

Characterization of Convective Heat Transfer Coefficients of a Self-Aspirated Hot Gas Temperature Probe

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Master of Science
Degree
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Dedication

For my Dad. The best engineer I know.

Acknowledgements

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Abstract

The objective of this work is to provide a Nusselt Number in a Reynolds Number and Prandtl Number correlation for various surfaces of an aspirated total temperature probe exposed to high temperature flow. The experiment discharged thermally stabilized dry air through large scale models of the probe surfaces in a blow-down wind tunnel and a direct connect facility. The model contained electrically heated sections exposed to the flow which were thermally insulated and instrumented with thermocouples. Experimental data were recorded for several Reynolds numbers and heater positions across three configurations. Uncertainty analysis was performed by the Monte Carlo uncertainty propagation method. Reynolds number to Nusselt number correlations and their associated uncertainties were developed to a 95% confidence interval.

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List of Symbols / Nomenclature

A	Area [m^2]
C	Lumped constant used to minimize variation in h over time [J/K]
C_p	Specific Heat [$J/(kg\ K)$]
d_{ref}	Reference Diameter [m]
E	Electrical potential difference [V/m]
ESW	External Shield Wall
h	Convection coefficient [$W/(m^2K)$]
I	Electrical Current [A]
ISW	Internal Shield Wall
k	Conduction coefficient [$W/(m\ K)$]
m	Mass [kg]
Nu	Nusselt Number
Pr	Prandtl Number (0.713)
$q_{cond,ABS}$	Heat flux (conductive through ABS plastic) [W/m]
$q_{c,wires}$	Heat flux (conductive through wires) [W/m]
$q_{cond,wood}$	Heat flux (conductive through wood) [W/m]
q_{rad}	Heat flux (radiative) [W/m]
Re	Reynolds Number
SGFC	Sonic Gas Flow Calibrator
T	Temperature [K]
TCS	Thermocouple Sheath
ϵ	Emissivity coefficient of aluminum (0.09)
μ	Dynamic viscosity [$N\ s/m^2$]
ρ	Density [kg/m^3]
σ	Stefan-Boltzmann constant (5.67037×10^{-8}) [$W/(m^2K^4)$] or population standard deviation

1

Introduction and General Information

Total temperature probes used for measuring hot gas flows, such as in the exhaust stream of a turbine engine, must be cooled to survive the high temperature environment. The heat transfer caused by the temperature difference between the probe and the flow must be understood to ensure accurate total temperature measurement. This temperature difference is called the recovery factor. The combined effects of convection between the probe and the flow, conduction between the probe and the cooled support system, and radiation between the probe and any surrounding structure are the three major drivers of the recovery factor. This work seeks to develop a convection model of the probe via a wind tunnel simulation, which can later be used as a component of the probe recovery factor.

The total temperature probe being simulated is similar to “probe 6” described in (Glawe, Simmons, & Stickney, 1956). An open-ended tube serves as a thermal radiation shield for the thermocouple and contains the continuously aspirated gas sample. A thermocouple mounted inside a sheath at the centerline of the tube measures the temperature of the sample. The probe apparatus is mounted in a cooling jacket support system and immersed into the flow. Flow enters the open end of tube in the axial direction and exits through four choked vent holes which are positioned aft of the thermocouple. In the case of a supersonic flow, a bow shock will form in front of the probe inlet. Figure 1 shows a draft of the simulated probe, approximate streamlines, and surfaces where convection will occur which this experiment will investigate.

The Nusselt number of a flow interacting with a solid surface is the ratio of convection to conduction heat transfer between the surface and the flow; defined $Nu = hd_{ref}/k$. Nusselt number can also be written as a function of the dimensionless parameters Reynolds number, which is the ratio of inertial to viscous forces in the flow ($Re = \rho u d_{ref}/\mu$); and Prandtl number, which is the ratio of momentum and thermal diffusivities in the flow ($Pr = C_p \mu/k$). The objective of this work is to create correlations between Nu, Re, and Pr for a large scale model of

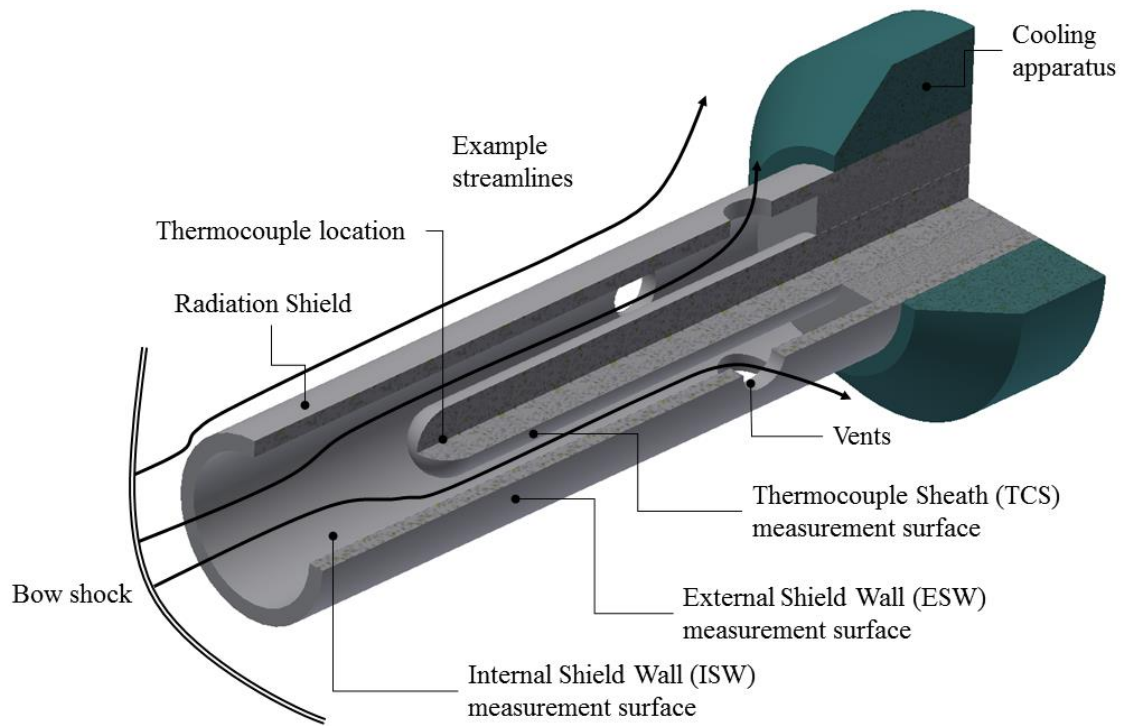


Figure 1: Cartoon illustration of the probe modeled in this experiment.

the probe which may then be used to calculate recovery temperatures of the real probe in a hot flow. For Prandtl numbers greater than 0.6, a function of the form $Nu = a Re^b Pr^{1/3}$ (Bergaman, Lavine, & Incopera, 2011) was assumed for similarity to the flat plate correlations; which are derived from the heat transfer solution of the energy equation for a flat plate in parallel flow. This experimental data is limited to room temperature air ($Pr \sim 0.713$) flowing through a large scale model. Therefore, this work cannot verify this correlation or develop a different correlation for higher temperature flows.

2

Methods and Materials

Three configurations were tested in order to estimate the convective heat transfer on the outer and inner surfaces of the probe shield, and on the internal sheath where the temperature measurement is made. The probe is meant to be installed in the exhaust stream behind a turbojet engine. By scaling up the probe, it was possible to instrument the model with thermocouples and a heater while using room temperature air to simulate the Reynolds numbers experienced by the real probe in a hot flow. The fundamental assumption in this methodology is that a Nu, Re, and Pr correlation does not depend on Mach number, and that the correlation is scalable. This assumption allows the experiment to be conducted without matching Mach number experienced by the real probe. Additionally, the vents in the model did not need to be choked even though vents of the real probe usually are; since the experiment simulated Reynolds numbers that occur inside the tube of the real probe.

Internal convection tests were performed with insulated models installed inside an 20.3 cm diameter PVC pipe, which served as a direct connect test facility. Process air was provided to the internal tests with a Sonic Gas Flow Calibrator (SGFC) (Flow Dynamics, Inc.). The external convection tests were performed in a 15 cm diameter blowdown wind tunnel powered by a temperature stabilized pressurized air supply.

2.1 External Shield Wall (ESW) Convection Model

Convection between the external shield and the freestream flow was simulated by a 2.54 cm diameter model of the external body of the probe with a flat face (Figure 2). This model is comprised of a 2.54 cm diameter by 3.175 cm long aluminum slug, instrumented with 8 type K thermocouples (Omega model KMQXL-062G-12), and a cartage type electrical heater (Omega PN: CSH-201100/120). This aluminum cylinder served as an insulated lumped mass with known input energy and temperature, and was used to take the heat transfer measurement. The instrumentation wires leaving the slug were passed through a 2.54 cm outer diameter by 20.3 cm long thin walled steel pipe, which provided structural support to the model.

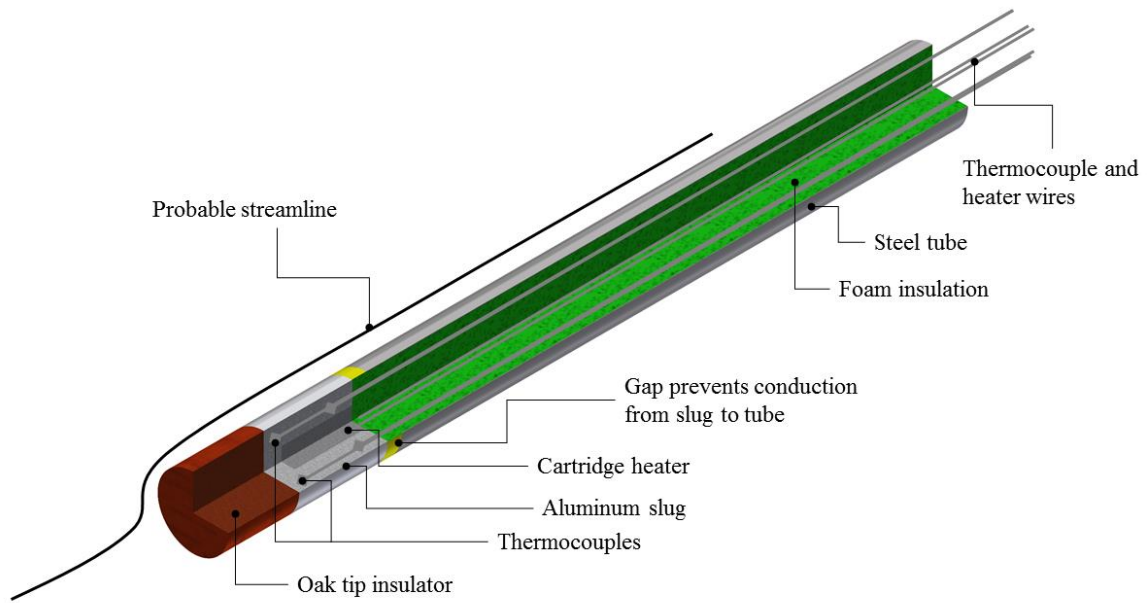


Figure 2: Schematic of the ESW model.

The instrumented slug was positioned in line with the pipe, with a 0.635 cm gap between the pipe and the slug to prevent conduction from the slug to the pipe. This assembly was held in place in a 2.54 cm inner diameter clamshell mold while epoxy based expanding insulating foam was poured in the opposite end of the pipe to complete the model. This is the same test article used in (Rhodes, Moeller, & Conner, Heat Transfer to Truncated Cylinder in Cross-Flow, 2015), however in this experiment the probe was oriented pointing into the flow rather than perpendicular to it. In order to observe changes in convection as a function of axial position along the shield, insulators of varying lengths were glued to the leading end of the 2.54 cm diameter model. The longer the insulator, the further downstream the heat transfer measurement would be taken. Oak was initially chosen because literature indicated a 0.04 W/m-K conduction coefficient, and 2.54 cm diameter oak dowel was readily accessible. Later work showed that the actual conduction coefficient was closer to 0.28 W/m-K, or high enough to require a relatively large correction in experimental results, which was less than desirable. However, the true conductivity of the oak dowel was not determined until after testing was complete, so these results include the correction associated with oak conductivity of 0.28 W/m-K. The model was fitted with a plastic ring at the aft end, which would be used to hold the model in a wind tunnel.

The ESW model was installed in the blowdown wind tunnel facility used in (Rhodes, Moeller, & Conner, Heat Transfer to Truncated Cylinder in Cross-Flow, 2015). Three rows of two threaded rods were tapped into the end of the wind tunnel, and tightened against the dimples in the plastic ring to hold it in place. Figure 3 is a cross-section drawing of the external model in the facility. Figure 4 shows a photograph of the installation.

2.1 Inner Shield Wall (ISW) Convection Model

Convection between the internal wall of the probe shield and flow exiting the probe vents was determined using a 5.59 cm internal diameter aluminum ring inside an insulated channel (Figure 5). Spiral grooves were cut into the outside of the aluminum ring to provide for a resistive wire heater.

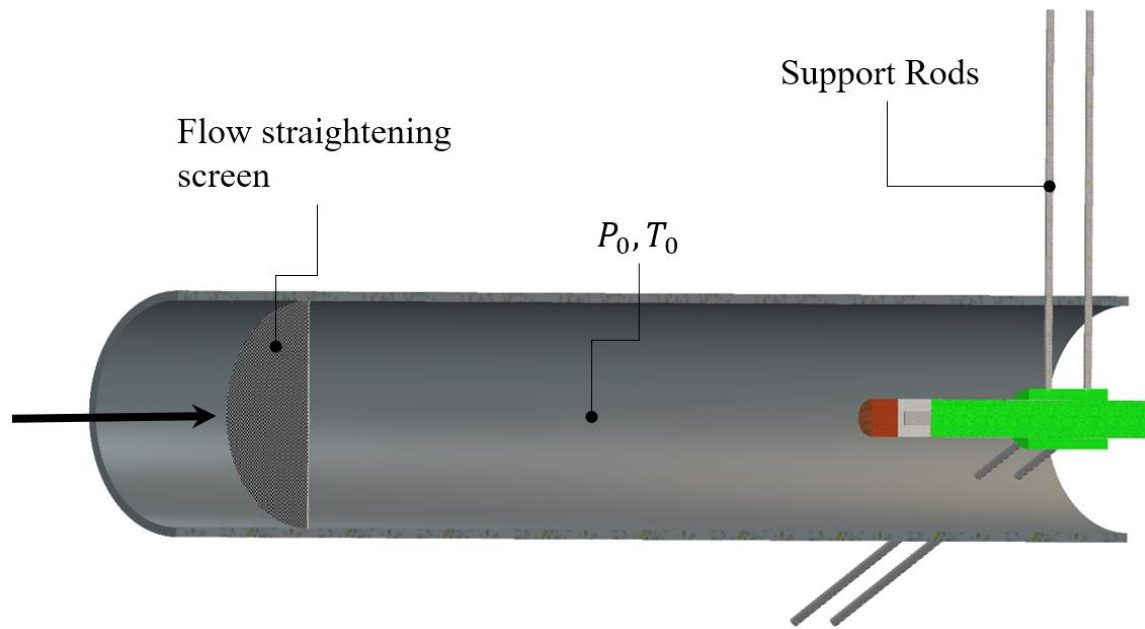


Figure 3: Schematic of the ESW model installed in the 15.24 cm blowdown wind tunnel.



Figure 4: ESW model installed in the 15.24 cm blowdown wind tunnel.

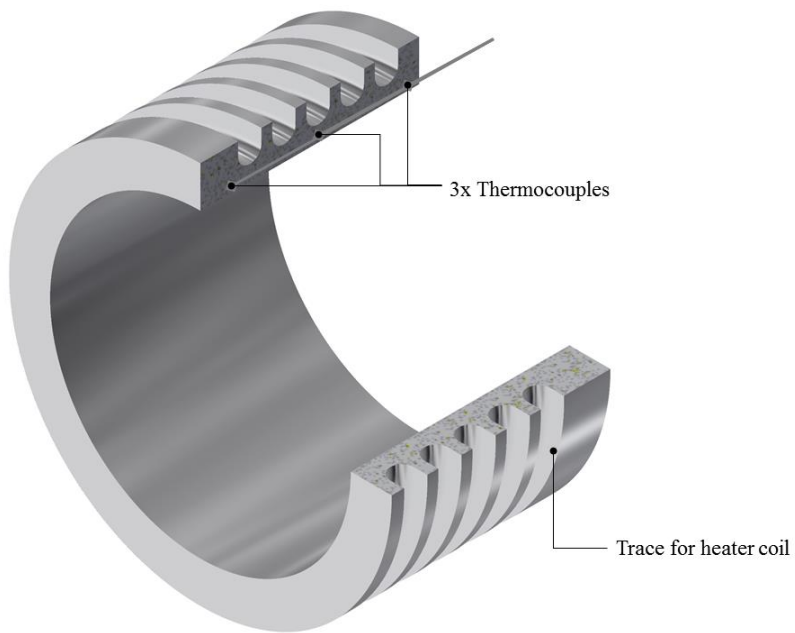


Figure 5: Heated aluminum ring used in the ISW measurement.

Three type K thermocouples were installed in the ring through holes drilled from the outside. The ring was installed in an insulated channel which simulated the inside of the probe as shown in Figure 6.

To keep the instrumented ring insulated so that heat transfer was limited to the inner wall exposed to the flow, the ring was encased in foam. The mold (Figure 7, Figure 8) used to form the foam was created with a 5.59 cm aluminum post and a section of the 20.3 cm PVC pipe.

The inner post of the mold was first used to create a 5.59 cm internal diameter fiberglass tube (Figure 9) encased in insulating foam, which provided a smooth insulated internal surface for the flow both upstream and downstream of the aluminum ring. Non-stick material was applied to the post, which was then wrapped in fiberglass cloth and painted with resin. When the resin was hardened, the fiberglass tube was slid off the aluminum post from the mold, the rough end of the foam was cut smooth with a band saw. This step is shown in Figure 10. Another section of fiberglass tube was drilled with 4x1.50cm holes to represent the probe vents. PVC pipe fittings were glued to the fiberglass to provide an exit path for the flow through the vents (Figure 11). The PVC fittings were sanded to the outer contour of the fiberglass tube to enable an air-tight seal to be made with epoxy glue. The fittings had a 2.43 cm minimum internal diameter, so the throats of the vents in the model remained at the 1.5 cm holes drilled in the fiberglass tube, which the fitting was secured over. The outer pipe wall of the mold was drilled with four holes to allow lubricated PVC pipes to pass to the vent fittings (Figure 12). The lubrication prevented the foam from adhering to the vent pipes, so that the pipes could easily be removed and reinstalled after the model was removed from the mold. By slicing or adding foam sections in front of or behind the section containing the aluminum ring, the axial position of the ring could be changed. The internal flow assembly was “stacked” on the inside surface of a 20.3 cm internal diameter PVC pipe end cap, and held down with threaded rod.

The entire internal flow assembly could then be installed in a 20.3 cm PVC pipe pressure vessel by sliding it in axially, and secured by bolts from the end cap to a flange on the pressure vessel. Holes drilled in the pressure vessel allowed the vent pipes to be installed.

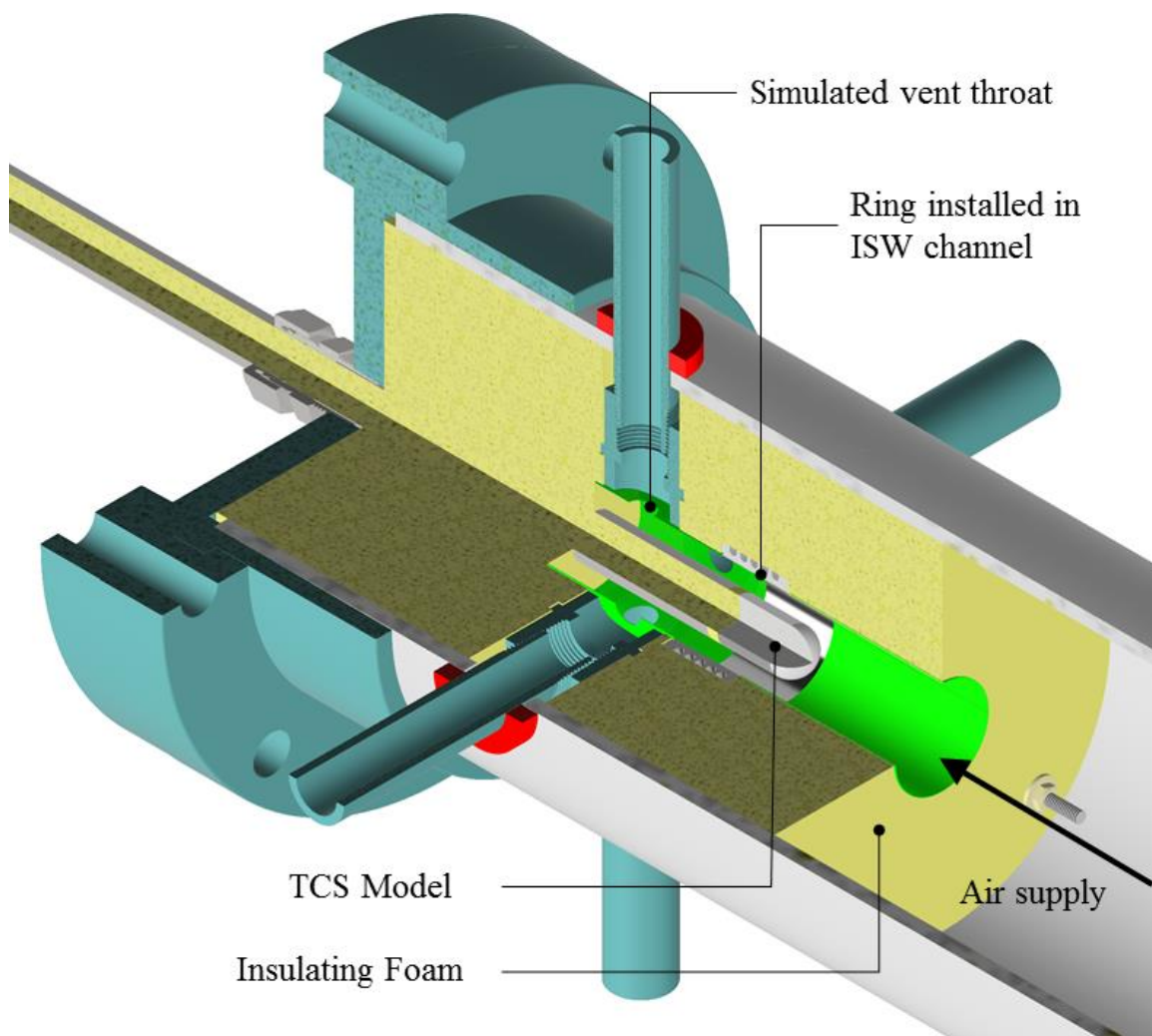


Figure 6: Installed ISW model ring and TCS model.

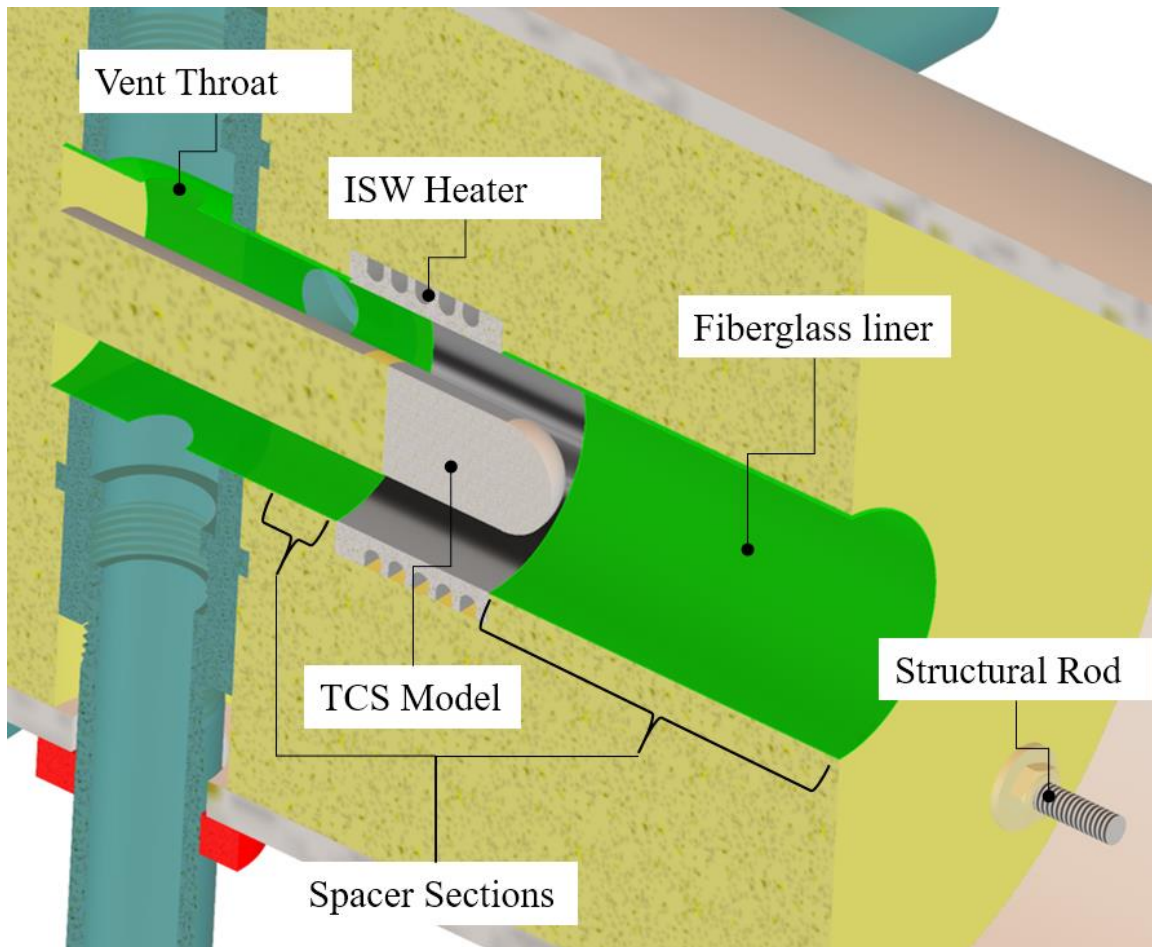


Figure 7: Close up view of the ISW/TCS assembly. Spacer sections can be added or removed to change the axial position of the ISW ring heater.

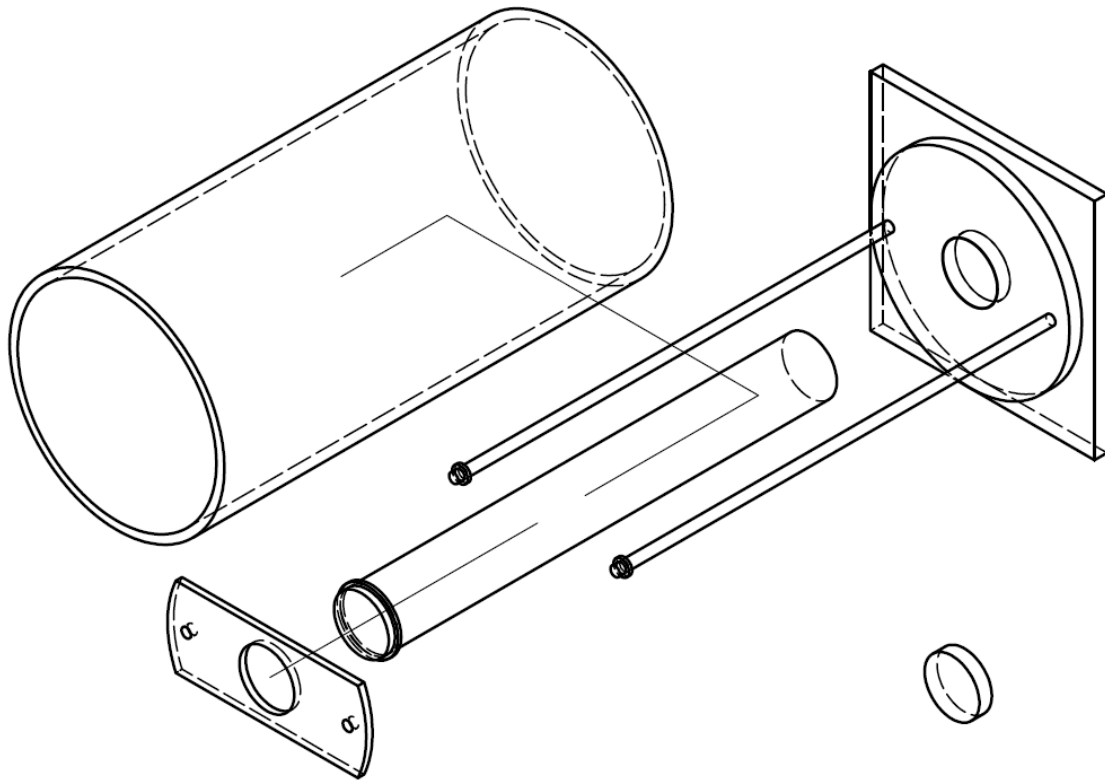


Figure 8: Mold used to form several components of the ISW and TCS models.



Figure 9: Fiberglass tube liner which provided a smooth internal flow path for the ISW and TCS tests.

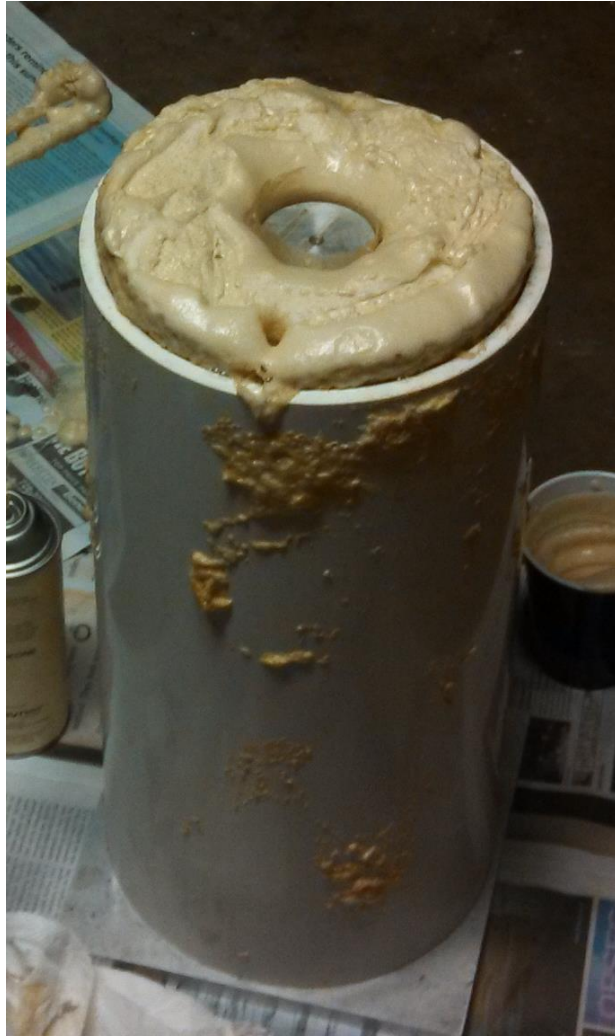


Figure 10: Forming the internal walls of the ISW model.

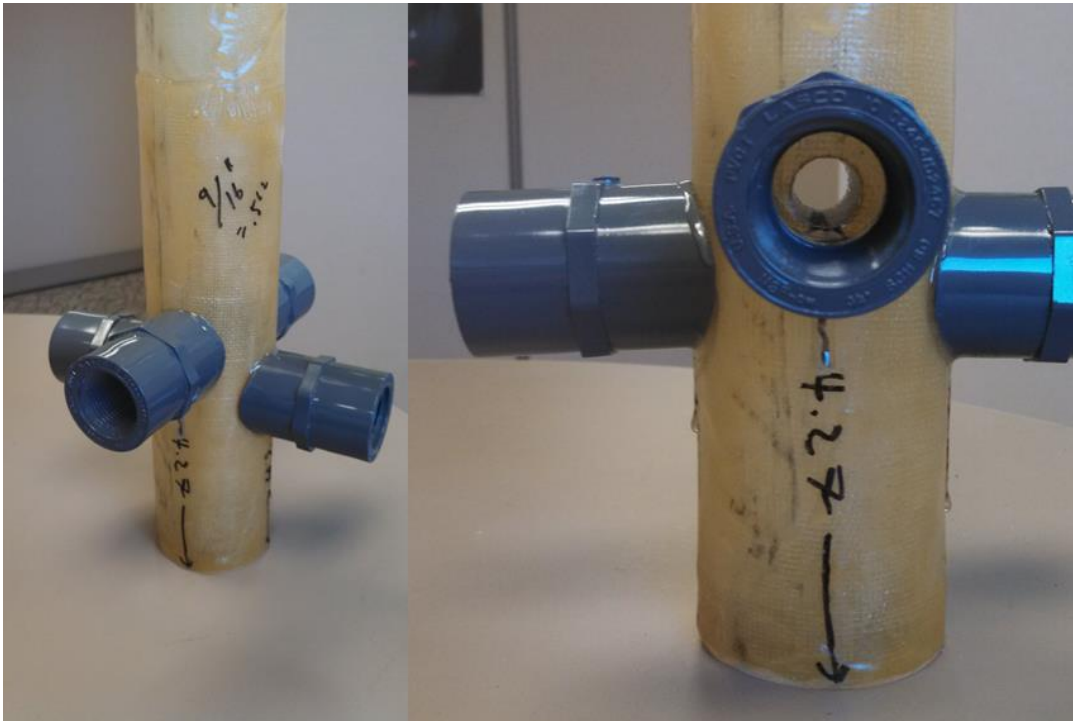


Figure 11: ISW model vent assembly.



Figure 12: Mold prepared to form insulation around the ISW model vents.

3-D printed plastic seals were fabricated and glued to the pressure vessel to ensure there were no leaks between the pressure vessel wall and the vent pipes. The opposite end of the pressure vessel was connected to a calibrated Venturi flow bench via a pressure fitting on an identical end cap, which was fitted internally with a flow break to ensure uniform internal flow.

Figure 13 shows the complete design of the ISW and TCS (discussed in section 2.2) pressure vessel, and the installation on top of the SGFC in the laboratory.

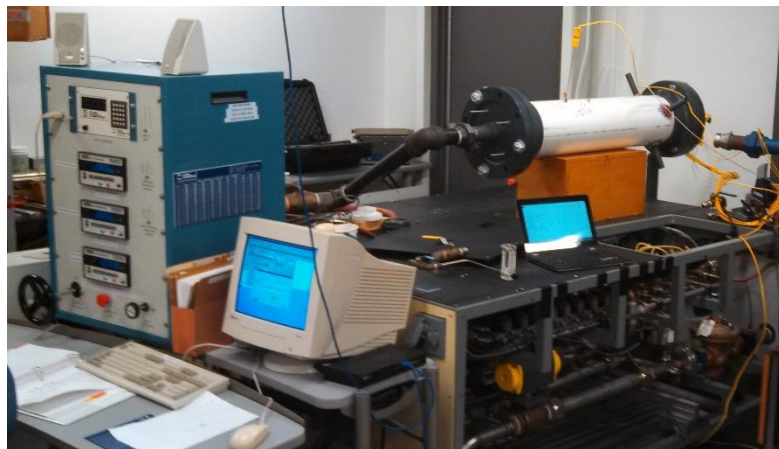
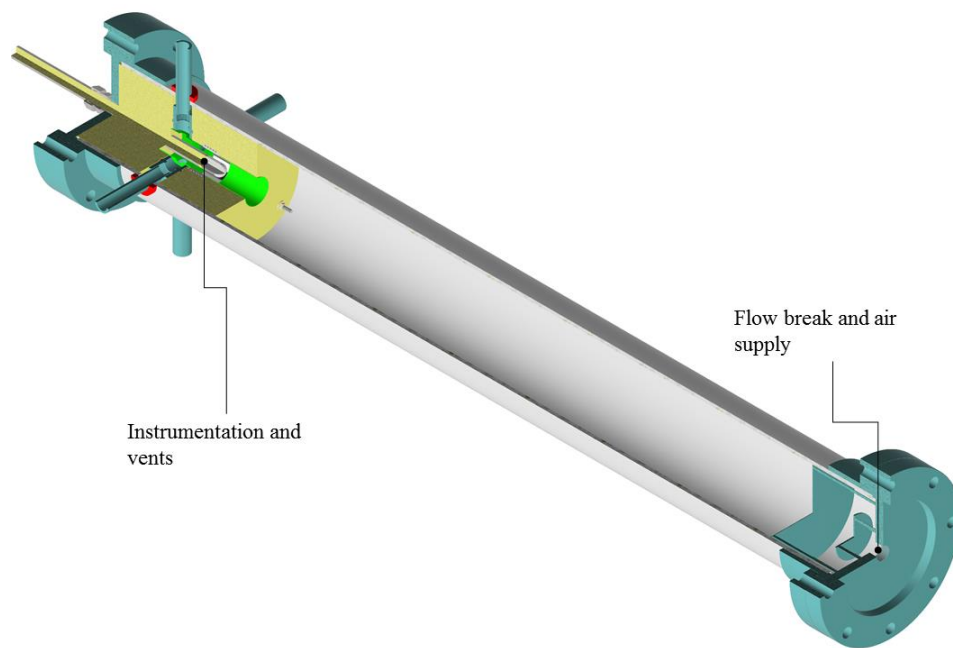


Figure 13: Completed pressure vessel used to simulate the internal flow in the probe. CAD drawing and laboratory installation shown.

2.2 Thermocouple Sheath (TCS) Convection Model

Convection between the internal thermocouple sheath (TCS) and probe internal flow was simulated by a heated and instrumented aluminum cylinder identical to that used in the external flow test. However, printed plastic was used rather than wood to create the nose insulator. The TCS nose insulator was a 2.54 cm cylinder with a hemisphere end and an internal porous honeycomb structure. The thermal conductivity of the plastic nose insulator was approximated by a volume-weighted average of the conductivity of the plastic and air contained in the porous structure of the printed insulator. For reference, the TCS model used the same design as the ESW model shown in Figure 2, but with rounded plastic tip insulator. The TCS model is shown installed in the simulated probe channel in Figure 6.

2.3 Data Acquisition

The data acquisition system (DAS) was a Labview™-based program that measured the thermocouples and voltages via a National Instruments CompactDAQ chassis. Voltage to the electric heater was controlled manually at a DC power supply. In the ES convection runs, mass flow through the wind tunnel was controlled by a system of regulators, and the mass flow was electronically sent to the data acquisition system. The same DAS was used for temperature recording in all tests. Mass flow was sent directly to the DAS in the ESW tests for Reynolds number calculation. In the internal and TCS convection tests, mass flow was provided by a Sonic Gas Flow Calibrator (SGFC) (Flow Dynamics, Inc.). No data connection exists between the SGFC and the data acquisition system, so the mass flow was logged manually in both the annular and TCS convection runs. Most Labview™ data was acquired at 1000 samples per seconds. The external convection calculations were performed on 10 sample moving averages (100 samples per second) of the data to reduce file size. The internal annular and TCS datasets were further reduced in post-processing to 100 sample moving averages resulting in 10 samples per second.

3

Test Execution and Analysis

Convection heat transfer was measured in the experiment using an energy balance. The ideal data point in this type of experiment is a steady state balance between the electrical heating provided by the heater in each model and the convection cooling provided by the flow, conduction losses through the thermocouple and heater leads, and radiation to the surroundings. Each data run ranged anywhere from 10 to 40 minutes in duration. In general, the data collection steps for each test run were as follows for every configuration:

1. Start flow at a mass flow rate set point calculated to provide the desired Reynolds number.
2. Turn on the power supply to start heating the model and watch the model thermocouple readings to ensure the model stays below about 120° C to prevent damage to the foam insulation.
3. Manually adjust the supplied current until the temperatures in the probe are constant to about 0.1° C for about a minute. For consistency, power should be selected so that probe temperature is rising to the steady state condition rather than dropping.

In this experiment data were continuously recorded during this process. The mean of each parameter of the last 60 seconds of each run was taken as the steady state data point in each run. It should be noted that allowing the model to reach a perfectly steady state temperature was impractical, so a correction described in section 3.1.2 was devised in the data reduction to account for any changes in temperature still occurring during the last 60 seconds.

In the ESW run (example in Figure 14) the heater power was not changed, so the temperature slowly rose to a steady state condition. To expedite data collection in the ISW (example in Figure 15) and TCS (example Figure 16) runs, the heater power was adjusted until the 0.1° K criterion was met. The adjustments can be seen as sharp changes to the slope of the temperature curve.

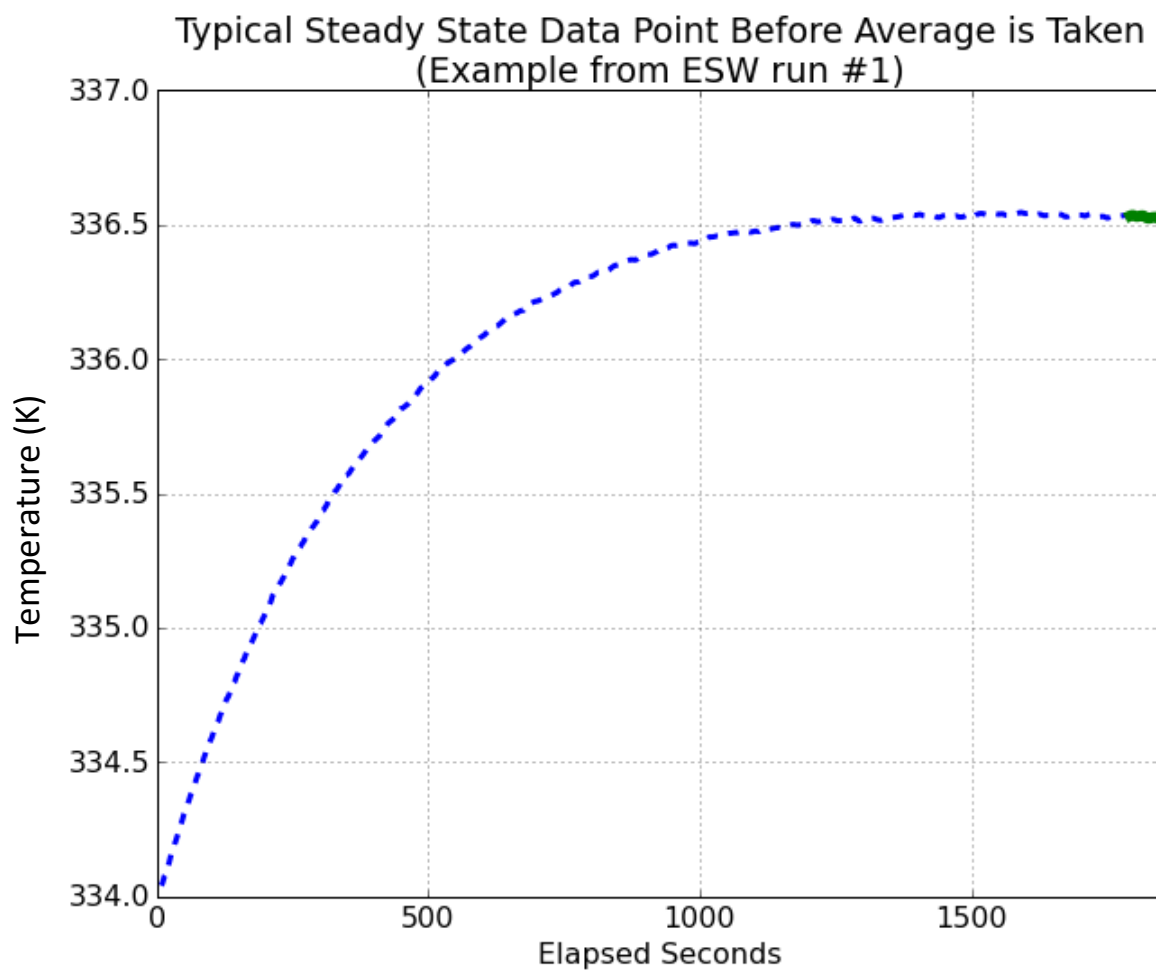


Figure 14: Example steady state data region (thick line) for an ESW run.

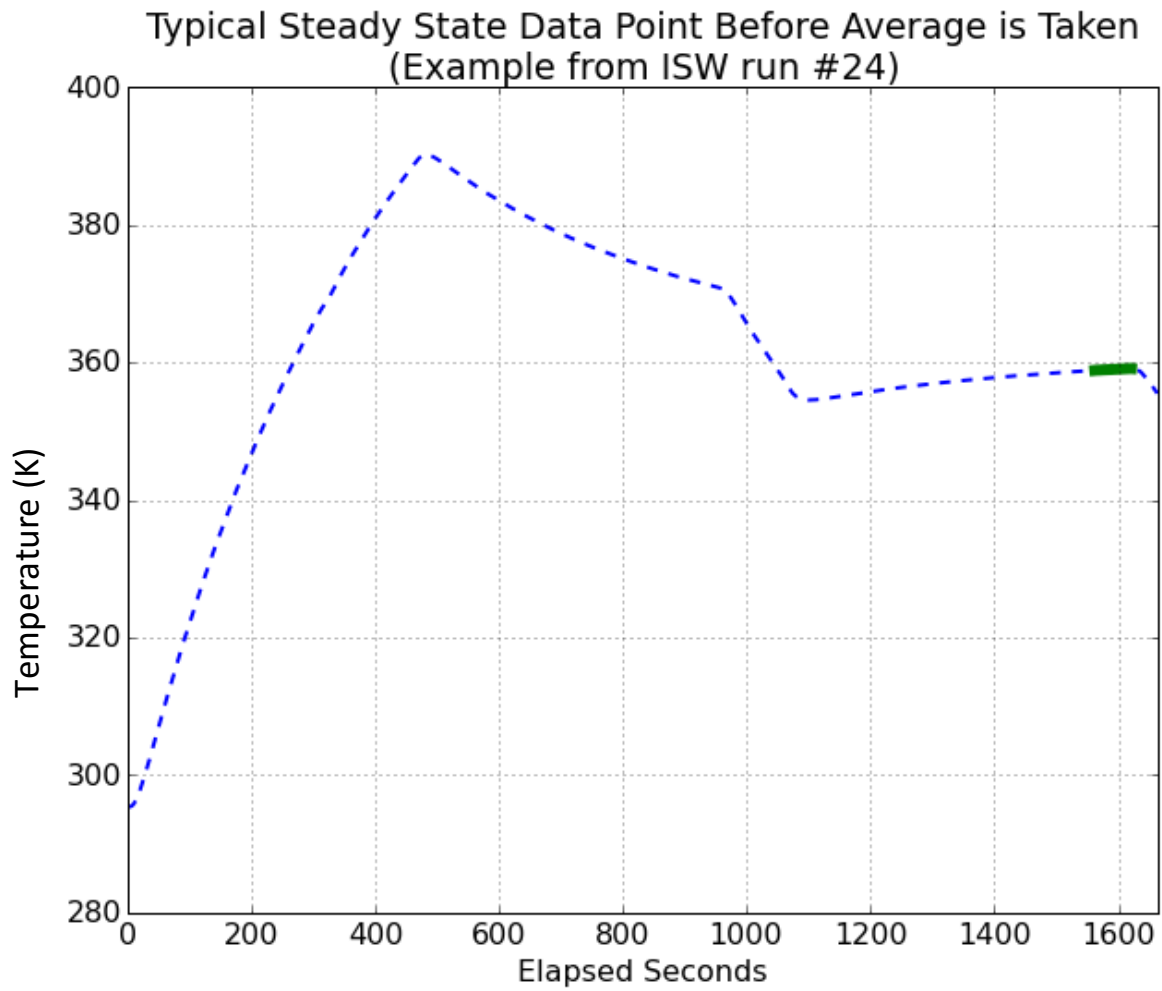


Figure 15: Example steady state data region (thick line) for an ISW run. Note that no data is averaged after the heater is switched off and starts to cool rapidly.

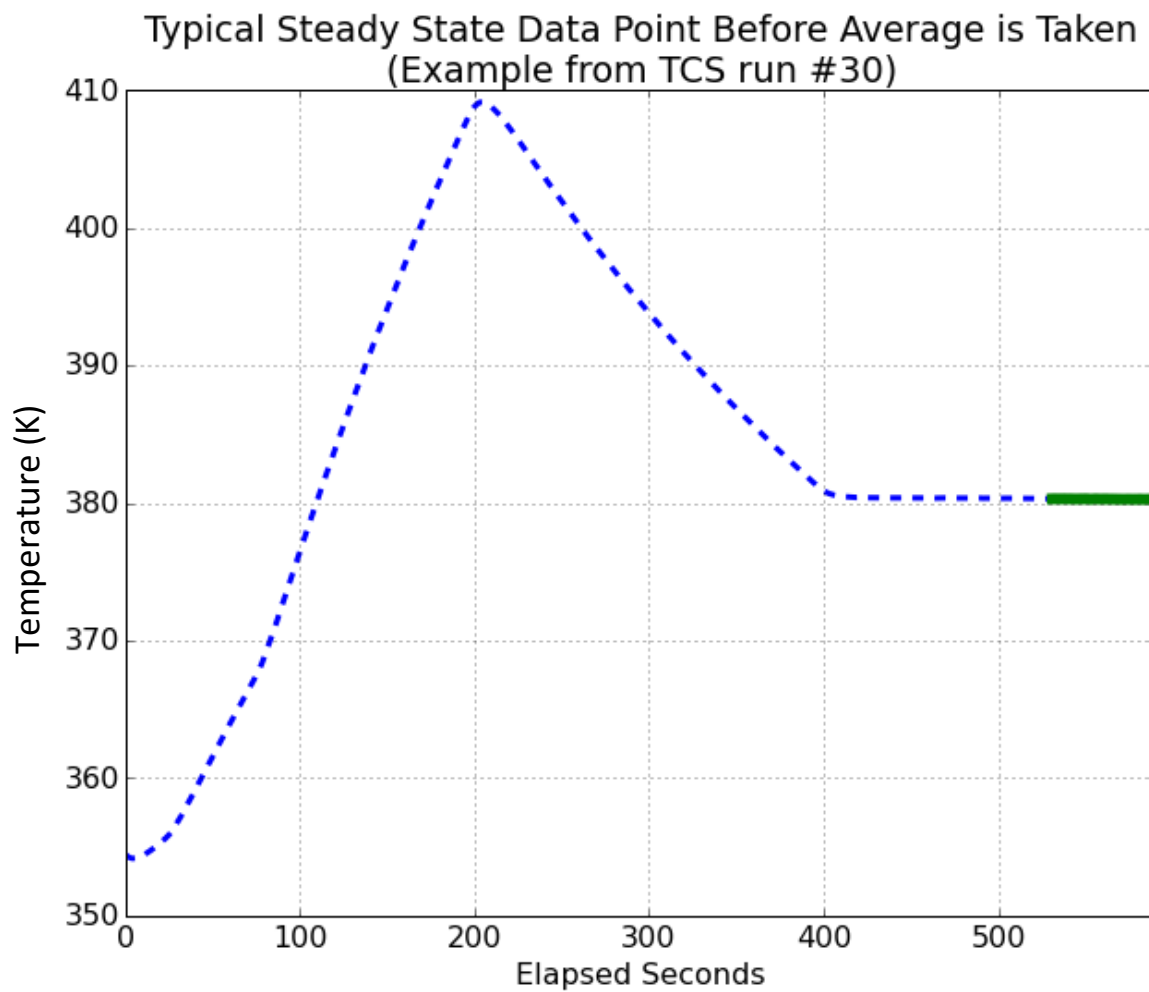


Figure 16: Example steady state data region (thick line) for a TCS run.

Each model configuration was run with four Reynolds numbers and three or four different axial positions of the heater relative to the first datum of the respective model. This test matrix is shown in the appendix.

3.1 Energy Balance Equation

$$hA(T - T_0) = IV - q_{loss}$$

The general data reduction equation used to calculate h , the convective heat transfer coefficient is shown above. The q_{loss} term represents several corrections which were applied to this equation to account for estimates of energy losses in the experimental setup due to conduction and radiation losses, and for any remaining rate of change of the temperature during the steady state point. The energy balance equations with corrections specific to their respective model configurations are listed below.

1. ESW Configuration Energy Balance:

$$h = \frac{IE - q_{cond,wires} - q_{cond,wood} - q_{rad} + C \frac{dT}{dt}}{A(T - T_0)}$$

2. ISW Configuration Energy Balance:

$$h = \frac{IE - q_{cond,wires} + C \frac{dT}{dt}}{A(T - T_0)}$$

3. TCS Configuration Energy Balance:

$$h = \frac{IE - q_{cond,wires} - q_{cond,ABS} - q_{rad} + C \frac{dT}{dt}}{A(T - T_0)}$$

The following sections describe the correction terms appearing in the numerators of these equations.

Convective heat transfer results were further reduced into the nondimensional Nusselt number, which is the ratio of convection heat transfer to fluid conduction heat transfer. The development of the correlation between Reynolds number and Nusselt number is discussed in section 3.1.

$$Nu = \frac{h d_{ref}}{k_{air}}$$

3.1.1 Correction for Conduction Losses through Wires

The wires connecting the heater to the power supply provided a conduction path from the heater to the ambient temperature in the room. This loss of energy must be corrected out of the energy balance used to calculate the convection coefficient. In the energy balance, the heat flux through the wires is subtracted from the heater input power. Heat flux through the wires is calculated using

$$q_{cond,wires} = m_{alu} C_{p,alu} \left(\frac{dT}{dt} \right)_{loss}$$

where $q_{cond,wires}$ is the conductive heat flux in Watts, m_{alu} is the mass of the heated aluminum section, and $C_{p,alu}$ is the specific heat of aluminum. The temperature loss rate $\left(\frac{dT}{dt} \right)_{loss}$ was determined experimentally by encasing the ESW model in insulating material, heating the model, and plotting the cooling rate of the insulated mode. The result of this conductive temperature loss test is shown in Figure 17. The steady state temperature loss rate was determined to be -0.0302 K/s. Conduction loss results, uncertainty, and regression analysis for all runs are listed in the appendix.

3.1.2 Correction for Losses through Tip Insulators

The TCS and ESW models both use insulating tips of varying lengths to change the axial position of the heated section. The insulating tips could not be made out of polyurethane foam due to the structural requirement for the tips to remain attached at the desired test Reynolds number, and the aerodynamic requirement for the tips to be relatively smooth. Since the tip is exposed to both the stagnation temperature of the flow and the temperature of the heater, thermal conductivity of the tip will allow heat flux to occur which and be corrected out of the energy balance. Based on literature (The Engineering ToolBox, 2015) stating thermal conductivity of 0.17 W/m-K, a 2.54 cm OD oak dowel was chosen to form the tips on the ESW model. However, after the ESW tests were complete it was realized that the thermal conductivity of wood has a very wide range that is sample dependent. The oak used in this experiment was tested in a HotDisk TPS 2500 S Transient Plane Source thermal measurement device, manufactured by Thermtest Inc. This test resulted in a thermal conductivity measurement of 0.28 W/m-K axially.

The TCS experiment was run later and design of the insulating tip was improved to use 3-D printed ABS plastic with an internal honeycomb structure. The thermal conductivity of the plastic (0.13 W/m-K) was mass-averaged with the thermal conductivity of air (0.0257 W/m-K) to account for the porous internal structure. The resulting thermal conductivity of the TCS tip was (0.0361 W/m-K) (Figure 17).

The heat flux equations for losses through the ESW and TCS tips to the stagnation conditions at the end of the tip assuming no heat loss through the cylindrical surface of the tips are

$$q_{cond,wood} = k_{wood} \frac{A_{wood/alu}}{\Delta x} (T - T_0)$$

for the ESW model and

$$q_{cond,ABS} = k_{ABS} \frac{A_{ABS/alu}}{\Delta x} (T - T_0)$$

for the TCS model where $q_{cond,material}$ is the heat flux in Watts, $k_{material}$ is the tip thermal conductivity, $A_{material/alu}$ is the area of the interface between the tip material, and the heated aluminum slug, Δx is the length of the tip, and $(T - T_0)$ is the difference between the average thermocouple reading in the heater and the experiment stilling (stagnation) temperature.

3.1.1 Correction for Radiation Losses

Radiation losses in the ESW and TCS model were included. The ESW model consists of a 2.54 cm OD heated cylinder at the centerline of a 15.24 cm ID wind tunnel. For radiation calculations, the TCS model is an identical heater at the centerline of a 5.59 cm ID duct (simulating the inner wall of the probe shield). The inner wall temperatures of the ESW wind tunnel and the TCS duct were assumed to be equal to the stilling chamber temperature. The resulting radiation loss equation is

$$q_{rad} = A_{alu/exposed} \sigma \epsilon (T_0^4 - T^4)$$

where q_{rad} is the radiation heat flux, $A_{alu/exposed}$ is the exposed area of the cylindrical heater,

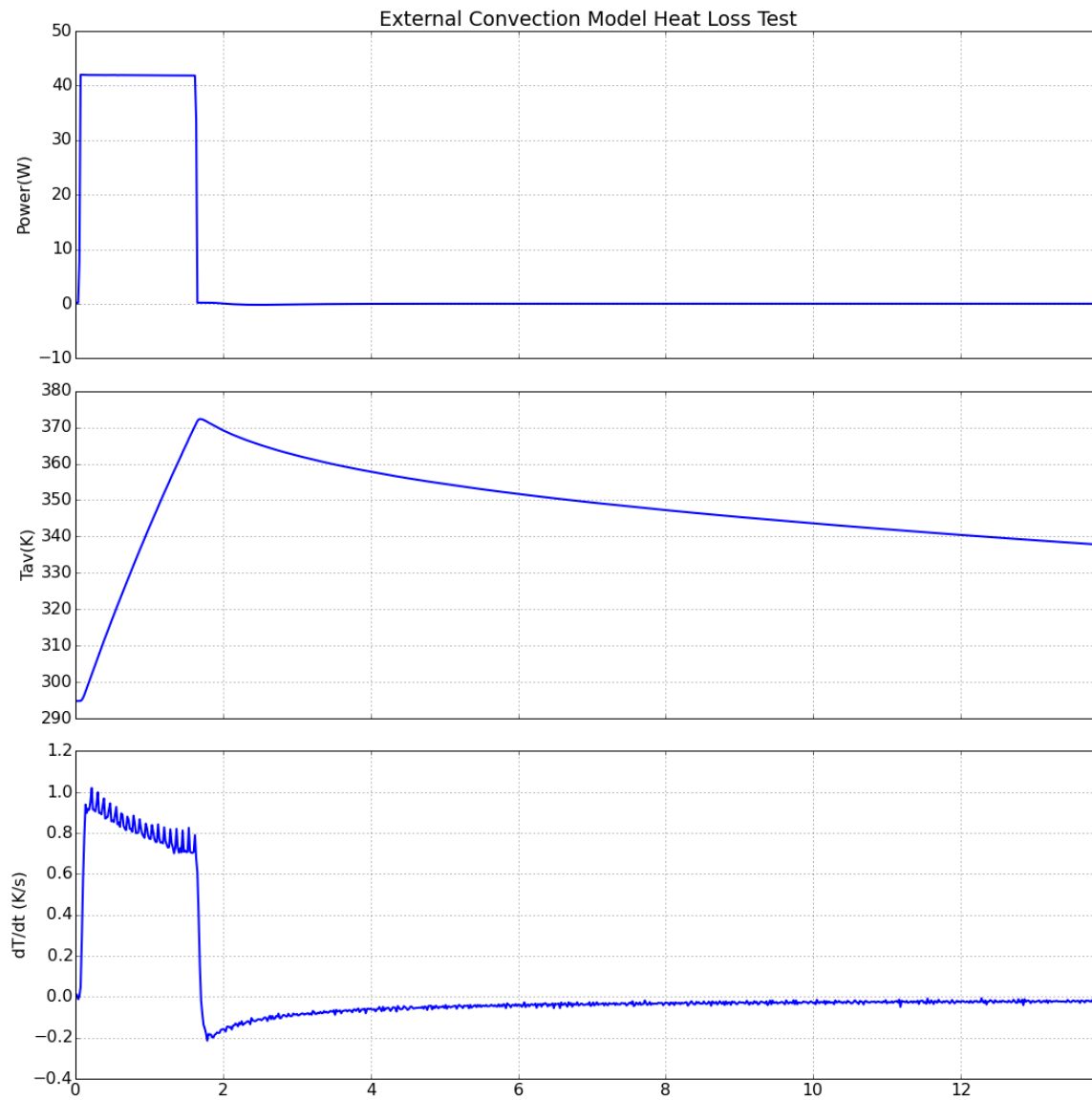


Figure 17: Plot showing the insulated model cooling over time. The conduction rate reached a steady state value of -0.0302 K/s.

σ is the Stefan-Boltzmann constant, ε is the emissivity of aluminum, T_0 is the stilling chamber temperature, and T is the heater temperature.

Due to the geometry of the ISW heater ring being an internal heated surface with an insulated outer surface, radiation losses in this configuration were assumed to be negligible. Most radiation from the inner wall of the ISW model would be absorbed by another location on the inner wall of the ring. Some heat emitted at an angle close enough to the axial direction along the ring would radiate out the ends of the ring. However, the radiation results from the ESW and TCS configurations were found to be so small that the partial radiation expected in the ISW configuration could be safely assumed to be an insignificantly small component of the overall heat transfer result for that configuration.

3.1.2 Correction for Residual Transients in Data Points

The data reduction for the convection calculation in each run assumes 60 seconds of steady state Reynolds number, heater input power, and probe heater temperature. Reynolds number and heater input power can be maintained within tolerance by the facility in every case. Input power for each run was selected so that temperature was rising to the steady state condition in each run. Achieving a zero K/s heater temperature time rate of change was operationally impractical due to the time required to achieve a perfect energy balance, so a maximum temperature rate of change tolerance of 0.1 K/s was selected. The minimum temperature rate of change tolerance was 0.1 K/s, so that each run was rising to the steady state condition to ensure consistency. This method of data collection resulted in up to 0.1 K/s residual transient in each run. To compensate for this, a constant (C) was multiplied by the time derivative of the heater temperature in each run ($\frac{dT}{dt}$), and subtracted from the energy balance as described in section 3.1. The constant was selected to cause the mean heat transfer calculated for the entire run to be as close as possible to the mean heat transfer calculated in the last 60 s of the run. Figure 18 shows calculated convection coefficients for the ESW runs before ($C = 0$) and after ($C = -500$) correcting for residual transients.

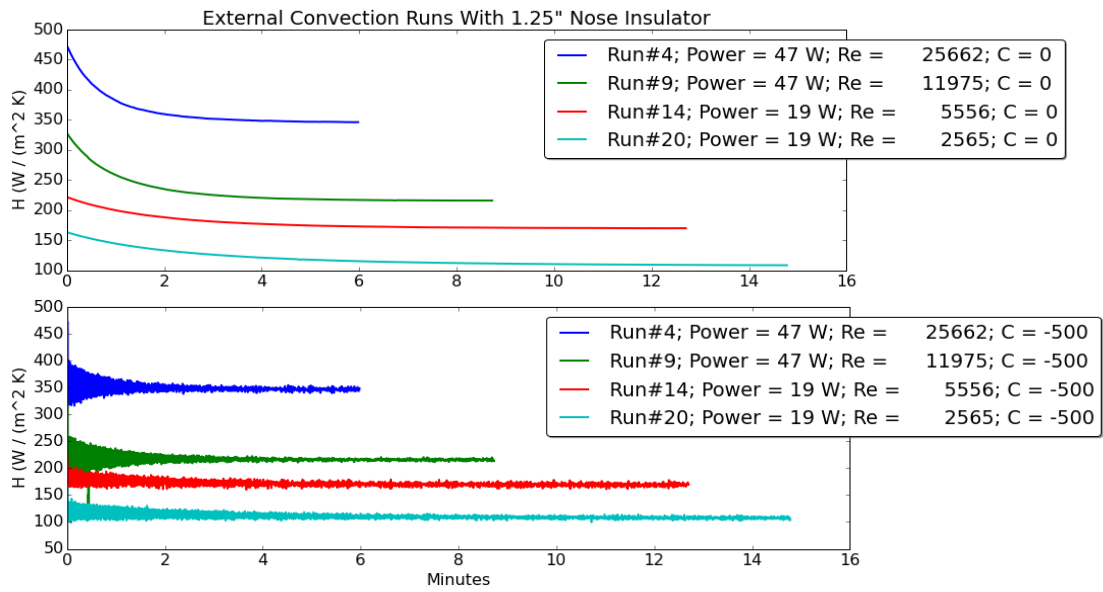


Figure 18: Example ESW runs before and after correcting for residual transient temperature changes ($C=0$ vs. $C=-500$)

Figure 19 shows the result of the same process on the ISW runs. In order to expedite data collection in the ISW runs, the heater power level was adjusted to search for a steady state convection condition. Power adjustments appear as discontinuities in the uncorrected data, and large spikes in the corrected data. Steady state heat transfer points were only taken during the last stable 60 seconds of the runs.

3.1 Regression Analysis

Data sets at each heater axial position for each configuration were fit to the form $Nu_c = aRe^b Pr^{1/3}$ via a power law transformation of a least squares fit. The subscript c on Nu_c identifies a value calculated from the fitted curve. The equations used to calculate the coefficients a and the exponents b are shown below for n data points in a set (Weisstein, 2015).

$$b = \frac{n \sum_{i=1}^n (\ln Re_i \ln Nu_i) - \sum_{i=1}^n (\ln Re_i) \sum_{i=1}^n (\ln Nu_i)}{n \sum_{i=1}^n (\ln Re_i)^2 - (\sum_{i=1}^n \ln Re_i)^2}$$

$$a = \frac{e^{\frac{\sum_{i=1}^n (\ln Nu_i) - b \sum_{i=1}^n (\ln Re_i)}{n}}}{Pr^{1/3}}$$

The quality of each curve fit was determined by taking the mean of the ratio of the absolute value of the residual to the uncertainty at each data point in a set. The criteria for determining the appropriateness of each curve fit was an average residual to uncertainty ratio (RRU_{av}) of less than one for all points taken at; i.e., the curve fit was considered appropriate when the majority of the fitted curve lies within the 95% confidence interval of the dataset.

$$RRU_{av} = \frac{\sum_{i=1}^n \left(\frac{|Nu_i - Nu_{ci}|}{U_{Nu_i}} \right)}{n}$$

$RRU_{av} < 1$ for the fitted curve to be within instrumentation uncertainty

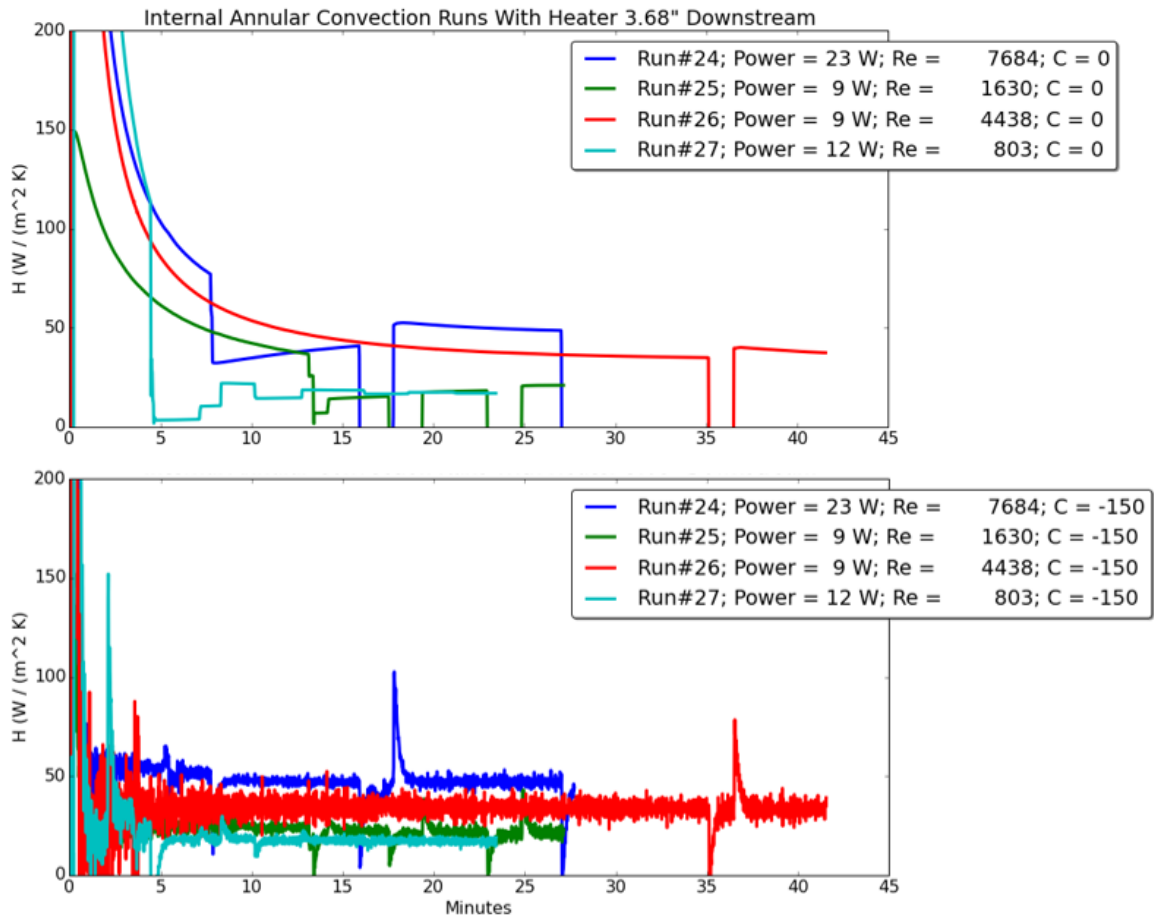


Figure 19: Example ISW runs before and after correcting for residual transient temperature changes ($C=0$ vs. $C=-150$)

4

Uncertainty Analysis

Parameter uncertainties were propagated through a numerical approach consistent with the Guide (Joint Committee for Guides in Metrology, 2008) to the Expression of Uncertainty propagation method that seeks to directly calculate the Probability Density Function (PDF) of a single output quantity from the PDFs of each input. The Monte Carlo propagation method was chosen over traditional first order Taylor series uncertainty propagation method for the following reasons:

1. Numerous input parameters would have required a high number of partial derivatives for the three test configurations. This would have led to a relatively complex and error prone data reduction code. Implementation of a numerical method was much simpler since the data reduction was already programmed.
2. Second order uncertainty effects are automatically captured in the Monte Carlo method. Second order uncertainty effects would be difficult or impossible to capture with the Taylor series method in this experiment.
3. The Monte Carlo method allows for the possibility that the PDF of the input or output quantity is a non-Gaussian distribution. This is especially useful when applying the principal of maximum entropy (Jaynes, 1957) to input uncertainties that cannot be tested. Gaussian input and output is automatically assumed in the Taylor series propagation method.
4. The Monte Carlo method produces a data set which can be shown on a histogram to easily view the PDF of the output.

Monte Carlo uncertainty propagation is implemented by iteratively calculating output values for each set of input values in the input PDF. The resulting array of output values is the output PDF. The population standard deviation of the output PDF is the standard uncertainty at one σ and 68% confidence interval. For this experiment, the standard deviation of the PDF of h was determined to converge in about 10^5 iterations.

The only available information to determine input PDFs used in the calculation of h where either the simply stated “*measurement $\pm$ uncertainty*” instrumentation uncertainties from manufacturer data sheets, or a subjective engineering approximation of the uncertainty in the parameter if the parameter lacks published uncertainties. These input uncertainties were not testable in the scope of this experiment. Therefore, by the principle of maximum entropy (Jaynes, 1957); the most trustworthy input PDFs for all parameters in the calculation of h is a uniform rectangular distribution. Input PDFs were generated with the Python `random.uniform(a,b)` function, where a and b are the upper and lower uncertainty bounds respectively.

5

Results

In this work steady state values of Nu for each run were plotted against Reynolds number on a log-log scale for each configuration (Figure 20, Figure 21, and Figure 22). Error bars on the plots show the numerically propagated instrumentation uncertainties. Numerical results for data points and uncertainty values of individual terms of the three energy balance equations can be found in the appendix.

Figure 23, Figure 24, and Figure 25 show the variation of the coefficient A and exponent B as a function of axial position. In general, the exponent B corresponds to the sensitivity of Nusselt number to Reynolds number, while the coefficient A corresponds to the overall magnitude of the heat transfer at that axial position. The purpose of these plots is to observe how the Reynolds number to Nusselt number correlations change as a function of upstream or downstream position along the surfaces which were simulated.

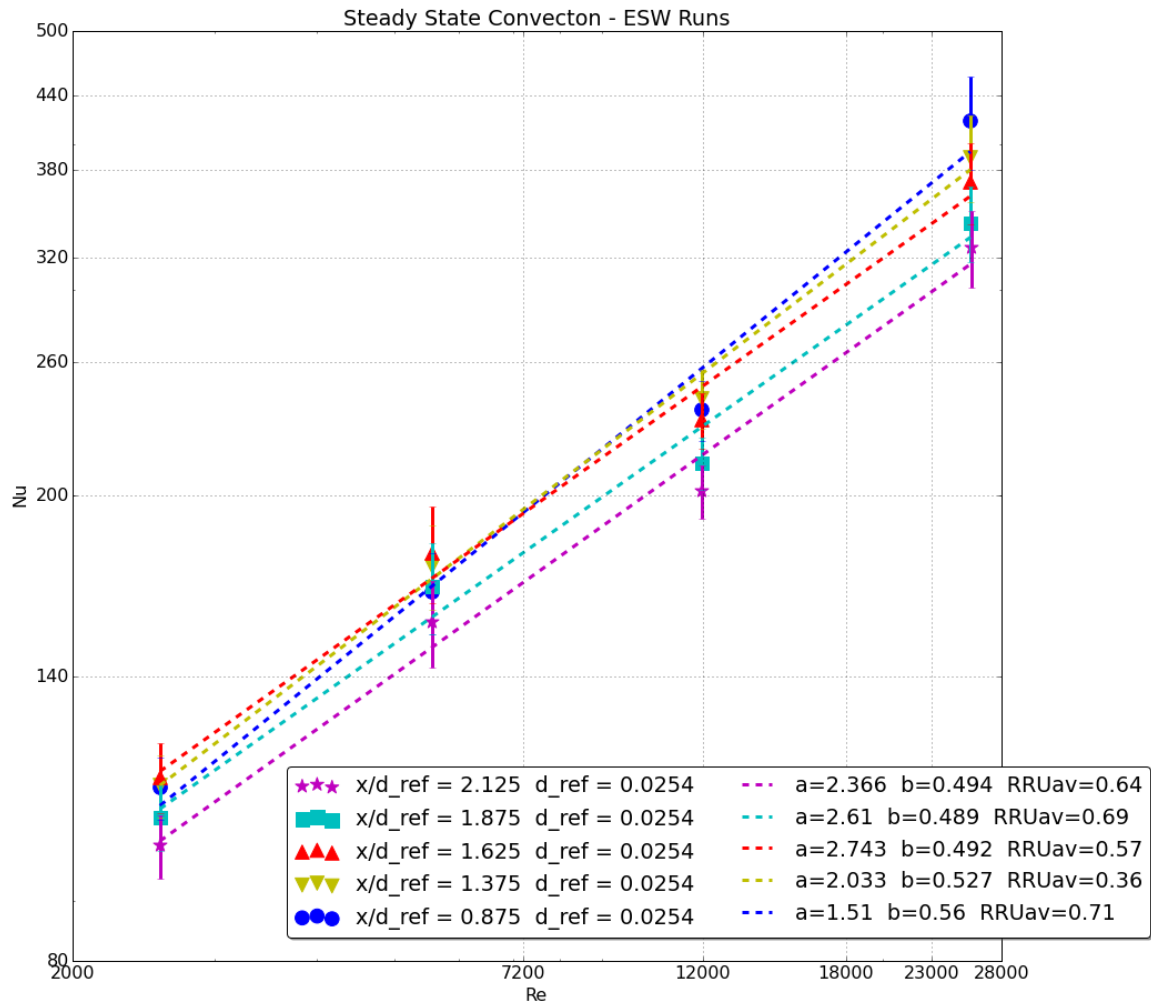


Figure 20: Steady state points and associated regression lines for the External Shield Wall configuration. Regression lines were within the majority of uncertainty bands for all data sets.

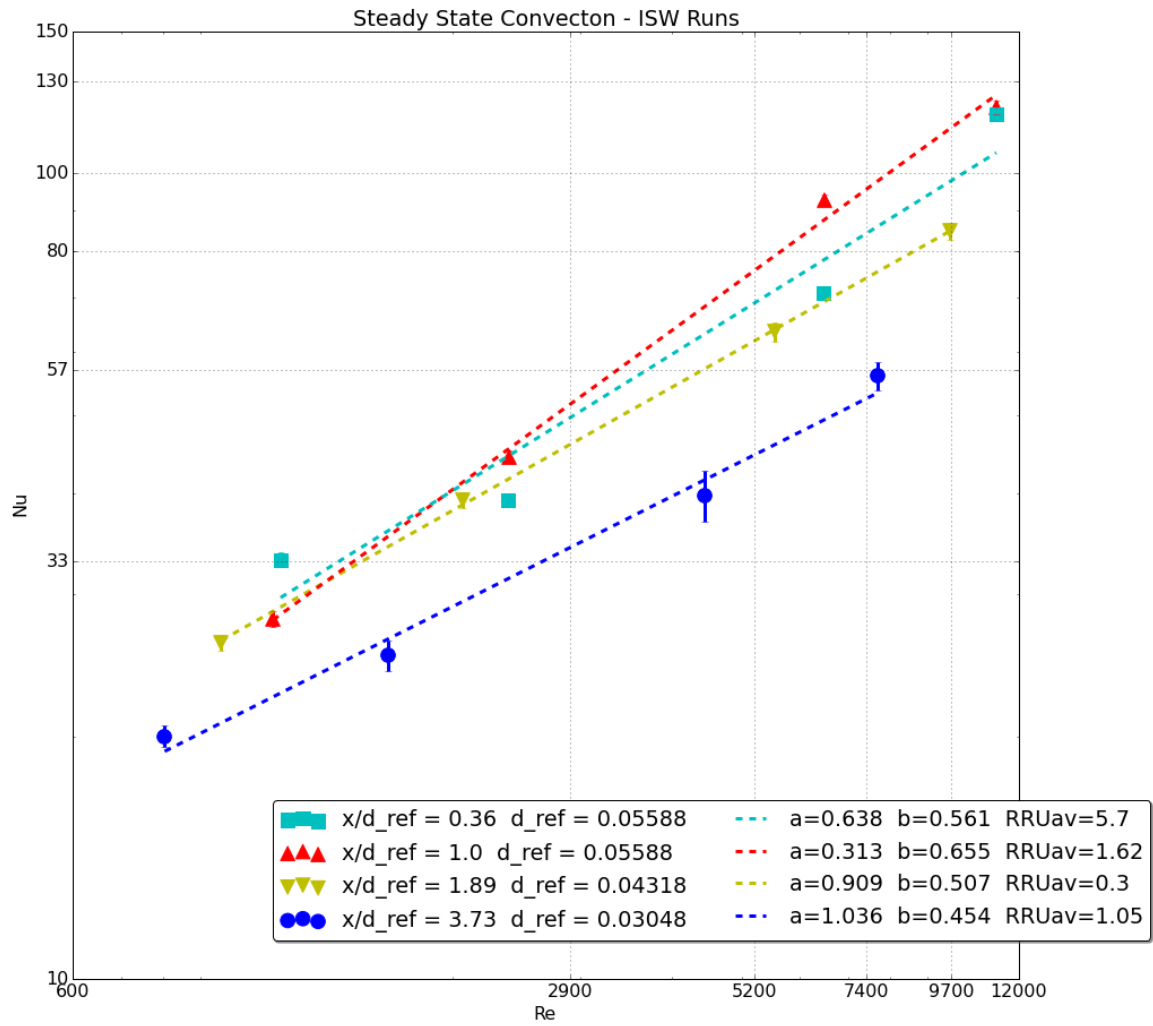


Figure 21: Steady state points and associated regression lines for the Internal Shield Wall configuration. Regression lines were outside of the majority of uncertainty bands for 3 of 4 data sets.

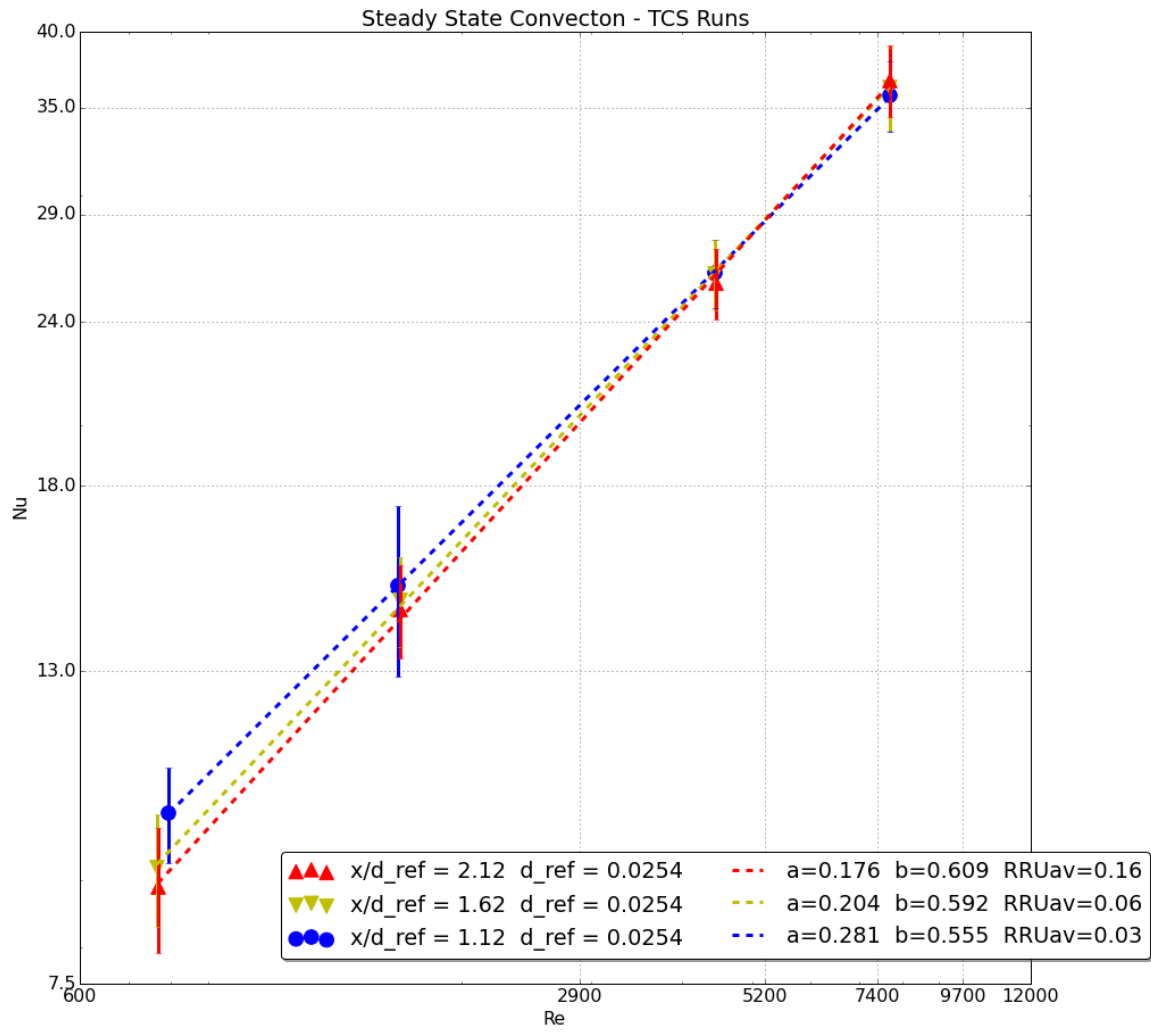


Figure 22: Steady state points and associated regression lines for the Thermocouple Sheath configuration. Regression lines are well inside instrumentation uncertainties.

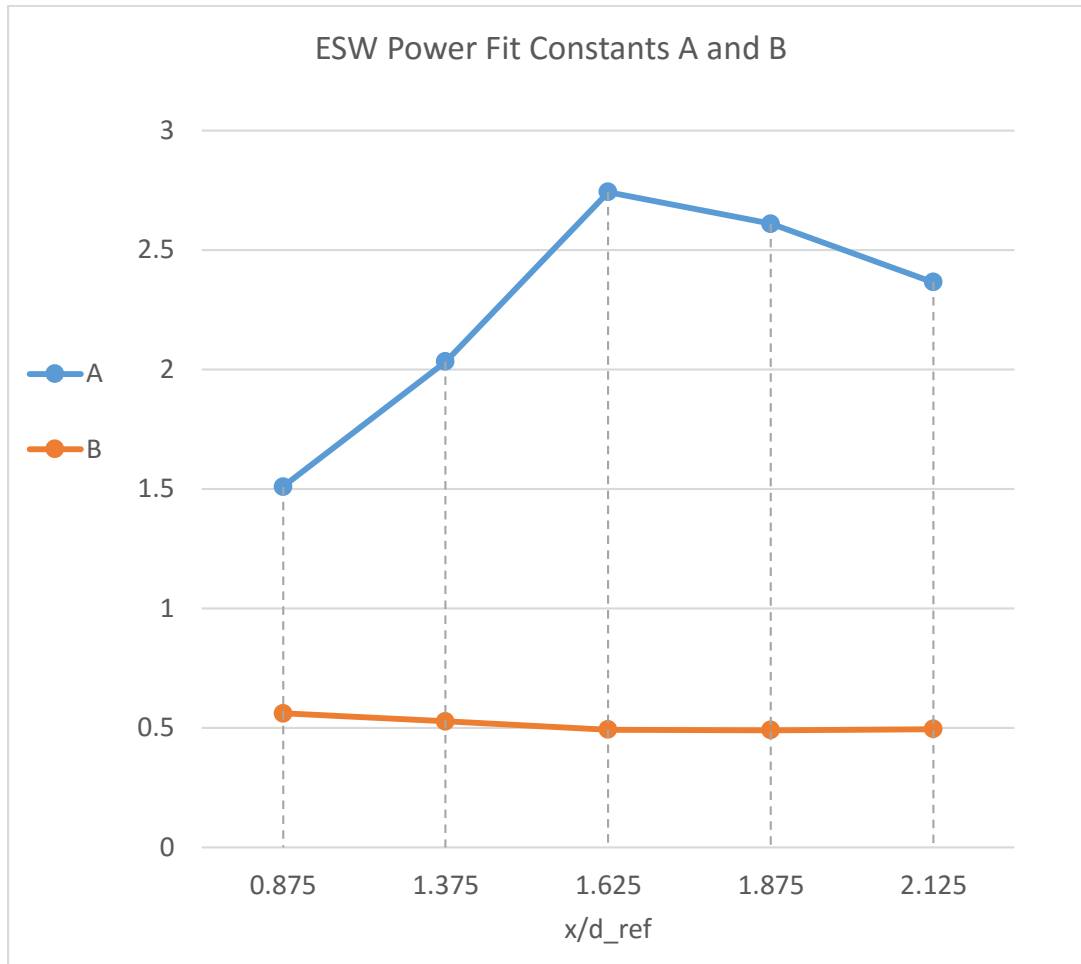


Figure 23: Changes in regression coefficients A (vertical intercept) and B (slope) of the ESW regression curves with axial position of the convection measurement.

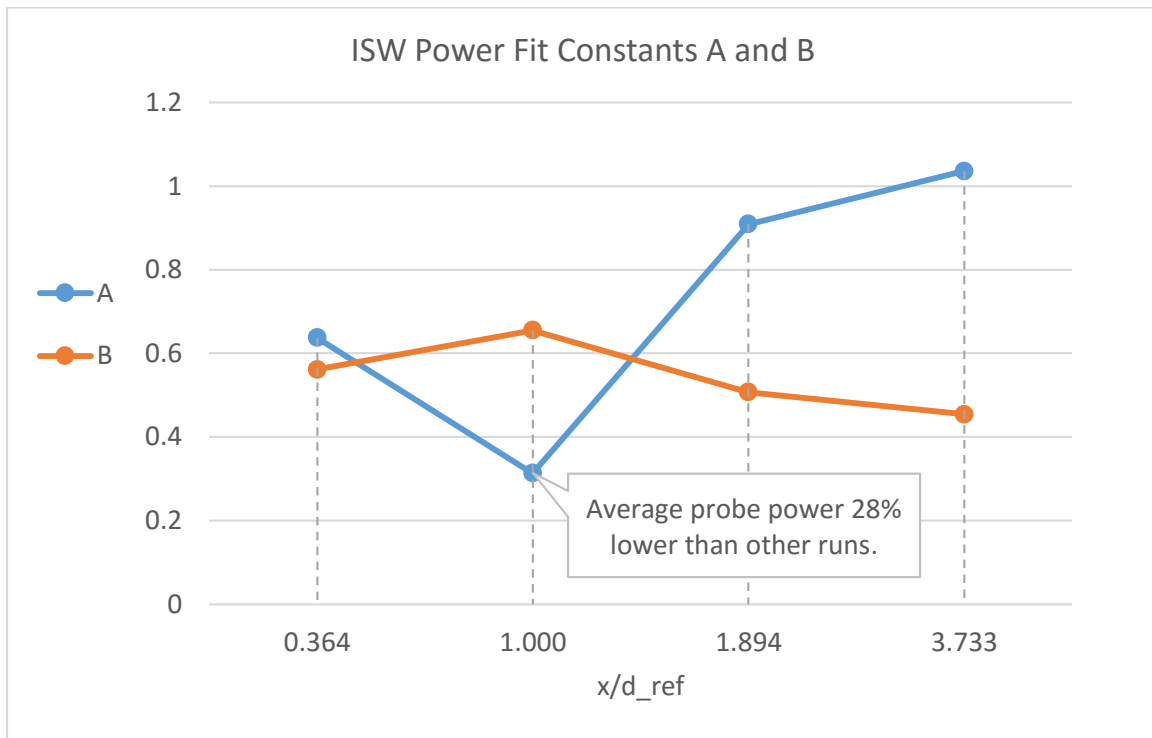


Figure 24: Changes in regression coefficients A (vertical intercept) and B (slope) of the ISW regression curves with axial position of the convection measurement.

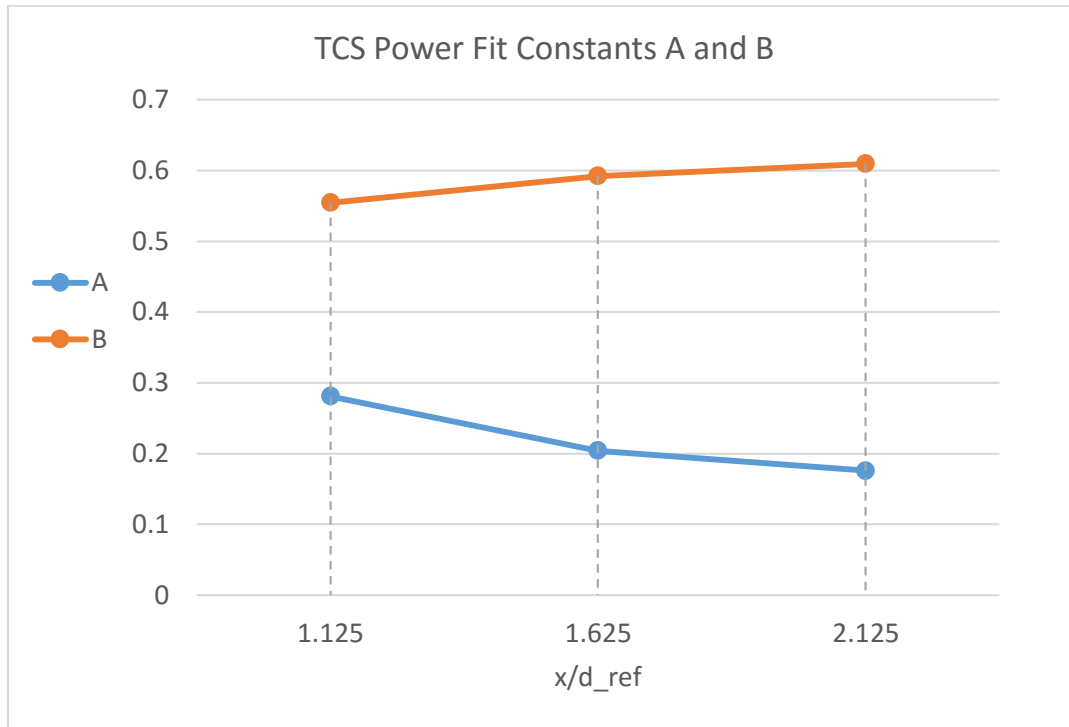


Figure 25: Changes in regression coefficients A (vertical intercept) and B (slope) of the TCS regression curves with axial position of the convection measurement.

6

Conclusions

Power law regression lines were fitted to experimental data for the External Shield Wall and the Thermocouple Sheath, within instrumentation uncertainty bands of a 95% confidence interval. The same regression model did not lie within the 95% confidence bands of the Internal Shield Wall. However, due to the efficiency of the ring heater, the internal test was run at much lower power levels for similar ΔT , which may have contributed to much tighter instrumentation uncertainties than those in the ESW and TCS models. Regardless, all regression lines subjectively appear to at least model the convection behavior on a surface of the probe, even if the fidelity of a data set was inadequate to determine the behavior at a specific axial position on a surface.

Boundary layer transition effects may have a significant impact on convection results as a function of axial position. In the ESW configuration shown in Figure 23, the coefficient A (which is proportional to the magnitude of the Nusselt number at a given axial position) can be seen to rise rapidly until $x/d_{ref} = 1.625$, and then gradually begin to fall. This change in the slope of A is very likely due to a change in the structure of the boundary layer. The plot of the exponent B is relatively flat for the ESW configuration, implying that that sensitivity to Reynolds number is relatively constant for all ESW axial positions tested.

The pattern of A and B is less clear in the ISW configuration. In general there is an increasing trend to A and a shallow decreasing trend to B . However, these trends are disrupted by what appears to be an outlier results at $x/d_{ref} = 1.0$. As noted on the plot, the set of ISW runs at $x/d_{ref} = 1$ was conducted at a 28% lower power level than the rest of the runs in that configuration. In theory, the difference in heater power should not impact the convection result, since power level is compensated for in the data reduction. The outlier may be caused by an error; an unaccounted for source of heat loss; or more interestingly, by some local flow phenomenon that beyond the scope of this experiment to model.

The patterns of A and B in the TCS configuration where relatively unremarkable and flat compared to the ESW and ISW runs. The overall Nusselt number results were lowest in the TCS

configuration, which may be due to the rounded tip of that configuration lending to more laminar (less mixing) local flow.

While these results offer greatly improved convection modeling of the probe, some applications may require greater fidelity. Two promising ways to improve this data further would be to apply viscous CFD to determine flow properties at the probe inlet and the transition of the inner channel from a circular duct to an annulus, or to repeat this experiment to determine the prediction interval of these results. The 95% confidence intervals reported here are sufficient to explain the quality of the data taken, but only a prediction interval will have significant bearing on the robustness of the regression lines calculated here.

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<http://mathworld.wolfram.com/LeastSquaresFittingPowerLaw.html>

Appendix – Table of Results

	External Shield Wall (ESW)																			
	x/d_ref=0.875				x/d_ref=1.375				x/d_ref=1.625				x/d_ref=1.875				x/d_ref=2.125			
d_ref [m]	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
Re	2566	5557	11974	25654	2565	5559	11972	25657	2566	5558	11974	25659	2566	5557	11976	25663	2565	5559	11971	25764
Nu	113	165	237	418	113	174	242	390	115	179	232	371	106	167	213	342	100	156	202	326
A	1.3403				1.8051				2.4355				2.3172				2.1005			
B	0.5598				0.5270				0.4924				0.4893				0.4937			
EI [W/m]	23	23	46	46	22	22	46	46	20	20	47	47	20	20	48	48	19	19	44	45
T_0 [K]	295	296	296	295	294	295	296	294	298	298	297	294	297	296	295	296	297	296	295	296
T [K]	366	346	368	337	363	342	366	339	358	338	373	343	361	339	378	348	364	342	377	347
ΔT [K]	71	50	72	42	69	47	71	45	60	40	76	48	65	43	83	53	68	45	82	52
C * dT/dt [W/m]	-0.035	-0.005	-0.002	0.008	-0.089	-0.075	-0.003	-0.003	-0.094	-0.056	-0.043	0.090	-0.133	-0.053	-0.027	0.013	-0.116	-0.064	-0.022	0.099
q_c,wires [W/m]	-1.682	-1.184	-1.699	-0.990	-1.639	-1.109	-1.680	-1.066	-1.425	-0.950	-1.792	-1.147	-1.534	-1.014	-1.962	-1.248	-1.605	-1.076	-1.931	-1.224
q_cond,wood [W/m]	-0.963	-0.678	-0.973	-0.567	-0.313	-0.212	-0.321	-0.203	-0.204	-0.136	-0.257	-0.164	-0.176	-0.116	-0.225	-0.143	-0.153	-0.103	-0.184	-0.117
q_raditation [W/m]	-0.134	-0.086	-0.137	-0.068	-0.128	-0.079	-0.135	-0.075	-0.111	-0.067	-0.149	-0.081	-0.120	-0.071	-0.166	-0.092	-0.128	-0.077	-0.163	-0.090
h [W/(m^2 K)]	114	167	240	423	114	176	245	394	116	181	235	375	107	169	216	347	101	158	204	330
errPow	0.3017	0.2986	0.5970	0.6017	0.2864	0.2889	0.5967	0.5995	0.2525	0.2533	0.6106	0.6125	0.2523	0.2533	0.6155	0.6155	0.2519	0.2506	0.5723	0.5755
err_q_cond,wires	0.1381	0.1380	0.1379	0.1378	0.1378	0.1381	0.1382	0.1382	0.1382	0.1381	0.1375	0.1379	0.1382	0.1383	0.1382	0.1379	0.1382	0.1380	0.1384	0.1379
err_q_c,wood	0.0031	0.0024	0.0032	0.0021	0.0010	0.0008	0.0011	0.0007	0.0007	0.0005	0.0008	0.0006	0.0006	0.0004	0.0007	0.0005	0.0005	0.0004	0.0006	0.0004
err_q_rad	0.0059	0.0055	0.0060	0.0053	0.0058	0.0054	0.0059	0.0053	0.0059	0.0054	0.0062	0.0054	0.0059	0.0054	0.0063	0.0055	0.0059	0.0054	0.0062	0.0055
err_CdTdt	0.0006	0.0001	0.0000	0.0001	0.0014	0.0012	0.0001	0.0001	0.0015	0.0009	0.0007	0.0015	0.0022	0.0009	0.0004	0.0002	0.0019	0.0010	0.0004	0.0016
err_delta_T	3.7192	3.7023	3.7397	3.6716	3.7020	3.6787	3.7224	3.6684	3.7468	3.6997	3.7532	3.6871	3.7264	3.6884	3.7428	3.6988	3.7360	3.6848	3.7441	3.6995
err_h	6.6848	13.1246	13.3960	38.1614	6.6480	14.2780	13.5920	32.8100	7.7059	16.9707	12.3544	29.3073	6.6471	14.8868	10.4315	24.9767	6.0605	13.1323	10.0315	24.2453
err_Nu	6.9038	13.2759	13.8229	38.3840	6.8449	14.4056	14.0371	33.0703	7.8407	17.0328	12.8055	29.6276	6.8028	14.9582	10.9292	25.3289	6.2158	13.2489	10.4794	24.5554

	Internal Shield Wall (ISW)															
	x/d_ref=0.364				x/d_ref=1				x/d_ref=1.894				x/d_ref=3.733			
d_ref [m]	0.0559	0.0559	0.0559	0.0559	0.0559	0.0559	0.0559	0.0559	0.0432	0.0432	0.0432	0.0432	0.0305	0.0305	0.0305	0.0305
Re	1160	2379	6456	11182	1132	2393	6487	11183	961	2067	5554	9645	804	1631	4438	7685
Nu	33	39	71	118	28	44	93	121	26	39	64	85	20	25	40	56
A	0.5661				0.2781				0.8070				0.9200			
B	0.5613				0.6553				0.5072				0.4539			
El [W/m]	8	12	20	31	7	14	28	31	11	17	19	29	12	9	9	23
T_0 [K]	294	294	294	294	294	294	293	293	294	294	294	293	294	295	293	294
T [K]	366	376	374	372	363	383	382	368	381	386	362	371	388	353	326	359
ΔT [K]	71	82	80	78	69	89	89	75	87	92	68	78	93	58	33	65
C * dT/dt [W/m]	0.267	-0.019	-0.078	0.001	-0.073	-0.241	-0.273	-0.129	-0.188	-0.067	0.115	-0.109	-0.035	0.137	-0.949	-0.686
q_c,wires [W/m]	-0.845	-0.973	-0.943	-0.927	-0.819	-1.060	-1.058	-0.891	-1.027	-1.093	-0.811	-0.923	-1.106	-0.686	-0.394	-0.766
h [W/(m^2 K)]	15	18	33	54	13	20	43	56	16	23	38	50	17	21	34	47
errPow	0.1072	0.1491	0.2524	0.4034	0.0936	0.1850	0.3676	0.3965	0.1395	0.2132	0.2465	0.3762	0.1594	0.1199	0.1201	0.2992
err_q_cond,wires	0.0819	0.0820	0.0821	0.0821	0.0819	0.0821	0.0821	0.0822	0.0821	0.0822	0.0822	0.0821	0.0821	0.0821	0.0822	0.0822
err_CdTdt	0.0044	0.0003	0.0013	0.0000	0.0012	0.0039	0.0045	0.0021	0.0031	0.0011	0.0019	0.0018	0.0006	0.0022	0.0155	0.0112
err_delta_T	4.1837	4.2189	4.2080	4.2051	4.1794	4.2475	4.2317	4.1815	4.2527	4.2632	4.1623	4.1851	4.2600	4.1422	4.0177	4.1640
err_h	0.6904	0.7243	1.3210	2.2157	0.6042	0.7621	1.5523	2.3363	0.6057	0.8463	1.7351	2.0541	0.6135	1.1373	2.8987	2.2776
err_Nu	0.6975	0.7354	1.3403	2.2471	0.6098	0.7753	1.5824	2.3641	0.6155	0.8629	1.7510	2.0816	0.6258	1.1422	2.8874	2.2949

	Thermocouple Sheath (TCS)											
	x/d_ref=1.125				x/d_ref=1.625				x/d_ref=2.125			
d_ref [m]	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
Re	794	1633	4444	7708	765	1649	4434	7691	767	1648	4456	7690
Nu	10	15	26	36	9	15	26	36	9	14	26	37
A	0.2493				0.1812				0.1560			
B	0.5545				0.5923				0.6094			
EI [W/m]	6	6	8	10	5	6	9	9	4	6	9	11
T_0 [K]	294	293	293	293	294	294	294	293	294	293	293	293
T [K]	396	391	371	380	391	385	390	370	381	382	385	382
ΔT [K]	101	98	79	87	97	91	96	76	87	88	92	89
C * dT/dt [W/m]	-0.057	0.532	-0.105	0.015	-0.001	-0.006	-0.009	0.062	0.005	0.002	-0.024	0.034
q_cond,wires [W/m]	-2.403	-2.316	-1.861	-2.070	-2.285	-2.163	-2.284	-1.806	-2.064	-2.095	-2.181	-2.097
q_cond,ABS [W/m]	-0.146	-0.141	-0.113	-0.126	-0.070	-0.066	-0.070	-0.055	-0.042	-0.043	-0.044	-0.043
q_raditation [W/m]	-0.317	-0.302	-0.246	-0.270	-0.300	-0.285	-0.299	-0.241	-0.273	-0.275	-0.285	-0.275
h [W/(m ² K)]	10	15	26	36	9	15	26	37	9	15	26	37
errPow	0.0716	0.0774	0.0979	0.1349	0.0637	0.0769	0.1176	0.1171	0.0562	0.0735	0.1113	0.1384
err_q_cond,wires	0.1380	0.1380	0.1379	0.1381	0.1380	0.1379	0.1379	0.1380	0.1377	0.1378	0.1382	0.1380
err_q_cond,ABS	0.0005	0.0004	0.0004	0.0004	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
err_q_rad	0.0086	0.0083	0.0072	0.0076	0.0082	0.0080	0.0082	0.0071	0.0078	0.0077	0.0079	0.0077
err_CdTdt	0.0124	0.1143	0.0224	0.0032	0.0002	0.0012	0.0020	0.0133	0.0011	0.0004	0.0052	0.0074
err_delta_T	4.0963	4.0653	4.0001	4.0294	4.0725	4.0596	4.0679	4.0081	4.0495	4.0325	4.0515	4.0382
err_h	0.8298	2.1353	1.5434	2.1515	0.8923	1.1285	1.5330	2.5590	0.9542	1.1521	1.5346	2.2050
err_Nu	0.8473	2.2398	1.5766	2.2322	0.9118	1.1591	1.5957	2.6284	0.9700	1.1801	1.5914	2.2906

Vita

Samuel David Stephens was born on August 7th 1987. He obtained his Bachelor of Science degree in Aerospace Engineering from Texas A&M University, College Station, TX in 2011. During his studies at A&M he was awarded an Air Force Scholarship to continue his education and start a career as an Aerospace Engineer and Officer in the United States Air Force. He was commissioned in the Air Force upon graduation from A&M, and was stationed at Arnold Engineering Development Complex, Arnold AFB, TN. He worked in the Turbine Engine Ground Test Branch as an Aeropropulsion Test Engineer for two years before being assigned to the Flight Systems Branch as a Wind Tunnel Test Engineer. He attended the University of Tennessee Space Institute starting in 2011. He was awarded a Master's degree in Aerospace Engineering from the University of Tennessee, Knoxville in December 2015.