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Development of an Experimental Rig to Measure the Transient Response of Crossflow Heat Exchanger

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Abstract

Data centers are most commonly cooled with steady flow of cooling air delivered to electronic equipment from centralized cooling systems. Our research is motivated by the potential for gaining energy efficiencies by using dynamic on-demand cooling that is delivered by systems that are distributed rather than centralized. The overall project concerns the design, fabrication, and testing of an experimental apparatus to measure the dynamic response of water-air cross-flow heat exchangers that are at the heart of dynamic cooling systems. We have built a unique, computer-controlled experimental apparatus to characterize dynamic heat exchangers and extract the major parameters that control their response. The experimentally derived parameters will be integrated into mathematical models of the heat exchangers that will be used in control schemes for integrated control of cooling and IT load allocation. The objective of this Undergraduate Research Project is to obtain qualification data for the air and water side operating in steady state with constant flow rate and inlet air and water temperature. Experimental measurements of water and air inlet and exit temperatures and flow rates will be used in order to qualify the apparatus by extracting heat exchanger parameters such as steady state effectiveness that can be compared to literature data.

Keywords: Heat Exchanger, Data Center, Dynamic Response

1. Introduction

A data center is a centralized location of networked computer servers that store, process, and distribute data for an organization[1]. In 2007, 1.5% of the electricity consumption in the United States was used for data centers[2]. Of the 1.5%, one-third to one-half of this energy was used for cooling[3]. Therefore, there is room for economic and energy sustainability savings through modeling the cooling systems of a data center[4]. Data centers are most commonly cooled with steady flow of cooling air delivered to electronic equipment from centralized cooling systems. Our research is motivated by the potential for gaining energy efficiencies by using dynamic on-demand cooling that is delivered by systems that are distributed rather than centralized. The overall project concerns the design, fabrication, and testing of an experimental apparatus to measure the dynamic response of water-air cross-flow heat exchangers that are at the heart of dynamic cooling systems. We have built a computer-controlled experimental apparatus to characterize dynamic heat exchangers and extract the major parameters that control their response. The experimentally derived parameters will be integrated into mathematical models of the heat exchangers that will be used in control schemes for integrated control of cooling and IT load allocation. The objective of this Undergraduate Research Project is to obtain qualification data for the air and water side operating in steady state with constant flow rate and inlet air and water temperature. Experimental measurements of water and air inlet and exit temperatures and flow rates will be used in order to qualify the apparatus by extracting heat exchanger parameters such as steady state effectiveness that can be compared to literature data. This research will further industrial knowledge of the dynamic effectiveness of different heat exchanger models. In addition, the data and results extracted from this experiment will be used and shared by other universities which are Georgia Tech, SUNY Binghamton, and the University of Texas at Arlington as well as industry members like Microsoft, IBM, and Facebook through the partnership of the National Science Foundation Industry/University Cooperative Research Center for Energy Smart Electronic Systems (ES2).

2. Objectives

The development of this experimental apparatus is driven by the desire for a research rig that can be easily used to get performance and design parameters of different types and models of heat exchangers. This data will be used in improving the efficiency of electronic devices, and applied specifically to things such as data centers. This will be accomplished through the analysis of a heat exchangers response to different thermal loads under steady state and transient conditions. The results of this research will allow for better characterization of heat exchangers and an improved method for the cooling of efficient arrangements of server racks in a data center. The objective is to design and assemble an experimental test rig to run steady state and transient tests on a cross flow heat exchanger. This will be used in the validation of the experiment in steady state by extracting heat exchanger effectiveness and other parameters and compare them to literature data. My goal is to participate in the preliminary data acquisition in transient mode and comparison to models of dynamic cross-flow heat exchangers. This will give allow me to gain an understanding of steady testing as well as transient testing. This data collection will serve as a learning experience in which I can compare the steady state data to recorded correlations in literature data.

3. Experimental Design

The design of this experiment is constructed such that the experiment can fulfill certain specifications. The experimental apparatus must be able to deliver uniform airflow at constant temperature to the heat exchanger. Also, it must be able to deliver water at constant or time-varying flow rate and constant or time-varying temperature entering the heat exchanger for the transient and steady state test[5]. The experiment will be comprise of a connected air and water loop which uses a system of valves, water heaters, and pumps to control the flow rate and temperature of water entering the heat exchanger while an axial blower and electric heaters provide uniform airflow at a constant temperature to the heat exchanger. These specifications must be met so useful and accurate measurement of exiting air and water flow rates and temperatures can be made[5].

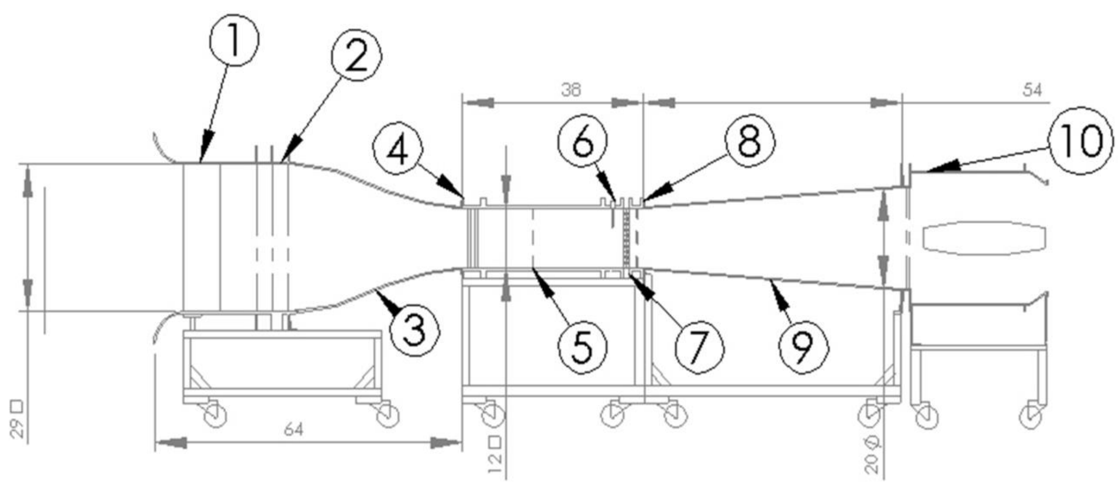

Figure 1. Air Loop Schematic

Figure 1 displays the technical schematic of the air loop used in this experiment. The air loop has many individual modular parts in its configuration. The air loop is a wind tunnel specially designed and constructed to complete operations integral to the testing phase of the experiment.

Table 1. Air Loop Components

1	Air Inlet	6	Inlet Air Temperature and Pressure Sensors
2	Inlet Flow Management Section	7	12"x12" Finned Area Heat Exchanger
3	Contraction 6:1	8	Exit Air Temperature and Pressure Sensors
4	AC Air Heaters	9	Diffuser
5	Mixing Plenum	10	Axial Blower

The air loop, seen in Figure 1 and labeled in Table 1, is a suction wind tunnel which creates the air loop through a system of connected components. The suction wind tunnel starts with an air inlet that filters the incoming air flow and removes particulates from the air[6]. The air flow proceeds to the inlet flow management component which is needed to straighten the air flow and remove large scale eddies[6]. The contraction is the next component in the air loop and is used to accelerate the air flow through a contraction volume and produce uniform flow that has the characteristic of low turbulence[6]. The AC air heaters are electrically powered heaters that heat the flow of air in the wind tunnel. The air flow then moves to the mixing plenum which mixes the newly heated air flow in order to create a uniform temperature profile[6]. The crossflow heat exchanger that will be tested uses a water loop to produce convective heat transfer to the air flow loop. Next, the diffuser decelerates the air flow to recover static pressure in the system[6]. Lastly, the axial blower uses suction as the driving force to produce the air flow that powers the air loop[6]. In Figure 2, the connection of the individual components as the air loop system can be seen[7].

Figure 2. Air Loop

Figure 2 displays the air loop in the laboratory setting[7]. The modular components and the support structure of the wind tunnel can be seen in its finished state at the Laboratory for Advanced Thermal and Fluid Systems at Villanova University.

The water loop is the combination of valves, pumps, heaters, and instrumentation that is used to deliver water at specific specifications. These specifications are determined by whether the testing being performed is transient or steady state. The water loop has many complex components that are necessary to complete these specifications.

The water loop can be susceptible to problems such as leaks so precautions such as teflon tape and epoxy seal are needed. The majority of the water loop was completed by Ph.D. candidate Marcelo Del Valle. I made contributions to water loop which mainly consisted of work on the tank support system as well as building the valve and piping support table which holds the air distribution system, the perturbation generator, the heat sinks, and heater controls. The air distribution system distributes air into the tanks to pressurize and charge the system as the water loop is not run by a pump[8]. There is a check valve to control the direction of air flow[8]. The regulator in the system ensures that air pressure coming from the building air compress system is set at a specific pressure[8]. The perturbation generator uses a 3-way valve and filter to control the flow of water into the heat exchanger[8]. The schematic for the water loop can be seen in Figure 3 and descriptions of the components in Table 2[8].

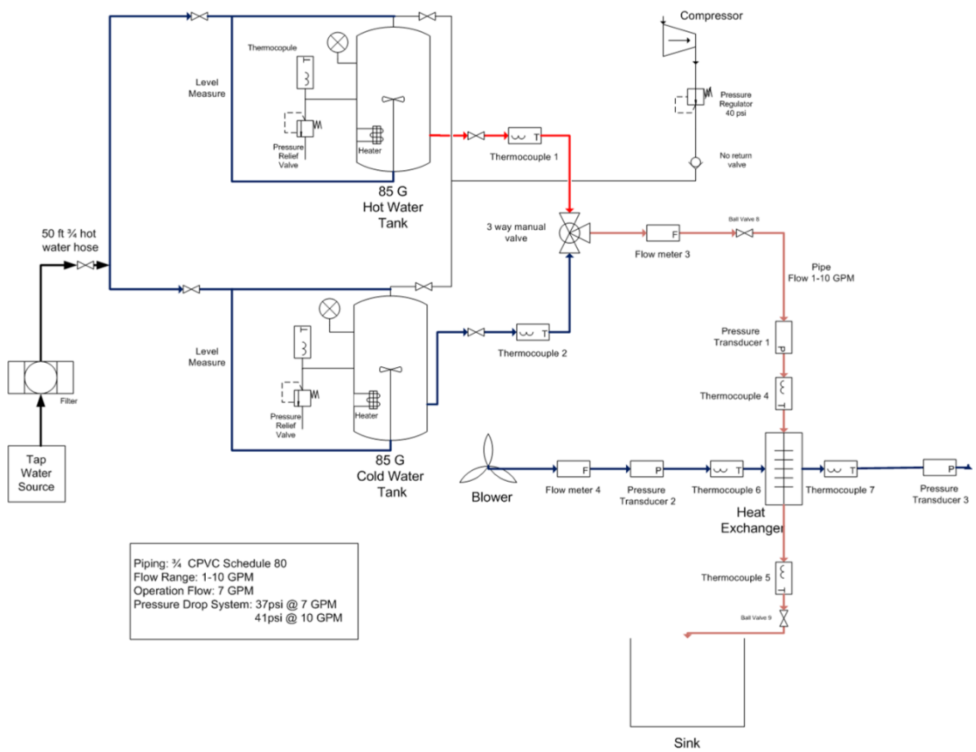

Figure 3. Water Loop Schematic

Figure 3 displays the technical schematic of the water loop. The schematic properly labels the valves, pumps, heaters, and instrumentation. The connections and interlocking of the individual components are seen in the schematic. The figure also capture the overall nature and characterization of the water loop system.

Table 2. Water Loop Components

	Component	Description
1.	Water Tank	Two 85-gallon tanks, one hot water and one cold water supply water to the heat exchanger
2.	Water Heater	Two water heaters work inside the water tanks with two mixing pumps to maintain a uniform water temperature
3.	Thermocouple	Seven thermocouples in the water circuit loop constantly give water temperature measurements
4.	Pressure Transducer	Three pressure transducers give pressure measurements at key points in the water loop
5.	Flow Meter	Four flow meters give measurements of the water flow rate in the loop
6.	Compressor	Charges the system by using air pressure to pressurize the water in the tanks so water loop can be run without a pipe
7.	Pressure Regulator	Sets air pressure coming out of the compressor to 40 psi
8.	Pressure Relief Valve	Two pressure relief valves installed for safety to release pressure from the system if air pressure in tanks exceeds safety limit
9.	Three-Way Manual Valve	Controls flow of water into the heat exchanger
10.	Water Levels	Maintain sections of water loop at constant elevation
11.	Filter	Air and water filter are used to remove oil from the building air compressor system in the air loop and minerals from the tap water source in the water loop

Figure 4. Water Loop

Figure 4 displays the water loop system in the laboratory setting[8]. The various connections of the system can be seen. The hosing, piping, tanks, and support structure are visible in their testing setup.

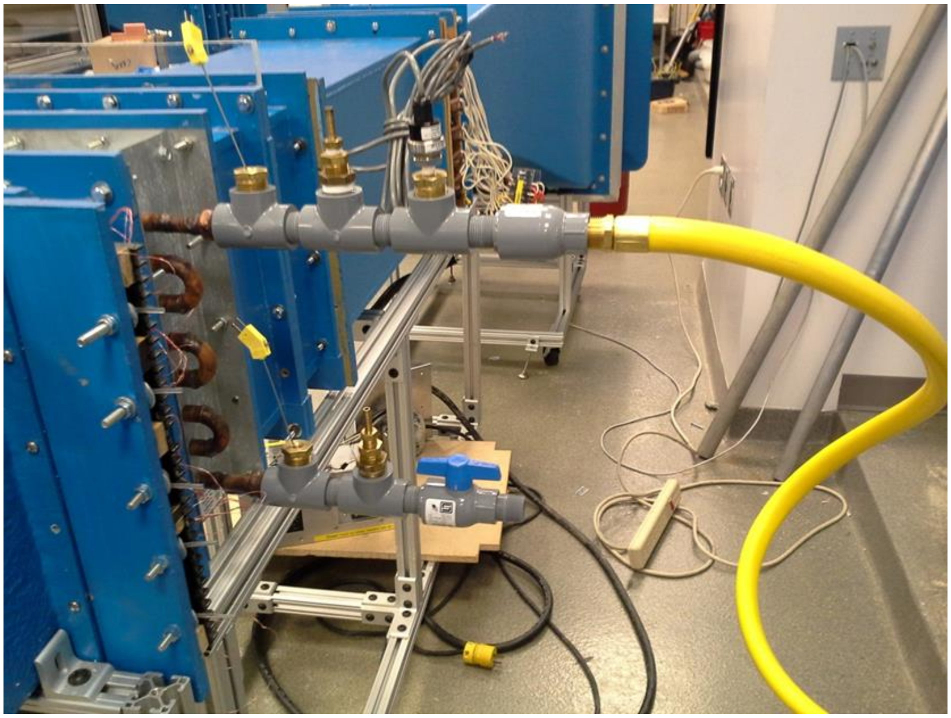

Figure 5. Heat Exchanger Apparatus

Figure 5 displays the inlet to the crossflow heat exchanger[8]. The yellow hosing is shown where the water is brought into the heat exchanger. Two thermocouples are shown inserted into gray piping.

In Figures 4 and 5, the water loop and inlet to the exchanger can be seen in their assembled form. The air side needs to be qualified in order to confirm that it would provide the air flow velocity profile needed by the heat exchanger. This is accomplished by collecting pressure measurements and from this calculating velocity to map out a velocity profile that can be compared to the expected velocity profile. These calculations are done using the Bernoulli equation, equation (1).

$$\mathrm{v} = \frac{\sqrt{2(P_T - P_{static})}}{\rho} \tag{1}$$

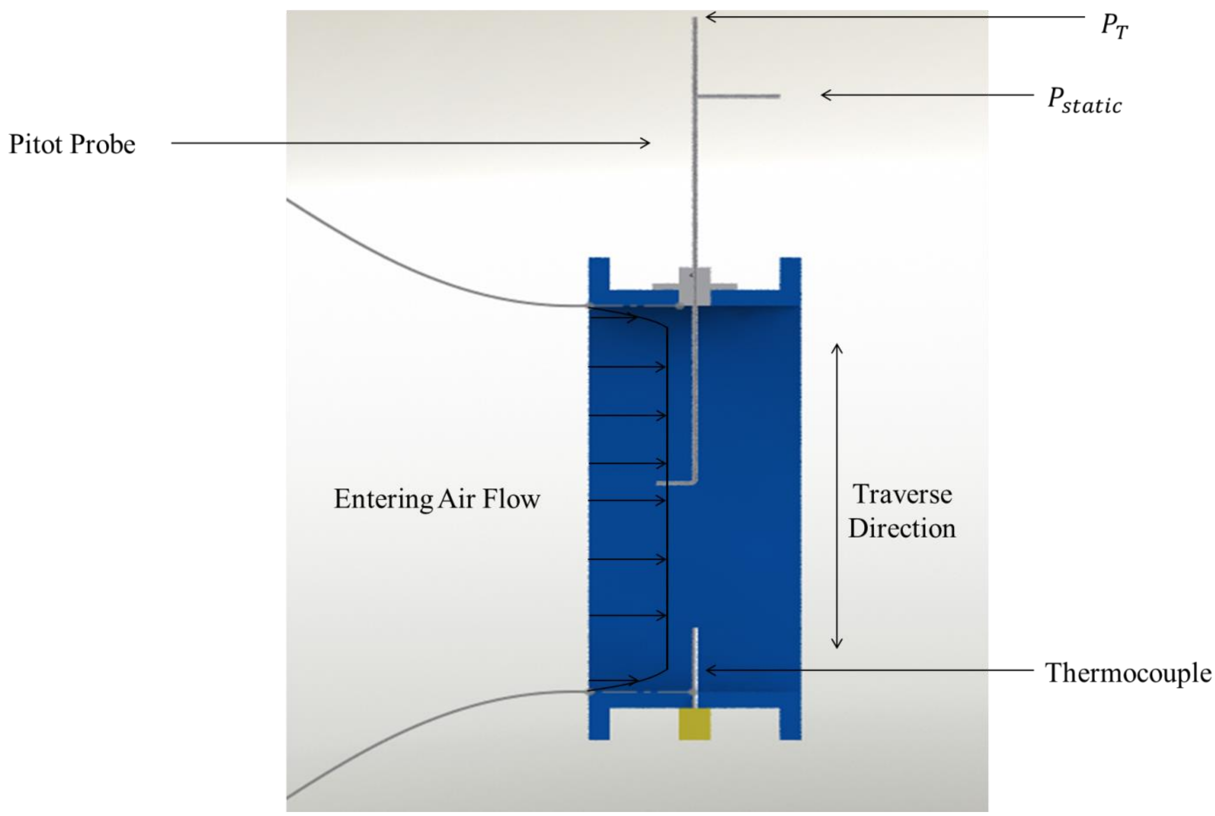

Figure 6. Velocity Profile Traverse Model

Figure 6 is a Solidworks computer aided design model of the velocity profile traverse[8]. This model displays the ideal fluid mechanics velocity profile for flow inside a wind tunnel. The direction of traverse is displayed. The location of the thermocouple, pitot tube, and entering air flow are shown. Points in the model are marked on the pitot tube to display where the different pressures are measured.

The method used to do the velocity profile traverse for air side qualification can be seen in Figure 6[8]. Air flow enters the section from the contraction. Using a pitot tube, which is a pressure measurement probe, pressure measurements are made along the centerline of the section from the bottom of the wind tunnel to the top at an increment of 0.5 inches. A baratron pressure transducer is used to measure the difference between total pressure and static pressure. Static pressure is measured using a digital barometer placed in the laboratory. The air temperature is measured from a thermocouple placed in the test section inlet. This temperature measurement is used to calculate the air density. From these values the air velocity is calculated along the center of the section and compared to the desired velocity profile shown in Figure 6.

4. Results

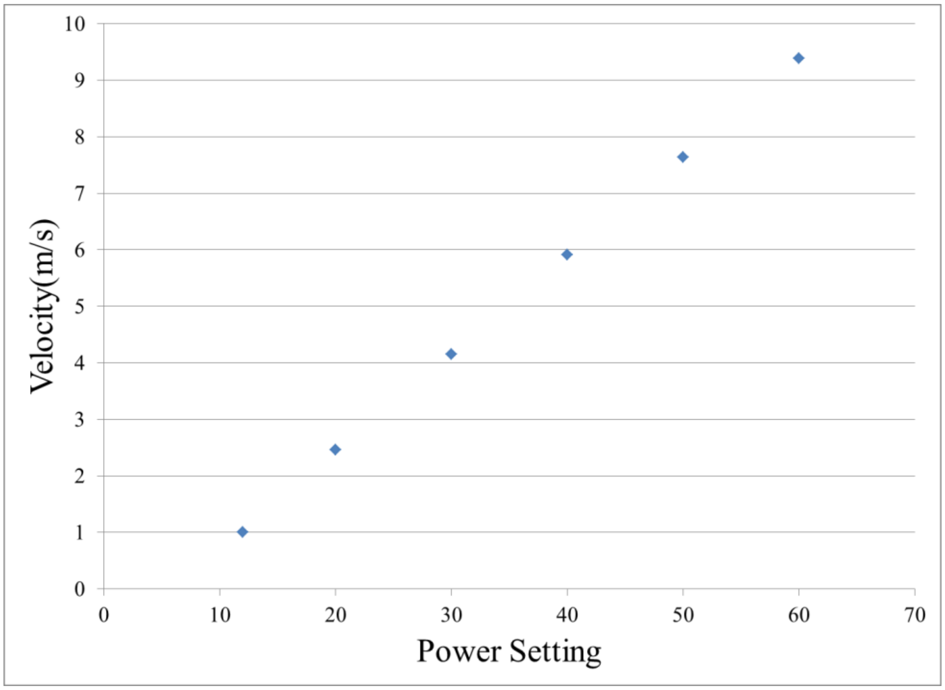

Figure 7. Velocity Based on Power Setting

Figure 7 presents the data from the velocity measurements using the pitot tube. The power setting is shown which is adjusted as the independent variable of this test. The trend is displayed in the graph.

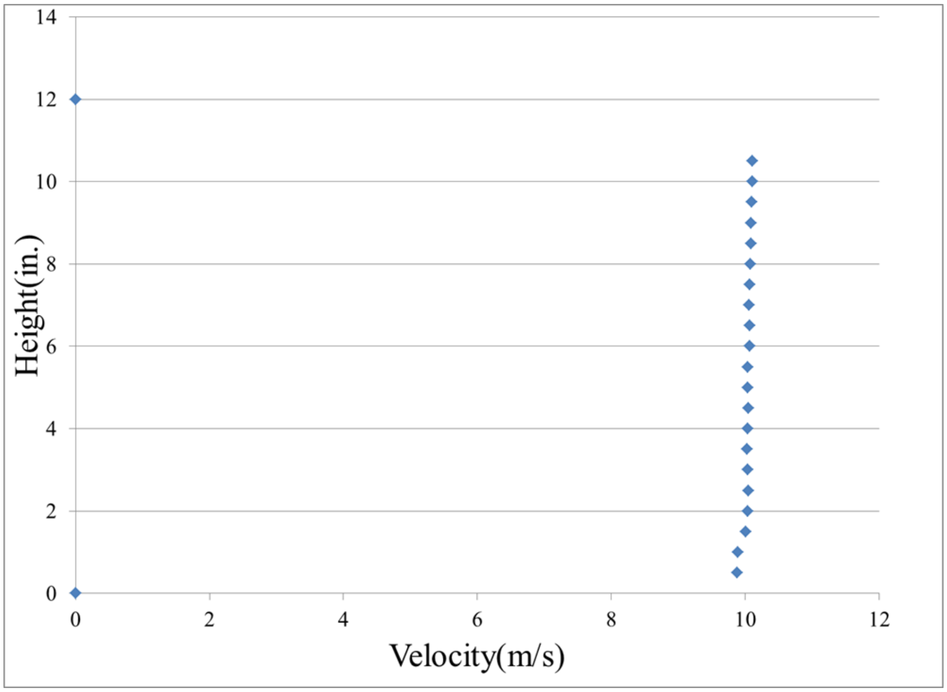

Figure 8. Pitot Tube Velocity Profile Traverse

Figure 8 presents the data from the velocity profile traverse shown in the Figure 6 Solidworks computer aided design model. The height is adjusted to produce this graph as it is the independent variable of the test. The trend of the test is displayed.

In Figure 7, the graph displays measured velocities taken by the pitot tube at the centroid of the wind tunnel section as the power setting on the axial blower is changed. The curve comes out to be linear therefore showing that the power setting is directly proportional to the air velocity. This is important because it assures that the axial blower is working properly. In addition, this provides a correlation between power setting and air velocity which is important as this relationship allows for the change of the power setting on the axial blower to a specific value while knowing the exact value of that air velocity. In Figure 8, the graph displays the velocity profile of the wind tunnel as the pitot tube is traversed from the bottom of the wind tunnel to the ceiling. The graph displays a vertical line of velocity data points showing that the air velocity remains constant during the traverse, with the exceptions being close to the top and bottom of the wind tunnel where the air velocity goes to 0 due to the no-slip boundary condition. This is important as it qualifies the air side loop as ready to undergo steady state testing because it delivers uniform flow into the wind tunnel and validates that the velocity profile of the wind tunnel matches the expected and desired velocity profile.

5. Conclusions and Future Work

In conclusion, the air side loop is qualified for steady state and transient testing. In addition, a correlation has been made between the power setting on the axial blower and the velocity at the centroid of the wind tunnel section. A correlation has also been made between the velocity in one of the wind tunnel sections and the height in the section. Now, the experimental rig is ready for testing. Measurements will be taken of the crossflow heat exchanger's response at steady state. After steady state data has been collected and analyzed, the instrumentation and equipment will be implemented in order to perform testing and collect measurements of the dynamic response of the crossflow heat exchanger. Experimental data from both the steady state and transient testing will be collected to compare to the computational models and produce the parameters necessary to perfect the computer models. Recommendations include that the rig is consistently checked for leaks in both the air loop and water loop. In addition, I recommend that before both steady state and transient testing begin that the wind tunnel velocity profile and velocity power setting correlation are checked and confirmed.

6. Acknowledgements

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