827	89.256123	88.898451	84.84389	86.817292	85.250234	70.970707	20.123468
4/9/2021 11:57:32.046	18.00	18.00	91.66717	93.49739	93.684031	85.434827	89.256123	88.898451	84.84389	86.817292	85.250234	70.970707	20.123468
4/9/2021 11:57:32.146	18.10	18.10	91.66717	93.49739	93.684031	85.434827	89.256123	88.898451	84.84389	86.817292	85.250234	70.970707	20.123468
4/9/2021 11:57:32.246	18.20	18.20	91.66717	93.49739	93.684031	85.434827	89.256123	88.898451	84.84389	86.817292	85.250234	70.970707	20.123468
4/9/2021 11:57:32.346	18.30	18.30	91.66717	93.49739	93.684031	85.434827	89.256123	88.898451	84.84389	86.817292	85.250234	70.970707	20.123468
4/9/2021 11:57:32.446	18.40	18.40	91.70476	93.53298	93.737368	85.507517	89.320367	88.961791	84.90985	86.860201	85.287527	70.965218	20.129368
4/9/2021 11:57:32.546	18.50	18.50	91.70476	93.53298	93.737368	85.507517	89.320367	88.961791	84.90985	86.860201	85.287527	70.965218	20.129368
4/9/2021 11:57:32.646	18.60	18.60	91.70476	93.53298	93.737368	85.507517	89.320367	88.961791	84.90985	86.860201	85.287527	70.965218	20.129368
4/9/2021 11:57:32.746	18.70	18.70	91.70476	93.53298	93.737368	85.507517	89.320367	88.961791	84.90985	86.860201	85.287527	70.965218	20.129368
4/9/2021 11:57:32.846	18.80	18.80	91.70476	93.53298	93.737368	85.507517	89.320367	88.961791	84.90985	86.860201	85.287527	70.965218	20.129368
4/9/2021 11:57:32.946	18.90	18.90	91.70476	93.53298	93.737368	85.507517	89.320367	88.961791	84.90985	86.860201	85.287527	70.965218	20.129368
4/9/2021 11:57:33.046	19.00	19.00	91.70476	93.53298	93.737368	85.507517	89.320367	88.961791	84.90985	86.860201	85.287527	70.965218	20.129368
4/9/2021 11:57:33.146	19.10	19.10	91.70476	93.53298	93.737368	85.507517	89.320367	88.961791	84.90985	86.860201	85.287527	70.965218	20.129368
4/9/2021 11:57:33.246	19.20	19.20	91.73317	93.55939	93.797917	85.576646	89.38329	89.003852	84.97561	86.904254	84.706146	70.978998	20.161237
4/9/2021 11:57:33.346	19.30	19.30	91.73317	93.55939	93.797917	85.576646	89.38329	89.003852	84.97561	86.904254	84.706146	70.978998	20.161237

4/9/2021 11:57:33.446	19.40	19.40	91.73317	93.55939	93.797917	85.576646	89.38329	89.003852	84.97561	86.904254	84.706146	70.978998	20.161237
4/9/2021 11:57:33.546	19.50	19.50	91.73317	93.55939	93.797917	85.576646	89.38329	89.003852	84.97561	86.904254	84.706146	70.978998	20.161237
4/9/2021 11:57:33.646	19.60	19.60	91.73317	93.55939	93.797917	85.576646	89.38329	89.003852	84.97561	86.904254	84.706146	70.978998	20.161237
4/9/2021 11:57:33.746	19.70	19.70	91.73317	93.55939	93.797917	85.576646	89.38329	89.003852	84.97561	86.904254	84.706146	70.978998	20.161237
4/9/2021 11:57:33.846	19.80	19.80	91.73317	93.55939	93.797917	85.576646	89.38329	89.003852	84.97561	86.904254	84.706146	70.978998	20.161237
4/9/2021 11:57:33.946	19.90	19.90	91.73317	93.55939	93.797917	85.576646	89.38329	89.003852	84.97561	86.904254	84.706146	70.978998	20.161237
4/9/2021 11:57:34.046	20.00	20.00	91.75601	93.58225	93.799218	85.648066	89.434152	88.983399	85.0571	86.935133	84.725585	70.952094	20.19964
4/9/2021 11:57:34.146	20.10	20.10	91.75601	93.58225	93.799218	85.648066	89.434152	88.983399	85.0571	86.935133	84.725585	70.952094	20.19964
4/9/2021 11:57:34.246	20.20	20.20	91.75601	93.58225	93.799218	85.648066	89.434152	88.983399	85.0571	86.935133	84.725585	70.952094	20.19964
4/9/2021 11:57:34.346	20.30	20.30	91.75601	93.58225	93.799218	85.648066	89.434152	88.983399	85.0571	86.935133	84.725585	70.952094	20.19964
4/9/2021 11:57:34.446	20.40	20.40	91.75601	93.58225	93.799218	85.648066	89.434152	88.983399	85.0571	86.935133	84.725585	70.952094	20.19964
4/9/2021 11:57:34.546	20.50	20.50	91.75601	93.58225	93.799218	85.648066	89.434152	88.983399	85.0571	86.935133	84.725585	70.952094	20.19964
4/9/2021 11:57:34.646	20.60	20.60	91.75601	93.58225	93.799218	85.648066	89.434152	88.983399	85.0571	86.935133	84.725585	70.952094	20.19964
4/9/2021 11:57:34.746	20.70	20.70	91.75601	93.58225	93.799218	85.648066	89.434152	88.983399	85.0571	86.935133	84.725585	70.952094	20.19964
4/9/2021 11:57:34.846	20.80	20.80	91.78747	93.59846	93.821265	85.71464	89.48734	88.993077	85.129714	86.974612	84.880399	70.961529	20.198055

4/9/2021 11:57:34.946	20.90	20.90	91.78747	93.59846	93.821265	85.71464	89.48734	88.993077	85.129714	86.974612	84.880399	70.961529	20.198055
4/9/2021 11:57:35.046	21.00	21.00	91.78747	93.59846	93.821265	85.71464	89.48734	88.993077	85.129714	86.974612	84.880399	70.961529	20.198055
4/9/2021 11:57:35.146	21.10	21.10	91.78747	93.59846	93.821265	85.71464	89.48734	88.993077	85.129714	86.974612	84.880399	70.961529	20.198055
4/9/2021 11:57:35.246	21.20	21.20	91.78747	93.59846	93.821265	85.71464	89.48734	88.993077	85.129714	86.974612	84.880399	70.961529	20.198055
4/9/2021 11:57:35.346	21.30	21.30	91.78747	93.59846	93.821265	85.71464	89.48734	88.993077	85.129714	86.974612	84.880399	70.961529	20.198055
4/9/2021 11:57:35.446	21.40	21.40	91.78747	93.59846	93.821265	85.71464	89.48734	88.993077	85.129714	86.974612	84.880399	70.961529	20.198055
4/9/2021 11:57:35.546	21.50	21.50	91.78747	93.59846	93.821265	85.71464	89.48734	88.993077	85.129714	86.974612	84.880399	70.961529	20.198055
4/9/2021 11:57:35.646	21.60	21.60	91.81854	93.63134	93.815518	85.786651	89.540586	89.02703	85.216499	87.013701	84.990923	70.958265	20.189117
4/9/2021 11:57:35.746	21.70	21.70	91.81854	93.63134	93.815518	85.786651	89.540586	89.02703	85.216499	87.013701	84.990923	70.958265	20.189117
4/9/2021 11:57:35.846	21.80	21.80	91.81854	93.63134	93.815518	85.786651	89.540586	89.02703	85.216499	87.013701	84.990923	70.958265	20.189117
4/9/2021 11:57:35.946	21.90	21.90	91.81854	93.63134	93.815518	85.786651	89.540586	89.02703	85.216499	87.013701	84.990923	70.958265	20.189117
4/9/2021 11:57:36.046	22.00	22.00	91.81854	93.63134	93.815518	85.786651	89.540586	89.02703	85.216499	87.013701	84.990923	70.958265	20.189117
4/9/2021 11:57:36.146	22.10	22.10	91.81854	93.63134	93.815518	85.786651	89.540586	89.02703	85.216499	87.013701	84.990923	70.958265	20.189117
4/9/2021 11:57:36.246	22.20	22.20	91.81854	93.63134	93.815518	85.786651	89.540586	89.02703	85.216499	87.013701	84.990923	70.958265	20.189117
4/9/2021 11:57:36.346	22.30	22.30	91.81854	93.63134	93.815518	85.786651	89.540586	89.02703	85.216499	87.013701	84.990923	70.958265	20.189117

4/9/2021 11:57:36.446	22.40	22.40	91.84871	93.66894	93.861885	85.882861	89.59249	89.033179	85.289623	87.071841	85.021035	70.980964	20.208673
4/9/2021 11:57:36.546	22.50	22.50	91.84871	93.66894	93.861885	85.882861	89.59249	89.033179	85.289623	87.071841	85.021035	70.980964	20.208673
4/9/2021 11:57:36.646	22.60	22.60	91.84871	93.66894	93.861885	85.882861	89.59249	89.033179	85.289623	87.071841	85.021035	70.980964	20.208673
4/9/2021 11:57:36.746	22.70	22.70	91.84871	93.66894	93.861885	85.882861	89.59249	89.033179	85.289623	87.071841	85.021035	70.980964	20.208673
4/9/2021 11:57:36.846	22.80	22.80	91.84871	93.66894	93.861885	85.882861	89.59249	89.033179	85.289623	87.071841	85.021035	70.980964	20.208673
4/9/2021 11:57:36.946	22.90	22.90	91.84871	93.66894	93.861885	85.882861	89.59249	89.033179	85.289623	87.071841	85.021035	70.980964	20.208673
4/9/2021 11:57:37.046	23.00	23.00	91.84871	93.66894	93.861885	85.882861	89.59249	89.033179	85.289623	87.071841	85.021035	70.980964	20.208673
4/9/2021 11:57:37.146	23.10	23.10	91.84871	93.66894	93.861885	85.882861	89.59249	89.033179	85.289623	87.071841	85.021035	70.980964	20.208673
4/9/2021 11:57:37.246	23.20	23.20	91.87561	93.70979	93.883637	85.959451	89.624527	89.019465	85.336407	87.11506	84.867111	70.982047	20.218133
4/9/2021 11:57:37.346	23.30	23.30	91.87561	93.70979	93.883637	85.959451	89.624527	89.019465	85.336407	87.11506	84.867111	70.982047	20.218133
4/9/2021 11:57:37.446	23.40	23.40	91.87561	93.70979	93.883637	85.959451	89.624527	89.019465	85.336407	87.11506	84.867111	70.982047	20.218133
4/9/2021 11:57:37.546	23.50	23.50	91.87561	93.70979	93.883637	85.959451	89.624527	89.019465	85.336407	87.11506	84.867111	70.982047	20.218133
4/9/2021 11:57:37.646	23.60	23.60	91.87561	93.70979	93.883637	85.959451	89.624527	89.019465	85.336407	87.11506	84.867111	70.982047	20.218133
4/9/2021 11:57:37.746	23.70	23.70	91.87561	93.70979	93.883637	85.959451	89.624527	89.019465	85.336407	87.11506	84.867111	70.982047	20.218133
4/9/2021 11:57:37.846	23.80	23.80	91.87561	93.70979	93.883637	85.959451	89.624527	89.019465	85.336407	87.11506	84.867111	70.982047	20.218133

4/9/2021 11:57:37.946	23.90	23.90	91.87561	93.70979	93.883637	85.959451	89.624527	89.019465	85.336407	87.11506	84.867111	70.982047	20.218133