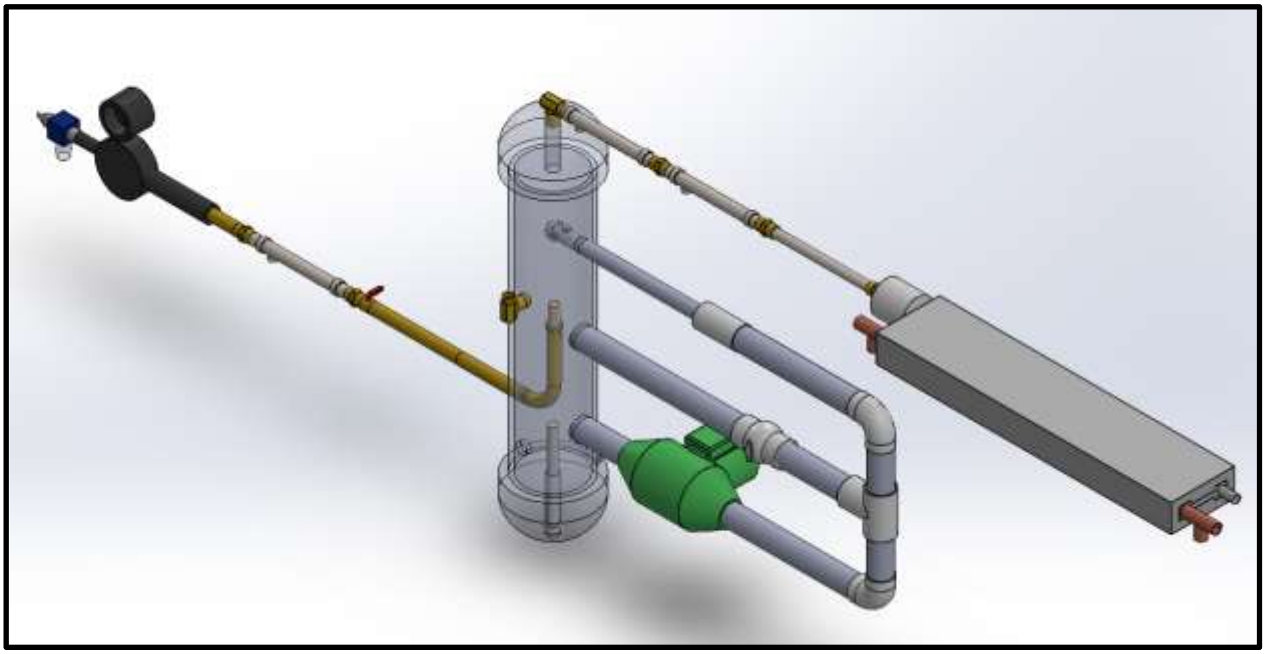

Furnace Heat Exchanger

Apr 27, 2021

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Table of Contents

Problem Scope

The furnace heat exchanger project was completed at the Oklahoma State University campus in Stillwater, Oklahoma. The project included ten undergraduate students, a project mentor, project champion, project coordinator, and occasional advisor support. Tasking for the undergraduate students included the design, construction, presentation, and eventual testing of a device which simulates flue gas within the tubes of a secondary heat exchanger in a typical residential furnace. After the design is certified, the apparatus will then be used to confirm results of a CFD study being conducted in conjunction with the senior design project.

The CFD study is being performed by a Ph.D. student who is likely studying the turbulent flow within the tube, and how the fluid exchanges heat with the tube walls. The tube has a turbulator inserted to create a turbulent and indirect flow through the inner passage. This turbulence forces fluid interactions with the outside of the tube, which increases the heat transfer coefficient between the fluid and the inner tube surface. Measuring the temperature gradients along the tube surface will help validate the computational analysis of the fluid flow within the tubes. This computational analysis will then predict/confirm the energy content of the simulated flue gases as it exchanges heat with the tube walls.

In order to simulate the flue gases, the design would require replication of the dewpoint and temperature conditions of flue gases entering and exiting the secondary heat exchanger in a furnace. The conditions that needed to be met were as follows:

Minimum volumetric air flow rate	0.15 CFM (0.255 m^3/h)
Maximum volumetric air flow rate	0.7 CFM (1.19 m^3/h)
Minimum dry-bulb temperature for the inlet of the test section	350°F (177°C)
Maximum dry-bulb temperature for the inlet of the test section	500°F (260°C)
Maximum dew-point temperature for the inlet of the test section	150°F (65.56°C)
Minimum dry-bulb temperature for the outlet of the test section	90°F (37.78°C)
Maximum dry-bulb temperature for the outlet of the test section	150°F (93.34°C)
Dew-point temperature for the outlet of the test section	90°F (32.23°C)

Table 1 - Project Limitations

Although the simulated flue gas is not an entirely accurate replication of flue gases in an actual heat exchanger, the difference is considered negligible in this application.

The potential limitations with the project stem mainly from having to prove that certain conditions were met. The potential difficulties with proving this lie with uncertainties associated with measurement equipment and methods. The increased temperature and humidity that the project deals with also increases the difficulty of finding equipment that will accurately take these readings, as lots of these types of monitoring devices are not suitable for high temperature or high humidity. This requires more specialized types of data acquisition equipment to be used, types of which were not readily available for the scale of project being performed by the undergraduates.

Environmental, Health, Safety (EHS)

Safety was a primary consideration in the creation of the apparatus. All members of the team were required to get their NCL White Badge, as well as complete any required specialized safety training for manufacturing equipment. All applicable PPE was worn during the appropriate phases of the construction process. Safety glasses, hearing protection, and work gloves were the primary forms of PPE worn. Safety glasses were determined to be required for the operation of the apparatus, since compressed air was used to supply airflow in the system. Safety Data Sheets were referenced for the appropriate PPE to wear during the use of potentially hazardous materials.

The sustainability factor heavily relies upon the materials used to build the apparatus and chemicals used in bonding/sealing the joints. The PVC used is a common material, and although not considered hazardous it does not easily bio-degrade in nature. It would be about as sustainable as plumbing in most households across the modern world. The PVC glue and RTV silicone was procured in reasonable amounts and was not wasted. The bottles will be used until entirely depleted, then disposed of appropriately. Most other materials used in the apparatus are recyclable metals or reusable components.

The primary ethical considerations of the project are to ensure that the final product is safe for the user to operate, without any unreasonable risk of injury to person or damage to equipment. Another ethical consideration is the methods and results from testing the device. Honesty and integrity were used in communications, and methods of testing were conducted in a way that left room for little bias to influence the results.

Professional considerations include ensuring the apparatus is easy to operate and has the longevity to operate for a reasonable amount of time without parts failure. It was also designed to be operated without excessive noise production. The potential large scale impact of the project is to help in the improvement of the efficiency of heat exchangers, potentially reducing the overall energy consumption of heat exchangers.

Stakeholders

Dr. Jeff Ferguson (Cyntergy). MSME, PE, CPMP, NCEES

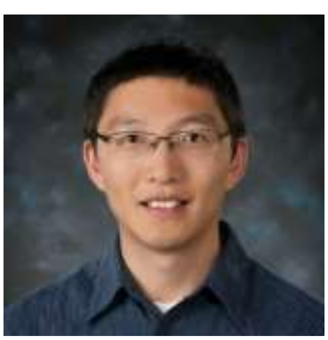
Dr. Ferguson has advised the team as far as teamwork and proper communication. He has provided a strong sense of structure within the team with his expertise in managing engineering projects within Cyntergy.

Dr. Chris Seeton (Shrieve) Ph.D.

Dr. Seeton has provided many ideas and held much knowledge for this team with his extensive experience in the HVAC industry. Many of the design concepts from this project have been suggested by Seeton and implemented with the support of our engineering principles. Seeton asks all the right questions to ensure we are considering every aspect in our design.

Dr. Roy Crawford (Johnson Controls Inc) Ph.D.

Dr. Crawford has given us the idea and project scope which we base our project design off of. He provides additional suggestions to implement into our design to ensure it accomplishes the goal of each party.



Dr. Tao Geng (Johnson Controls Inc.) Ph.D.

Dr. Geng has provided a furnace from Johnson Controls Inc. to base our study off of. He has provided data sets, along with CAD drawings, to base the set test conditions around and has provided ideas in which to begin testing this study.

Additional Stakeholders

Dr. Christian Bach, Ph.D .

Dr. Bach has served as our project champion and mentor throughout this process. He has provided us all with ideas for designs with his experience researching and testing. Dr. Bach serves as our first source to contact with questions.

Dr. Aaron Alexander, Ph.D.

Dr. Alexander has served as our project champion, as well as leading the overall delivery of the project. He has provided us with adequate solution methods for testing the project as well as answering any questions we have had along the way.

Dr. Laura Southard, Ph.D.

Dr. Southard is a project coordinator for many of the interdisciplinary design projects and has assisted in answering questions about the course and providing current structure for the course.

Engineering Analysis

Inlet Section

Overview

The purpose of the inlet section is to regulate the flow of air through the system to a minimum of .15 CFM and a maximum of .7 CFM. This was achieved through the use of a needle valve located right after the pressure regulator. The inlet section also contains an inline heater to bring the intake air up the same temperature of the water in the humidifier. The specific heater that was used to heat the inlet air was an Omega 50 watt duct heater.

Figure 1 Cad drawing of Inlet section

Process

The inlet heating section of this project served a few purposes. The main purpose of heating the air up to 150°F was to provide the air with a higher potential to reach the necessary dew point of 150°F. By preheating the air, the humidifier heater did not have to be turned up as high.

Humidifier Section

Overview

The purpose of the humidifier section is to allow for the air to obtain enough humidity to reach a dew point of 150°F. This is achieved by taking the air from the first heater at a dry bulb temperature of 150°F and allowing it to bubble through a water column also set to 150°F. The air reaches saturation at this temperature, setting it as the air's dew point so long as the air is kept above this temperature. Having the first inline heater and the water heater both set to the same temperature eliminates the need for heat transfer calculations between the air and the water since the ΔT is 0°F. This allows the humidification process to be more predictable and ensure that the air reaches the necessary temperature to obtain a dew point of 150°F.

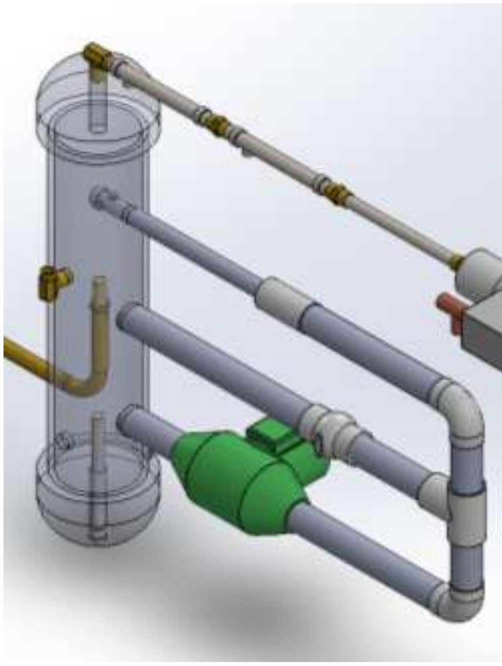


Figure 2 - CAD Drawing of Humidifier

Figure 3 - Pic of Humidifier

Process

The humidifier is designed to give the air as much surface area in contact with the water as possible to ensure that the air reaches saturation, setting the dew point at 150°F. This is accomplished by passing the air through an air diffuser, originally intended to be used as a muffler stone for air tools. This diffuser disperses the air into many small bubbles, maximizing the amount of air in contact with the water. The water in the humidifier is heated by a 250W immersible cartridge heater placed in the bottom of the main tower of the humidifier. The output of the heater is controlled by an RTD sensor located between the top of the heater cartridge and the bottom of the air diffuser. The RTD is wired to a relay designed to cut power to the heater should the water temperature exceed the maximum allowable temperature of 200°F. Uniform water temperature is maintained with the use of a 1/20 hp circulating pump to ensure there is a negligible temperature gradient within the water. There is also an internal water spray bar located above the top of the water column designed to give air an additional chance to become humidified after the bubbles breach the surface of the water column. The spray bar is fed from a tee fitting located on the circulation loop of the water. To verify that the spray bar is operating as designed, a borescope camera was fitted to the top of the humidifier with the camera extending into the humidifier and the display mounted above the top. The camera lens is fully adjustable in length to allow the user to be able to inspect any internal part of the humidifier's main column. Filling and draining the humidifier is accomplished with a 90° elbow fill port located at the top of the water level, and a ball valve located at the bottom of the water column. The fill valve is placed directly at the top of the water level to prevent overfilling, and the drain valve has a drain tube attached to it to route the water into a bucket placed below the table. The humidifier section is held in place by hose clamps that secure it to three pieces of unistrut mounted to the apparatus table. The entire humidifier is also wrapped in insulation to prevent any unnecessary heat transfer between the system and its surroundings.

Figure 4 - Air Diffuser Stone

Design Alternatives

Secondary Heaters

Overview

The purpose of the secondary heaters is to raise the temperature of the heated gas that comes from the humidifier. As the humidifier goal is to output fully saturated heated gas, the secondary heaters increase the gas temperature to avoid any condensations in the system and to bring the temperature up to the required range of the test section inlet.

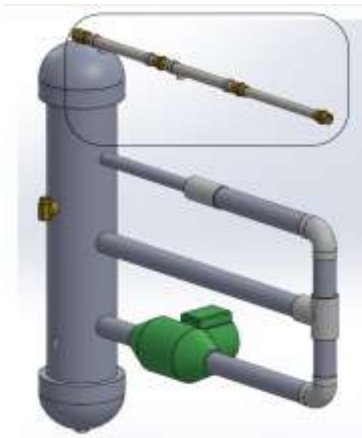


Figure 5 - 3D Secondary Heaters

Figure 6 - Secondary Heaters

Process

The inline heater has a controlled surface temperature up to 538°C (1000°F). As the gas enters the first heater at 65.5°C (150°F) with a volumetric flow rate of 0.7 CFM and a heater surface temperature of 530°C (986°F), the gas temperature increases. In that case heat transfer occurs and the gas leaves at 158.4°C (317°F). The gas temperature at the outlet of the first heater is still below the range required for the inlet test section temperature (149-260°C/300-500°F), so the second heater post-humidifier is necessary to reach the required temperatures. The conditions for the second heater to achieve the requirements are for the gas entry temperature and volumetric flow rate to be 158°C (317°F) and 0.7 CFM, respectively, and the heater surface temperature to be 530°C (986°F). After that, the gas leaves the heater at 250°C(480°F) to the test section (Figure 7).

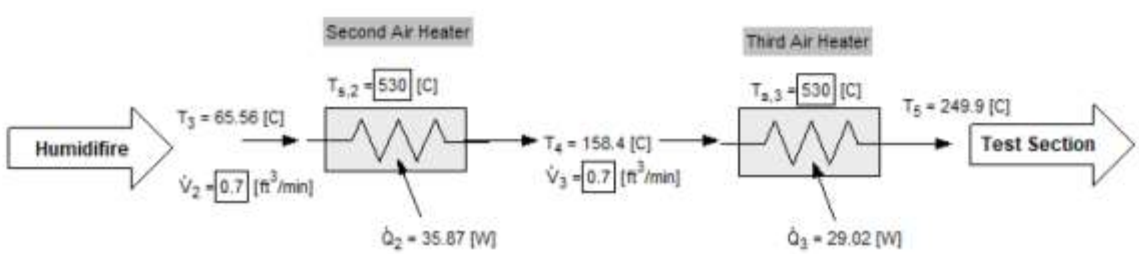


Figure 7 - EES - Secondary heaters

Goals

- Outlet gas temperature at a range of 149-260 °C (300-500°F).

- Condensate flow measurement
- Temperature measurements along the test section as requested by JCI.

Specifications

- Omega Inline Heater
    - 50 W
    - Exit Air or Gas Temperatures to 1000°F (540°C)
    - Inlet Air or Gas Temperatures to 250°F (121°C)
    - ⅜" NPT fittings

Test Section

Alternative Concepts

Below is a comparative analysis between each sub-system analysis which outlines the differences between each alternative.

I. Temperature Gradient Measurement

The temperature gradient is one of the main goals for this project and is weighted heavily when regarding the decision for selection. Outlined below are the capabilities for collecting temperature measurements and the relative complexity for each task.

1) Water-cooled - Temperature gradient measurements are impossible due to the complexity and geometry of our design.
2) Mixed air-to-mixed air (Unfinned) - Temperature gradient measurements will be readily available with this design, and locations will be unhindered.
3) Unmixed air-to-mixed air (Finned) - Temperature gradient measurements will be available with the design, although exact locations may be slightly hindered.

The two air-to-air heat exchangers provide sufficient simplicity to achieve the desired temperature measurements for this design. These two would be preferable over the water-cooled.

II. Enthalpy Data

Enthalpy capture is the essence of the secondary heat exchanger, so harvesting as much of this latent heat as possible and accounting for the heat transfer is a primary objective. Listed below is a comparison between each of the alternatives:

1) Water-cooled - The water-cooled design allows for the most accurate consideration of heat exchange within the tube with respect to the total amount. This design alternative also allows an abundance of heat removal as the flow rates can vary substantially with the valve configuration.
2) Mixed air-to-mixed air (Unfinned) - With a mixed air stream blowing over the tube section and an inability to measure the heat transfer accurately on the cold side, this design does not accurately harvest or account for the enthalpy relative to the other design alternatives.
3) Unmixed air-to-mixed air (Finned) - With an unmixed air stream blowing over the tube and additional surface area to collect energy from, this design will harvest the necessary amount of heat. Again, as an unmixed stream flows over the tube with a small temperature difference from the inlet and outlet, accounting for the total heat transfer is limited to analysis of the hot gas.

The water-cooled design allows for the most accurate accounting for heat exchange within the tube in a total sense. However, intermediate measurements of how the gas is reacting within the tube walls can provide valuable information on relationships between the hot gas temperature and the amount of heat being transferred in particular sections.

III. Instrumentation

In order to achieve the desired thermodynamic dew-point temperature (32.2°C/90°F) at the outlet the test section requires a lot of instruments. Due to several processes involved in the test section, obtaining accurate measurements can be a difficult task. Nonetheless, precise instrumentation is required to ensure that everything is in working order. The following are some of the necessary instrumentations for each concept.

1) Water-cooled - Fabricated fittings allow insertion of temperature measurement sensors in the inlet and the outlet of the test tube, but it is complicated to insert thermocouples distributed along the test tube without being affected by the cooled water. In the inlet and outlet fitting an RTD is used to measure the temperature of hot gas as the gas enters the test section tube, then cools down to the desired temperature. However, on the outlet fitting a humidity sensor is integrated to also measure a moisture percentage in the gas.
2) Mixed air-to-mixed air (Unfinned) - We planned to use resistance temperature detector (RTDs) in both fittings to measure the temperatures, as well as using 9 adhesive thermocouples on the test tube; for a few reasons, mentioned in the revision section below, we will use thermocouples instead of RTDs and use weld-on thermocouples as opposed to the adhesive style. There is a humidity sensor in the outlet fitting to ensure the calculation of the dew-point temperature. As for the condensation, we will collect it in a small graduated cylinder to measure the total

condensate flow. The pressure measurement will be determined by a differential transmitter in the inlet/outlet fitting, which will provide the flow rate within the pipe.

3) Unmixed air-to-mixed air (Finned) - On the test section, finned tube temperature sensors will be installed on the inlet/outlet fittings and a humidity sensor will be installed on the outlet fitting. A thermocouple will be used in the inlet fitting to detect the temperature of the inlet gas as the temperature is increased at the secondary heaters section. Along the test section tube surface, 9 weld-on thermocouples will collect data on the gradual change in temperature of the hot gas up to the outlet of the test tube. For the outlet, multiple instrumentation sensors are being used, the first being a thermocouple. An additional relative humidity sensor will gather moisture content data on the gas as it exits. Finally, a graduated cylinder will be used to harvest any condensed moisture from the gas. Figure 10 depicts a schematic of this particular design alternative.

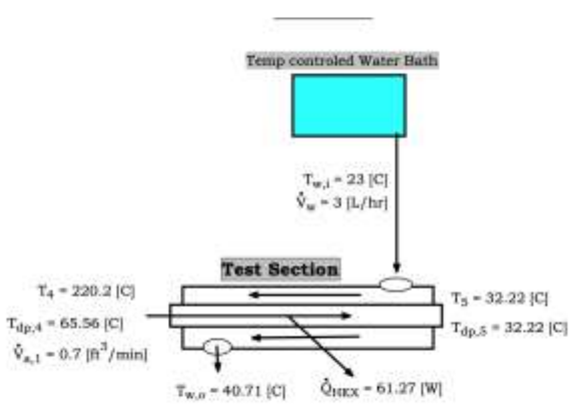


Figure 8 - water-cooled

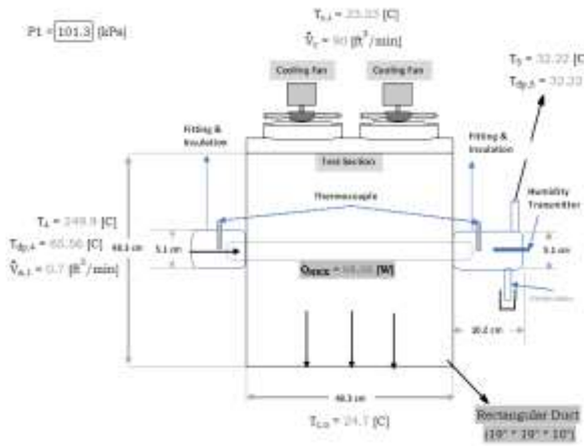


Figure 9 - Air to air heat exchanger without fins

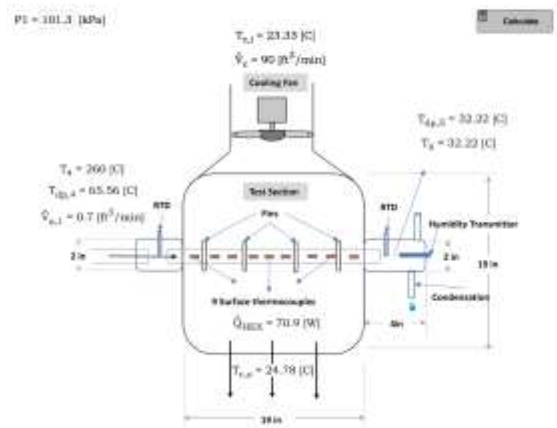


Figure 10 - Air to air heat exchanger with fins

Final Design (Conduction Heat Transfer)

The conduction heat transfer concept is an 18” long aluminum square bar. The aluminum bar is designed in a dog bone style with a 0.5” steel “test tube” inserted at one side of the bar for the heated air and a copper tube on the other side for chilled water. The idea of using an aluminum bar as conduction heat transfer is that the aluminum has a high thermal conductivity, at about 205 W/m-K. This will increase the heat transfer due to a very small resistance through the aluminum material(*Figure 12*).

The temperature of the cooled water is maintained by a water cooler bath at constant temperature and an immersed pump in the constant water bath.

I. Temperature Gradient Measurement

A. Test tube:

On the test tube, 6 thermocouples are inserted in the tube to measure the change of temperature as the heat transfers out of the heated gas, and 2 thermocouples are inserted into the inlet and outlet of the test tube(*Figure 11*).

B. Cooled water:

A pair of RTDs are used to measure the inlet and outlet of the cooled water.

II. Calculations / Methods

The flow through the aluminum bar is a counter-flow heat exchanger. The cooling water flows from the constant water bath by a pump. The specifications considered to calculate the conduction heat transfer were air volumetric flow rate at 0.7 CFM, a turbulator inside the tube, and an assumed Reynold number of 10,000. However, the heat transfer needed to reduce the temperature to 43.44 C is 66.55 W by correlation (1). Therefore, as the heat will transfer through the aluminum bar to the cooled water a conduction heat transfer correlation (2) was used to determine the heat transfer where R_{total} (thermal resistance) is the R sum of the steel tube, aluminum bar, and copper tube, which is equal to 0.615 K/W.

$$\dot{Q} = mC_p\Delta T \quad (1)$$

$$\dot{Q} = \frac{\Delta T}{R_{total}} \quad (2)$$

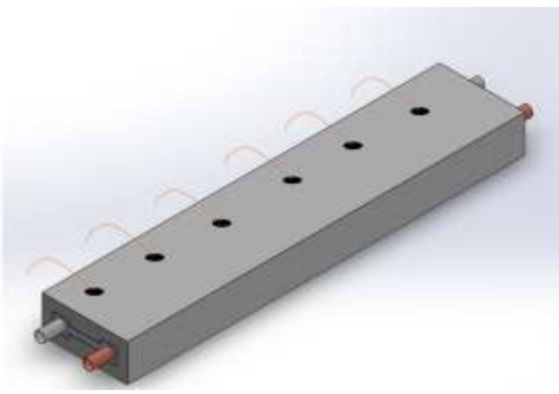


Figure 11 - Thermocouples

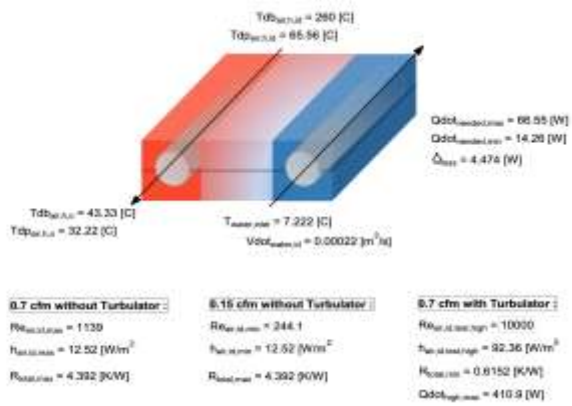


Figure 12 - Conduction Heat Transfer

Testing and Quality Plans

The testing of our apparatus was successful in multiple ways. Although some components failed during the testing process, this is the exact reason for the testing portion of a design. Our testing process consisted of checking the following aspects of our design:

- Volumetric flow rate
- Circulation pump operation (both)
- Spray bar functionality
- Humidification capability
- Thermocouple response
- RTD functionality

- Inline heater operation
- Electrical safety shutoffs
- Condensation generation
- Constant temperature bath operation

Testing of each aspect was done individually, then completed as a whole to test the entire system's functionality.

Volumetric flow rate

Originally, the testing plan for volumetric flow rate called for verifying operation of the air flow system with an analog flow meter which relayed information to a data acquisition device (DAQ). Upon receipt of the analog flow meter and subsequent programming attempts, the analog flow meter was not able to be implemented fully in our design. It was still attached to our apparatus, but is not considered functional yet.

Although this flow meter's functionality was not able to be confirmed, we adopted a new testing method which involved simple fluid mechanic measurements. This test consisted of a graduated water column, an inflatable bag, and a timer. The testing procedure went as follows:

1. Air pressure to the system was turned on.
2. The air pressure regulator was set to 3 psi.
3. The needle valve was opened partially.
4. The graduated water column was filled with water to an initial mark of 8000 ml.
5. Whoever held the bag, then inserted their hand into the water.
6. A measurement of the volume of displaced water was recorded for the hand.
7. The inflatable bag was attached to the test section outlet
8. The timer was started as the bag was attached to the outlet.
9. After an amount of time passed, the bag was pulled from the outlet and the timer stopped.
10. The bag was then inserted into the bath along with the previously measured hand.
11. A measurement of the displaced volume of water was recorded for both the hand and the bag.
12. The volume displacement of the hand was then subtracted from the combined hand/bag test.
13. This value was then divided by the time measurement and recorded as the proven volumetric flow rate for the conditions of the system at the time.
14. Steps 4 through 13 were completed ten times at varying time intervals so the bag was filled at different volumes for each test.
15. The needle valve was then marked to indicate the position at which our test was performed.

Our average volumetric flow rate recorded for our testing was 0.53 CFM. This landed us within our goal of 0.15 to 0.7 CFM. Further testing for the volumetric flow rate will be needed to verify operation of the analog sensor when it has been integrated with the DAQ. It is recommended to verify the results of the analog sensor with the same method outlined above.

Circulation Pump Operation

Testing of the circulation pump was not outlined in our testing plan, but was deemed appropriate by the team members during the testing phase of our apparatus construction. The circulation pump simply needed to circulate water and create turbulence for mixing the water within the column.

After the installation of the original pump, it was noted that the pump was getting rather hot. An amp draw on the pump was taken and it was confirmed that the pump was over-working. After turning the pump off, the manual was referred to and a note was made of the pump being improperly positioned. After repositioning the pump and an attempt to turn it on, the pump would no longer function.

One of the team members had happened to purchase a somewhat identical pump (flanges were shaped differently) prior to the project, so it was decided to use that one and ensure it was mounted appropriately. After installation, the pump was tested as follows:

1. The humidifier was verified to be filled to just below the fill port.
2. The pump was turned on.
3. An amp check was performed on the pump and the pump seemed to be well within FLA.

After the pump was verified to be operational, a borescope ended up being installed which allowed for a visual inside the humidifier. This also helped confirm proper pump operation.

Spray Bar Functionality

Testing of the spray bar was just as simple as the circulation pump. The testing consisted of positioning a bypass valve on the outlet side of the pump to send more/less flow through the spray bar depending on the level of misting by the bar. The testing procedure was completed as follows:

1. The humidifier was verified to be filled to just below the fill port.
2. The pump was turned on.
3. The borescope was turned on.
4. Adjustments to the bypass valve were made until the spray bar produced a fine mist of water droplets.
5. An amp check was performed on the pump to confirm it was still within the FLA.

The spray bar was confirmed to be functional and the amount/size of water droplets coming in contact with the air was a good confirmation.

Humidification Heater

Testing of the humidifier as a whole was considered complete after confirming operation of the immersion heater. The humidifier temperature was monitored through the safety device's digital display. This device was the protection against overheating, and was set to 155 degrees. The testing procedure for the heater is outlined below:

1. The humidifier was verified to be filled to just below the fill port.
2. The pump was turned on.
3. The heater's variac was plugged in.
4. Adjustments were made in small increments to the variac's voltage output.
5. After each adjustment, the system was left for five minutes until the next adjustment.
6. This process was continued until the humidifier was approaching the operating temperature of 150°F.
7. The heater was then left for 10 minute increments until the temperature was no less than 148 degrees.

The final voltage setting for the variac was ~110V with 140V being the maximum setting for the variac. During this process, the temperatures were monitored and the heater was visibly inspected to ensure it showed no signs of failure.

Thermocouple Response

After installation, the thermocouple values were to be verified by the serial monitor on the DAQ. The thermocouples would then need to be calibrated for proper data capture. After installation, the testing process for the thermocouples were conducted as follows:

1. The DAQ was turned on to ensure the thermocouples were registering.
2. The program was generated and uploaded to the DAQ device.
3. The serial monitor was started and the inputs were noted.
4. After noticing a few inputs were giving erroneous values, the connections were checked.
    a. One module was found to be incorrectly soldered or the solder joint was damaged. This module was replaced.
    b. One module was found to have wires touching each other prior to the actual temperature sensing junction. The wiring for this module was corrected.
5. An ice water bath was assembled.
6. The thermocouple leads were then inserted into the ice bath and the temperature recorded.
7. Similar testing was performed with a different style thermocouple (bulb jacket), and the results were recorded.
8. A boiling water bath was assembled.
9. The bulb jacket thermocouple was inserted into the boiling water and the temperature was recorded.

It was noted after the ice bath test, that the thermocouples were reading a value which was off by about 3°F above the actual temperature. The ice bath should be a constant 32°F, however the thermocouples were reading around 35°F. The similar testing with the bulb jacket style of thermocouple returned the same results.

The boiling water test realized similar results, although there was a slight amount of deviation in linearity. The bulb jacket thermocouple was reading about 2°F higher than the boiling point of 212°F. This concluded the testing for the thermocouples.

RTD Functionality

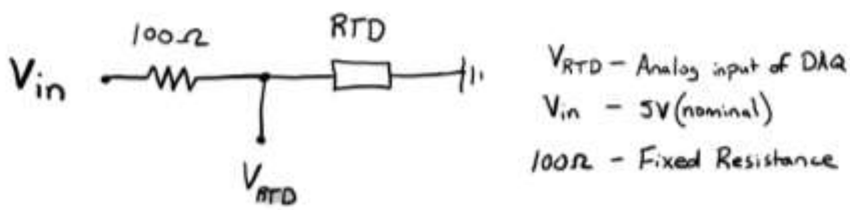
The RTD sensors were installed on the water side of the heat exchanger and needed to accurately read temperatures between 40°F and an anticipated 60°F. This information was relayed to the DAQ where it displayed the readings on the serial monitor. The testing procedures for the RTDs were conducted as follows:

1. The DAQ was turned on to ensure the thermocouples were registering.
2. Programming for the RTDs were generated and uploaded to the DAQ.
3. The serial monitor was turned on and the values were noted.
4. Initial erroneous values were troubleshot and the cause of the errors were remediated.

   Note: After the troubleshooting/remediation, the DAQ eventually ended up displaying values which were reasonable.

5. Upon confirmation of appropriate readings, the RTDs were submerged into an ice bath and the temperatures were noted.
6. The RTD was then attached to the test section in the appropriate pipe connection.
7. The calibration bath for the test section was then started up and run until it was reading 10°C for 5 minutes.
8. The values on the RTD were then recorded.

After initial startup, troubleshooting was required on the DAQ to determine the cause for erroneous values. After checking resistance values on the RTD and checking voltage readings, it was determined that the original device purchased for converting RTD measurements into readable DAQ values was not operating properly. The issue with the chip was unable to be resolved, so a voltage divider circuit was constructed, as seen below.



The voltage divider uses a known voltage input coupled with a series of resistors, one being known and the other being measurable. With a simple application of Ohm's law, the difference in voltage across the known resistor can be compared to the voltage measurement across the unknown, and with the two a relationship can be formed which will give an equation for the resistance of the unknown resistor. The equation for the voltage divider is shown below:

$$R_1\left[\frac{V_{in}}{V_{RTD}}-1\right]^{-1}=R_{RTD}$$

After constructing the voltage divider circuit and testing, the values were offset by about 5°C at multiple temperatures. It is possible that the values in the look up table of the programming may need to be adjusted. Further instructions for testing this theory is discussed in a later subsection.

Inline Heater Operation

Testing of the in-line heaters were conducted with air flowing at the desired rate which has been outlined earlier in this section. The heaters were being tested for the ability to generate enough heat for the moist air to reach desired temperatures The testing procedure for the heaters is outlined below:

1. Air flow to the unit was turned on and adjusted according to the procedures outlined in the volumetric flow rate subsection.
2. The variacs were adjusted to the lowest setting possible.
3. The switch on the variac was turned on.
4. In intervals of about 2 minutes, the voltage was adjusted higher by about 5V.
5. As the heaters rose to temperatures monitored by thermocouple, the voltage reached was lowered until The desired temperature stabilized.

Electrical Safety Shutoffs

The safety shutoff are possible the most important devices on the entire apparatus. Proper testing and functionality is crucial for confidence in the ability for the apparatus to safely provide the ability to generate the simulated flue gas. There are multiple electrical safety devices which are all wired in a control series.

In order to properly go over the testing procedure, understanding of the circuit must be made clear. The sequence of wiring for the 120V power is broken down below for better understanding:

1. The 120V power circuit is initially energized by a standard plug for an outlet.
2. This plug is wired to the line side of a GFCI which is housed within an electrical enclosure.
3. The power is then run across a relay which is closed/opened by the 24V safety circuit.
4. The 120V power then continues to the power strip where all devices are plugged in.

The 24V control circuit is responsible for energizing/de-energizing the power circuit in case a faulty component produces unsafe conditions. The wiring sequence for the control circuit is outlined below:

1. The 24V power begins at the transformer.
2. The circuit then continues to the PENN A421 temperature sensor and switch, where the circuit is open if programmed temperatures are exceeded and outside of the pre-adjusted range. This first sensor monitors conditions within the humidifier.
3. After the initial temperature sensor within the humidifier, the circuit then passes to the second PENN A421 where like deviate from the pre-adjusted range, the circuit will be opened.
4. Aside from the temperature sensors, the thermocouple values can be set within the arduino program to open the circuit at a set temperature with a microcontroller compatible relay. This allows for the temperature within the system to be monitored and shut off at any point desired. The circuit then passes to the relay where if all safeties are closed, the 24V coil will energize the relay and allow the 120V power to pass through.

The safety devices and GFCI testing procedures consist of temperature adjustments and function checks of simple switches within the devices. Before any testing, the area was cleared of any tools and clutter which could cause safety hazards or interfere with testing the electrical devices. The testing procedure for the GFCI is outlined below:

1. All power consuming components were double-checked to make sure they were switched off prior to testing.
2. A voltmeter was tested for functionality by checking a known live power outlet on the wall.
3. The enclosure power cord was plugged into the same power outlet which was previously used to test and confirm voltmeter operation.
4. Voltage was confirmed to be present by using a voltmeter to test across the line and neutral legs of the GFCI.
5. The GFCI was tested by simply pushing the 'Test' button on the front of the outlet until it engaged the internal safety switch and the reset button popped out.
6. The voltage across the hot and neutral legs were confirmed to have been removed by using a voltmeter to test across the same line and neutral legs of the GFCI.
7. Once tested, the GFCI was then reset and tested again for potential across the legs.

After testing the GFCI, the safety circuit was then tested. The specific procedure for testing is outlined below:

1. The variacs supplying power to the humidifier heater which was monitored by the PENN A421 sensor were plugged in.
2. After confirming the device was reading an appropriate value, the PENN A421 sensor was adjusted to a value which was higher than the current reading.
3. After adjustment, power to the humidifier heater was adjusted in 5V increments at 2 minute intervals until the temperature of the sensor began to rise.
4. This process lasted for 3 iterations until the PENN A421 sensor rose in value enough to trip the PENN A421 sensor.

Condensation Generation

Condensation generation is one of the primary resources for measuring the energy transfer within the test section of the apparatus. This condensation was collected by a graduated cylinder which has a resolution of 0.1 ml. The testing plan was focused on generating a certain amount of condensation during a specified time period.

Although the testing procedure was impacted by unforeseen circumstances, some information was still gathered and the condensation measurement capability was verified. The procedure for testing the generation/flow is outlined below:

1. The graduated cylinder was placed under the drain outlet for the test section.
2. The airflow and humidifier were both started just as they were in the previous subsections.
3. The humidifier temperature was adjusted to the point which it would normally operate.
4. Collection of condensate was noted at a rate of about a drop every 3-4 seconds with the small portion of testing and troubleshooting we did actually.
5. Visibly saturated vapor was also noted to be exiting the exhaust pipe of the testing section.
6. After collection, the humidifier was turned off and drained.
7. The exhaust port to the test section was then covered to push the water out of the condensate p-trap.
8. After the system was dried out, the air supply to the apparatus was shut off.

The condensate generation rate was a bit higher than expected. With an increased gas temperature, the condensation generation may have been a bit lower due to the capability of the air to hold a larger mass of water.

Constant Temperature Bath Operation

For heat removal, the constant temperature bath will need to keep the water temperature at the predesignated temperatures needed for a steady state analysis of the system. This means the bath should be able to remove as much heat as the gas is able to transfer to the tube. The full component test was to be completed during the final system test since that is the actual heat transfer which would happen, however a limited test was performed which proved the system could reach the temperature required for the test. The limited testing procedure went according the the following outline:

1. The air flow and humidifier were started as outlined in previous sub-sections.
2. The constant temperature bath was started.
3. The temperature on the constant temperature bath was adjusted to 10°C (50°F)
4. After reaching temperature, the constant temperature bath began pulsing a satisfied LED while keeping the temperature at 10°C.
5. Condensation generation and temperature differences were noted.
6. After testing, the bath, humidifier and air stream were all shut down and drained as outlined in previous subsections.

The constant temperature bath could not be fully tested to handle the heat load of the system at full capacity, but the unit is able to achieve desired temperature conditions at the particular load it was tested.

System Interoperability

After all components were individually tested, the entire system was then ready to be tested as a whole. The sequence for start up which was employed was in the following sequence:

1. DAQ
   a. The DAQ was started up first to ensure that the temperatures of the system could be monitored any time the system was started.
   b. RTD temperatures and thermocouple temperatures were confirmed to be at the appropriate temperatures as outlined in an earlier subsection.
2. Air flow
   a. The air flow was established so the rest of the system would have adequate air flow if required for heating/cooling purposes.
   b. The air was adjusted as outlined in previous subsections.
3. Electrical Systems/Safeties
   a. Electrical systems were checked to ensure each component was turned off before connecting to the power source.
   b. After energizing the electrical system, the safety devices were confirmed to be adjusted to the appropriate values as outlined in the previous subsections.
4. Humidifier
   a. The humidifier pump, heater, and spray bar adjustments were adjusted according to the procedure outlined in the above subsections.

   A brief period of time was allowed for the humidifier to get up to operating conditions before continuing with the rest of the start up procedure.

5. Constant temperature bath
   a. The constant temperature bath was started and adjusted to the required temperature for testing purposes as outlined in previous subsections.

    b. RTD measurements were confirmed to be within the range which was previously noted. (15°C)(59°F)
6. Electric Heaters
    a. The electric heaters were started during the final stages of testing as outlined above.
    b. One of the heaters ended up failing soon after being energized, which ended up tripping the safety circuit.
    c. After the heater failed, the apparatus was unplugged.
    d. Testing resistance across the heater revealed the heater element was open and no longer functional.

After the heater failed, the testing was discontinued. This was considered a testing session with limited success, as we found a defect in our design before delivery of the product. The failed portion of the testing is obviously the inability for the heaters to perform under the particular circumstances of their installation.

Further Testing Requirements

The testing of our apparatus left some further testing requirements which will need to be completed before the apparatus is ready to be used. Further testing topics include the in-line heater functionality, thermocouple calibration, RTD programming, and calibration bath loading capabilities. These topics are discussed further.

Inline Heaters

With the failure of the inline heaters, there will be further testing/redesign required for the apparatus. Additional methods for the heat addition must be formulated to fulfill required functionality of the apparatus in order for it to validate the CFD study.

Although the particular cause of the failure is not entirely known, it has been determined that either the very low air flow, high humidity, or a combination of both caused the heater to fail. Possible solutions for each issue are outlined below:

- Humidity issue test/proposed solution - Utilize an external heater immediately after the humidifier to preheat the gas, bringing the air temperature above saturation. A turbulator could be used to create more energy transfer from the tube walls. This would also eliminate any condensation buildup on the inner walls of the tube.
- Air flow issue test/proposed solution - With an external heater being used, the air flow condition would not be a factor since any in-line heaters requiring constant heat removal from their elements would be removed. Instead this energy would be conducted through the tube walls to the gas inside. Austenitic stainless steel pipes would need to be used for the wrapped portion of the heaters, and care would need to be taken when adjusting the output for temperature. Insulated fittings would need to be used closer to the humidifier to prevent any overheating of the CPVC.

Additional safeties would need to be installed around the external heaters to ensure they are not capable of generating too much heat. A datasheet for the proposed external heaters are provided in the appendix for reference.

Thermocouples

An issue encountered while using the thermocouple modules we ordered was the ability to troubleshoot the values it was receiving/converting/transmitting, as the values are converted internally then transmitted as digital signals. They are also supposedly cold junction compensated, which means they automatically adjust their readings according to the temperature of the junction at which they are measuring.

The primary way to troubleshoot this issue is to reference how many bits the arduino is receiving from the thermocouple module's digital signal, then compare that to the temperature range the module has. This range will then be broken up into 4096 portions, this value will be the number of volts per bit. This number can then be multiplied by the number of bits being sent and the product of which subsequently evaluated against the appropriate voltage/temperature relationship for the K-type thermocouple.

This type of testing should end up with results close to the accuracy of the thermocouple module resolution, which is 0.25°C. This solution would require additional programming, but it should be reasonably simple for anybody with even limited programming experience and knowledge of how thermocouple milli-voltage generation works.

RTD Programming

The RTD programming was completed as a last ditch effort, as the RTD module ended up producing erroneous values during testing without a known cause. As mentioned before, the voltage divider circuit was created and the resistance gathered from that. A look-up table was implemented in the code, which is interpolated from according to the resistance value being read.

This program could be improved upon by building a separate voltage divider circuit to calculate the actual voltage output of the DAQ as the DAQ itself would be receiving it. The voltage output when tested after the original testing session, was about 4.91 volts when read by a voltmeter. This could be another source of error during the original test session.

A solution for the above problem would be compound and is listed below:

- 3rd voltage divider - Aside from the voltage divider circuit for each RTD, a third could be constructed to measure the outgoing voltage from the DAQ. The DAQ has a nominal voltage output of 5V, but when tested it was 4.91. The voltage divider circuit would use identical known resistors, and the voltage measured across one could then be doubled and used as the reference voltage for the RTD voltage divider code.

- Troubleshooting/Verifying Resistance - The temperature scale in the RTD code is graduated by 5°C per iteration. If the code wasn't quite perfect, a value could be artificially elevating the temperature by a whole 5°C. This troubleshooting could be done by adding tracers to the iteration process and determining where the process ends and cross reference values in the lookup table to confirm.

The RTD program, again, was a last ditch effort to remediate the issue experienced by the RTD module we originally planned on using. There is a strong level of confidence of the voltage divider circuit being implemented if the circuit was able to be analyzed a bit further.

Test Section Operation

With the failure of the in-line heaters, it was not possible to fully test the tube temperature gradient. Once the air temperature is able to be brought up to the required operating temperature, the test section will be ready for testing. At this point, full system validation could be achieved. Without this remediation, the apparatus cannot function as intended.
Regardless of the failure, engineering standards shall be used to take some necessary readings to ensure that we have steady measurements based on these standards, and that our design will function proficiently.
We planned to take at least ten readings; while 20 or 50 readings would yield a slightly better result, 10 readings is usually sufficient. The engineering standards also specify how long we can take readings from each instrument connected to the test section in order to calculate uncertainty. Our current instruments are thermocouples and RTDs, but a humidity sensor should be attached to the test section, specifically mounted to the exhaust outlet air to determine relative humidity or dew-point temperature.
To obtain our values, a number of readings and time intervals must adhere to engineering standards, which are detailed below.

Temperature measurements

Using RTDs and thermocouples, we shall follow the ASHRAE 41.1 standard which states that under steady-state condition, the number of readings is based on the temperature difference per second that the instrument presents. For example, if the instrument shows the following readings: 10.25 C, 10.10 C, 10.14 C, 10.21 C, 10.25 C, where each reading was established in each second, the standard recommends 3 readings for 1 minute—1 reading per 20 seconds—if $\Delta T/s$ is 0.25°C/s or less. It would take about 3 minutes to get at least 10 readings, which is a popular arithmetic choice. After obtaining the needed readings, the uncertainty analysis should be performed to assess the error in measurements. Uncertainty analysis is explained below.

Humidity measurements

Using a humidity sensor that operates under the scale range in the exhaust outlet air, we shall follow the ASTM D4230 standard. The standard states that at 90F—our desired temperature, we should have 10 to 25 readings taken at an equally spaced time interval for a period of approximately 15 minutes. Uncertainty analysis is performed after obtaining the necessary readings.

Uncertainty analysis

$$\bar{X} = \frac{1}{N}\sum_{j=1}^{N} X_j \qquad (1)$$

$$s_X = \sqrt{\sum_{j=1}^{N}\frac{(X_j - \bar{X})^2}{N-1}} \qquad (2)$$

$$s_{\bar{X}} = \frac{s_X}{\sqrt{N}} \qquad (3)$$

$$b_{\bar{X}} = \left[\sum_{i=1}^{k}(b_i^2)\right]^{1/2} \qquad (4)$$

$$U_{\bar{X}} = K\sqrt{(b_{\bar{X}})^2 + (s_{\bar{X}})^2} \qquad (5)$$

$\bar{X}$	mean
N	Number of readings
X_j	Reading measurement
s_X	Standard deviation
$s_{\bar{X}}$	Standard uncertainty
$b_{\bar{X}}$	Systimatic error
b_i	Systimatic error source
$U_{\bar{X}}$	expanded uncertainty
K	correction factor

Figure 13 - Uncertainty analysis equations

According to ASME PTC 19.1 standard, there are three steps to determine uncertainty of a result, which are as follows:

1. Uncertainty due to random error

   It can be established by determining the sample mean or average value of the measurements, the standard deviation, and the standard uncertainty. See equations (1), (2), and (3) in figure 13.

2. Uncertainty due to systematic error

   Systematic errors are usually estimated using engineering judgment (ISO Type B) and sometimes using previous data (ISO Type A). Such systematic errors are instrument calibration (B) environmental influences (A) and effects of conduction heat transfer surroundings (B). See equations (4) in figure 13.

3. Expanded uncertainty

   To evaluate expanded uncertainty, we need a correction factor, which can be calculated using confidence level (C.L.) from calculating the standard deviation. The C.L. is obtained as follows: C.L.% = 100 - $(s_X/\bar{X})$*100. Some coverage factors are: k = 1 for a confidence level of approximately 68 %; k = 2.58 for a confidence level of 99 %; k = 3 for a confidence level of 99.7 %. See equations (5) in figure 13.

After obtaining uncertainty due to random error, uncertainty due to systematic error, and expanded uncertainty, we can express the uncertainty measurement as $\bar{X} \pm U_{\bar{X}}$.

Engineering References, Codes, and Standards

Engineering standards are formal documents that establish engineering methods and practices to ensure the safety and quality of our design. For considerations such as safety, installation, and electrical connection, any improper installation, service, use, alteration, or maintenance can cause electrical shock and other conditions which may cause property damage and personal injury. Therefore, we will follow all safety codes and the standard operating procedure (SOP) and wear personal protective equipment (PPE). The project's safety and quality will be ensured by the engineering standards listed below.

The ASHRAE 41.1 is a standard method for temperature measurements to ensure adequate and consistent measurement procedures. It is applicable for testing heating equipment and components in our design (inline heater and humidifier). These measurements include air and water under steady-state conditions. This standard states that for sampling systems under steady-state conditions, the instrumentation used (thermocouples and RTDs) shall have a continuous reading of 1 minute, and the number of readings depend on the following maximum intervals: for 0.5°C/s (1.0°F/s) or greater, 1 reading per 5 seconds—12 readings; for 0.25°C/s to 0.50°C/s (0.5°F/s to 1.0°F/s), 1 reading per 10 seconds—6 readings; for less than 0.25°C/s (0.5°F/s), 1 reading per 20 seconds—3 readings.
The ASHRAE 41.1 is included in the test planning section to indicate how frequently and for how long we intend to record data for each instrument sensor (thermocouple and RTD).

The ASME A13.1 specifies the means of identifying pipe content, as well as the size, color, and placement of the identification marker. Pipe markers indicate the contents of the pipe and arrows at both ends for flow direction. This standard is applicable for pipes containing water (safety green background marker with white legend) and air (safety blue background marker with white legend). Each legend should identify the contents, as well as any additional information needed, such as temperature and pressure.

The ASME PTC 19.1 is a guide to the expression and evaluation of uncertainties in test measurements. There is always a margin of doubt in any of our design’s measurements, it needs to be expressed as a margin or interval with a confidence level (e.g. 20°C ± 1°C). This standard assists in obtaining the best uncertainty estimate by using both Type A and Type B uncertainty approaches, as well as Random and Systematic Errors with examples applicable to temperature measurements. Following this guide also assists in estimating the mean and standard deviation of temperature, flow rate, humidity, and pressure drop measurements.
The process of evaluating uncertainties in our measurements is explained in the test planning section to establish a fundamental limit to the accuracy of our data.

The ASTM D4230 is a test method that covers the determination of the thermodynamic dew-point temperature of ambient air for measuring humidity. This standard states that at a condensation temperature of 32.2 °C—the desired dew-point at the outlet fitting of the test section, there will be 10 to 25 readings for 15 minutes to calculate the average value and the standard deviation of the dew-point temperature. For dew point at 32.2°C, the hygrometer (humidity sensor) requires 5 minutes to reach equilibrium with the ambient humidity after clearing the mirror of all condensates.
The ASTM D4230 is also included in the test planning section to specify the number of readings and the considerable time to record data for the humidity sensor that should be mounted in the hot air exhaust outlet.

The NFPA 70 is a general guideline for electrical installation and removal of electrical equipment, conductors, and raceways. The standard includes general-purpose equipment and wiring methods and materials (e.g. wiring devices, cables). Some of the most helpful details in this standard include high-voltage and low-voltage rule classifications, actual versus maximum current ratings, and temperature ratings for wires and cables.
There are multiple devices (an immersion heater and three inline heaters) in our design that hooked up in a system in order to power it. All of the wiring was connected to an enclosure and has been insulated.

The NFPA 78 is a guide on electrical inspections. It provides specific procedures to assist in the inspection process. It is applicable to ensure that the design electrical components are safe to use, avoid malfunctions, and keep the system efficient.

The OSHA 1910.120 is a procedure for removing, containing, clearing, or in any other manner of processing or handling hazardous substances in order to make the workplace safer for people and the environment.

The OSHA 1910.304 is for wiring design and protection that applies to electrical use systems. It includes the use of grounding, circuit breakers for overcurrent protection, and ground-fault circuit-interrupter (GFCI) protection.
We used a GFCI outlet to detect a short circuit or an overload, as well as connecting the table to the ground system.

The OSHA 1915 Subpart I provides guidance on how to apply personal protective equipment (PPE) and clarifies the PPE selection for some operations (e.g. welding, grinding, brazing, cutting, and heat treating) of the design set.

Knowledge Management and Experimentation Plan

For our team's final design and building process our team's previous FDR knowledge and experimentation plan contained many gaps and uncertainties that were resolved with team research on DAQ, HVAC, and ASME process standards. With our final design and finished build, we believe our team had completed most of these uncertainties, however we were not able to resolve all of them due to several part failures and time constraints.

As far as our current uncertainties with the given time constraints, our heat exchanger was able to successfully function by producing an outlet flow rate of moist air. The heat exchanger however has several malfunctioning parts including two out of three broken inline heaters, small leakage spots (2-3) in the humidifier section. We also never successfully found an effective method to measure the saturation levels leaving the humidifier, as well as finding an accurate temperature reading with the lack of temperature sensors.

By the end of our team's design and build, we did have several knowledge gaps filled. One of the most critical items our team was able to conquer was to successfully produce a numerous amount of air flow rates from the inlet and outlet of our heat exchanger. Our team was also successful in producing a warm-moist air content right before we encountered heater malfunctions. By the end of our building and designing process, our team had made a solid foundation for equal contributions in unique skill sets. With our solid team foundations, for the past several weeks every team member communicated and contributed efficiently to where our group could produce the most success with our given deadlines.

Cost Analysis

Cost Variance

The cost variance between the Final Design Report and the Final actual cost were due to the change in design that happened after the Final Design report. Three major alterations were made to the testing apparatus which reduced the amount of materials needed for the project and the complexity of the build.

The first change was to the air delivery. The change for air delivery was that a septic tank air pump was to be used to push air through the system. However that was changed to use shop air for the lower cost to use and the ability to use the compressed air system as a surge tank in order to obtain steady flow.

The second change to the design was the humidifier. To change the humidifier there were initially two circulation pumps for two different circuits which were changed to a single pump. The single pump again reduced the cost and complexity of the overall system.

The third change was the test section where the heat exchanger was changed from a forced air convection to a water cooled setup. The water cooled method used more items that were already obtained which drove the overall cost down lower due to the reduction in materials that needed to be purchased.

The final major driver behind the variance in cost was the difference of the data acquisition equipment that was purchased. Arduinos were used instead of the National Instruments circuits due to the closeness of the budget to the limit.

The Cost that was quoted in the Final Design Report was $5873 and the final cost of the project was $4663.32. For an itemized list refer to the appendices.

Risk Management

In order to institute risk management successfully into the project, a complex risk management matrix has been created. The matrix encompasses all potential risks that might be encountered throughout the entirety of the project, whether that risk occurs in the assembly or testing phase of the project. Each risk was assessed on both its likelihood to occur as well as its severity. For the risk matrix legend, the rows are labeled A-E, and the columns are labeled 1-5.

		Minor	Moderate	Significant	Major	Severe
		1	2	3	4	5
Rare	A	1A	2A	3A	4A	5A
Unlikely	B	1B	2B	3B	4B	5B
Moderate	C	1C	2C	3C	4C	5C
Likely	D	1D	2D	3D	4D	5D
Almost Certain	E	1E	2E	3E	4E	5E

Table #2: Risk Matrix Legend

Assembly			
Risk	Initial PR	Mitigation	Final PR
Lacerations from tools	3C	PPE/Safe Practices/Training	3A
Power Tool Injuries	4C		4A
Burns	4D	PPE/Handling Methods	3B
Exposure to chemicals	3E	Good Ventilation	1D
Fire hazards	4C	Training/Safeguarding	3A

Testing			
Risk	Initial PR	Mitigation	Final PR
Water proximity to electricity	5C	Enclosures/GFCI	3A
Burns	4D	Insulation	3B
Electrical Shock	5C	Insulation/Enclosures/GFCI	3A
Overheating Components	3C	Temperature Controls	1A

Existing/Discovered			
Risk	Initial PR	Proposed Mitigation	Final PR
Humidity in Electric Heaters	3E	Concept Redesign/Exterior Heating	Eliminated

Table #3 Risks & Mitigation Chart

Each risk is associated with a general description describing the risk, an initial rating, how the specific risk was mitigated, and the resulting score after that mitigation. One particular risk that was constantly looked after throughout both the assembly and testing of the project was burns from high temperatures. The likelihood of receiving such burns was likely, along with it being a major injury. There were four heaters located throughout the test stand. In order to ensure that no individual accidentally burned themselves on these heaters, the proper PPE was always worn while the heaters were running. The two inline duct heaters were caged off to further discourage any interaction with the heaters while they are on.

The first risk that was encountered during the assembly of the project was lacerations from tools. This was considered a significant risk but moderate in terms of likelihood. When power tools were used such as a grinder or a cordless drill, it was always ensured that the person operating such tools had the proper training and knowledge of how to safely use them.

While assembling the humidifier section, cpvc primer and cement were used. Before preparing the surface, it was ensured that the work room was well ventilated. This adequate ventilation allowed for the team to safely apply the cpvc cement to the humidifier.

During testing, water and electricity were always present. In the event that these two accidentally met, it would result in severe injuries. In order to ensure the safety of all members, all electrical components were routed away from any water sources and were properly secured in an enclosure. The entire electrical side of the project was also run off of a single GFCI. In the instance that water met with electricity, the GFCI would trip, opening the circuit. As for any component that contained water, extensive waterproofing and leak testing were done before electricity was ever sent to the circuit.

In order to prevent any of the heaters from overheating, they were hooked up to individual variacs where the voltage was controlled manually. Penn A421 safety switches were also installed at varying locations. These safety switches were set to only operate in a prespecified range and shut off if the temperature exceeded the upper limit.

Upon running the initial humidity tests, it was discovered that the moisture in the air caused the exposed heating elements inside the duct heaters to fail. Once this fault in the design was discovered, it was too late to come up with a new method to heat the steam and get it approved for the expo. Some possible ideas on how to implement heating after the humidifier included the use of either band heaters, conduction heaters, or an induction heater that would be placed around the exterior of the pipe located in between the humidifier and the inlet of the test section.

Project Plan

Work Overview Breakdown

Denver Long

<u>Tasks Completed:</u> The number of tasks completed this semester were numerous. The most notable tasks completed were designing/sketching multiple concepts for the CDR; completing the engineering ethics course; performing EES calculations, producing CAD drawings, researching parts and pricing; and designing concepts for the FD Review; writing multiple sections of the FD Report; writing the testing plan, learning/generating code for the DAQ, helping to bring the item orders to where they needed to be, organizing the budget spreadsheet, assisting with construction of the measurement/instrumentation enclosure, and presenting our design at the final project presentation. For this report, I wrote the testing and quality plan section in addition to helping to write the project scope. I also attended every meeting with the project champion during the semester and met with the stakeholders on multiple occasions to receive feedback and advice.

<u>Lessons Learned:</u> There were many tasks to complete this semester, and it seemed like less time than ever to complete them. That being said, it pushed me to work consistently harder and improve myself more than ever before in my life. Some of the lessons learned this semester include how to work as a team to quickly accomplish goals, communication skills, measurement/instrumentation skills, a little bit of CAD, and additional computer programming skills.

To elaborate on communication, I learned how to more effectively work with a team when you are not able to be around them consistently. Working from Tulsa with a Stillwater group was a difficult challenge to overcome, but the communication capabilities were sufficient enough to ensure I could be an effective teammate.

Furthermore, lessons on uncertainty/measurement methods were plentiful this semester and it helped me to realize how much more there is to effectively measuring physical phenomena than simply ‘reading the dial’.

Computer skills were already a decent tool in my belt, but I further expanded the knowledge by interacting with a little programmable controller. CAD was not however a tool in my belt, but after constructing a few drawings for the FDR, I feel pretty comfortable making assemblies on the Solidworks software.

In conclusion, taking this program at OSU has taught me possibly the most important lesson of my school career. Earning an engineering degree is a tough feat, and I’m sure an even tougher feat if progressing to the graduate and Ph.D. level courses. It has taught me that I really don’t know nearly as much as originally thought when I first started off in this program. It has also taught me to not only to be taught, but to teach myself and communicate the knowledge to others as well.

Zach Pfeifer

<u>Tasks Completed:</u> Redesigned humidifier, selected humidifier parts, built humidifier. Came up with and implemented an idea to use a borescope camera inside the humidifier. Made thermocouples for data acquisition. Helped with testing and validating values received from data acquisition. Helped assemble inlet heating and test sections. Troubleshot leaks in the humidifier and system. Worked on final presentation by creating and editing slides including, humidifier section, EHS, problem scope, engineering analysis, and engineering principles.

<u>Lessons Learned:</u> Learned the value of implementing ideas early, to allow more time for parts arrival and testing. Learned how to make thermocouples. Learned large amounts about placement of data acquisition instrumentation for reliable readings. Learned about fabrication, including how to modify PVC components with very little leakage. Learned the complexity of electrical systems and how to better control them.

Trysen Willits

I have completed multiple tasks throughout the semester such as designing the inlet section, assisting others with material choices, kept a parts list and purchasing list, Built the inlet and test section, assisted in troubleshooting, helped with volumetric flow rate testing, created the cost and knowledge management slides and created a portion of the engineering analysis section and the cost breakdown in the final report.

I have learned a few lessons from the project such as many others will try to degrade your idea but just prove them wrong and carry on. Other things I have learned is that when building to a timeline time is the most important concept and it needs to be maximized by doing all goals as soon as possible to leave time for testing and debugging. Finally the final lesson I learned was that teamwork can create better outcomes than any single person.

Mitchell Krause

Task Completed: Designed and modeled solidworks schematics and assemblies throughout the semester. Designed and sketched various blue prints with dimensions and bill of materials. Hands on building with humidifier section. Assisted in finding and assembling general parts as well as organizing parts for each day of building. Tested volumetric flow rate trails with excel calculations. Contributed to final schematic assemblies in final project powerpoint slides.

Lessons Learned: Looking back at this project as a whole, I have learned many things including precise dimensions when it comes to drafting, hands on building experience, team management, and how to deal with time constraints. I ultimately had a great experience as someone who has never been experienced with HVAC systems, especially when it comes to drafting and designing all the specific components that makes the functionality of a heat exchanger possible.

Kaden Rackley

Task Completed: Soldered thermocouple and RTD connections. Helped construct the inlet heating section of the project. Aided in design of the inlet heating section. Put together multiple versions of the project video for submission. Proofread reports for errors before submission. Assisted in finding and assembling general parts as well as organizing parts for each day of building. Put together slides on engineering standards in the final presentation. Overall helped in many areas where needed.

Lessons Learned: Organization and planning are incredibly important in an engineering project. Teamwork involving all members of a team is a valuable part of working in a group. Communication with all team members is important for having a well-running project. Your teammates are there to help, and it is important to reach out for help when you need it.

Hassan Alhassan

Task Completed: The main section I have been working on is the test section. Worked in installing inline heaters, humidifier column and its components, test section, mounting parts, insulations and Low's trip for parts. involved in troubleshooting and fixed leaking issues, calculating air volumetric flow rate with a bag of air method. working on test section concepts (calculations and diagrams on EES). Contributed to the Heat section before and after humidifier (Calculation and diagram on EES).

Lesson Learned: learned new handy fabrication methods. learned from our failure. Learned new features on EES. Time management was the best lesson I learned. learned how it is important to have details and information as much as you can from the stakeholders. learned how clear communication between team members can achieve the goal easily.

Mohammed Bin Amer

Taske Completed: Research and understanding of applicable standards relevant to our project. Completed engineering codes and standards. Suggested some ideas related to the test section. Completed drawing of test section concept. Assisted in heating section calculations. Completed calculations—EES—related to the test section with the test section. Assisted in completing the part list needed for the test section. Contributed to the building of the set-up test.

Lesson Learned: Communication is better face-to-face, and many activities will be hard to carry out outside of group meetings. Always listen to what the clients want for their products—delivering their requirements is a main key to accomplish a project. Learned that time management will achieve our goals faster. Also learned that project failures happen, and actions to mitigate the problems must be dealt with.

Jacob Schimmels

Tasks Completed: Researched, designed, ordered parts for, constructed, calculated, and tested all things humidifier on our apparatus. As team planner, the weekly progress report and Gantt Chart were put in my responsibility as well to complete each week. Assisted in the completion of CDR, FDR, SOP, Energization inspection, EXPO presentation, and the final report as well. Also completed several lowes trips for additional parts and repairs, and last minute parts orders from Grainger for when lowes did not have items necessary.

Lesson Learned: Always pay close attention to the suggestions of the stakeholder/client. Their experience in the industry is unmatched and each suggestion should be implemented or considered to implement. Time management will help a team/group out tremendously. Teamwork involving all students to keep each other accountable was a key to success for our team. Overall failures and mishaps will happen as a team and the only way to improve is to learn from the mistakes you have made and realize what could have been done differently to avoid the same error in the future.

Thomas Martinson

Tasks Completed: Assisted in the heat transfer calculations for the multiple test section designs. Worked on filling out the purchase sheets for part orders. Helped the humidifier team in assembling the humidifier and installing the spray bar etc. Created the outline for the final presentation and transferred over relevant material. Milled out the test section and assembled it onto the test bench. Built the inlet heating section along with the other MET's. Was sure to attend every team meeting and every parts order.

Lessons Learned: The main lesson that I learned was that working in a group requires everyone to divide and conquer. If multiple people are working on something that can be done with just one or two people it tends to cause some delay in the process. It is also worth mentioning, that the worst case scenario should always be anticipated. In our case, this worst case scenario was parts being delivered late as well as the parts not being entirely compatible. Moving forward, it is always a good idea to get a second opinion on a design or part selection, just to ensure that there are no oversights.

Hayden Bullinger

<u>Tasks Completed</u>:Throughout this project, I partook in each sub team's calculations, analysis and building to maximize the most I could out of my efforts. I typically created most of the documents and outlined them all in order to keep everyone on track along with updating the weekly progress updates and submitting them. I was sure to meet with most all of the stakeholders at least twice within this project to obtain feedback. In the initial analyses of each segment, I would spend a few days with each category assisting the analysis and contributing to help as much as possible. I spent endless hours on CDR, FDR, and Final Review presentations along with each of the respective reports to ensure that most topics were covered and everything that pertained to our project was available. When it came to the construction of the design, I assisted in the foundation building, built the current humidifier, made several of the lowes trips, plumbed some of the air piping, wired all of the electrical power supplies and safeties, and began testing each piece of the design until the Final Review presentation.

<u>Lessons Learned</u>: This project taught me much more than just the engineering content within. As team leader, I had a lot to learn as far as leading everyone and utilizing their strengths to benefit progress as much as possible. I learned how important means of good communication is, especially when remote students are a part of the project. Updates are always needing to be made, and the effort never ends. Staying on schedule is extremely important to ensure proper completion of every small and large task. I learned that the initial project scope was rather vague and more effort should have been taken to ensure that everyone knew what the exact end goal was. Overall as I pursue an engineering career, I have obtained attributes that will help communicate and act as an engineer should in the industry.

Appendices

First and Secondary Heaters


```
{----------------------Air Heating-----------------------}
"assumption"
{P1 = 101.3 [kPa]}
T[1] = 23.33 [C]
T_o = 60.11 [C] {Assumed}
T_m = (T[1]+T_o)/2
RH = 0.4
{V_dot = 0.15 [ft^3/min]}
T_dp[1]=dewpoint(AirH2O,T=T[1],R=RH,P=P1)
h[1]=enthalpy(AirH2O,T=T[1],D=T_dp[1],P=P1)


V_dot_1 = V_dot *convert(ft^3/min,m^3/s)
    u = V_dot_1 / A
    A = pi *(d/2)^2
m_dot = V_dot_1 * rho
   rho=density(AirH2O,T=T_m,D=T_dp[1],P=P1)
cp=cp(AirH2O,T=T_m,D=T_dp[1],P=P1)
mu=viscosity(AirH2O,T=T_m,D=T_dp[1],P=P1)
mu_s=viscosity(AirH2O,T=T_s,D=T_dp[1],P=P1)
Pr=prandtl(AirH2O,T=T_m,D=T_dp[1],P=P1)
k=conductivity(AirH2O,T=T_m,D=T_dp[1],P=P1)


{Constatn Surface Temp Tube}
d = 10*convert(mm,m)
L = 89 *convert(mm,m)
{T_s = 400 [C]}
A_s = pi * d *L

{Heat Transfer Eq}
{m_dot * cp * (T[2]-T[1]) = h * A_s * DELTAT_Lm}
m_dot * cp *convert(kJ/kg-K,J/kg-K) * (T[2] - T[1]) =  h_1 * A_s *  (T[1] - T[2]) / (ln((T_s-T[2])/(T_s-T[1])))
Re_D = (rho* u * d)/mu
L_e = 0.05 * Re_D * Pr * d
N_u = 1.86 * (Re_D * Pr * d / L)^(1/3) * (mu / mu_s)^(0.14)
h_1=N_u * k / d
Q_dot[1] = h_1 * A_s *  (T[1] - T[2]) / (ln((T_s-T[2])/(T_s-T[1])))


{----------------------Second Air Heater-----------------------}
T[3] = 65.56 [C]
To_2 = 158.4 [C]                          {Assumed} "----"
T_dp[3] = 65.56[C]
T_m_2 = (T[3]+To_2)/2

{V_dot_2 = 0.7 [ft^3/min]}
    u_2 = V_dot_2 *convert(ft^3/min,m^3/s) / A_2
    A_2 = pi *(d/2)^2
m_dot_2 = V_dot_2*convert(ft^3/min,m^3/s) * rho_2

" Properities"
```

```
rho_2=density(AirH2O, T=(T[3]+To_2)/2 ,D=T_dp[3],P=P1)
cp_2=cp(AirH2O,T=(T[3]+To_2)/2,D=T_dp[3],P=P1)
mu_2=viscosity(AirH2O,T=(T[3]+To_2)/2,D=T_dp[3],P=P1)
mu_s_2=viscosity(AirH2O,T=T_s,D=T_dp[3],P=P1)                          { mu at
Surface Temp}
Pr_2=prandtl(AirH2O,T=(T[3]+To_2)/2,D=T_dp[3],P=P1)
k_2=conductivity(AirH2O,T=(T[3]+To_2)/2,D=T_dp[3],P=P1)


"Constatn Surface Temp Tube"
d_2 = 10*convert(mm,m)
L_2 = 89 *convert(mm,m)
{T_s_2 = 400 [C]}
A_s_2 = pi * d_2 *L_2

{Heat Transfer Eq}
{m_dot * cp * (T[2]-T[1]) = h * A_s * DELTAT_Lm}
m_dot_2 * cp_2 *convert(kJ/kg-K,J/kg-K) * (T[4] - T[3]) =  h_2 * A_s_2 *  (T[3] - T[4]) / (ln((T_s_2-T[4])/(
T_s_2-T[3])))
   Re_D_2 = (rho_2* u_2 * d)/mu_2
   L_e_2 = 0.05 * Re_D_2 * Pr_2 * d_2
   N_u_2 = 1.86 * (Re_D_2 * Pr_2 * d / L_2)^(1/3) * (mu_2 / mu_s_2)^(0.14)
   h_2=N_u_2 * k_2 / d_2
Q_dot[2] = h_2 * A_s_2 *  (T[3] - T[4]) / (ln((T_s_2-T[4])/(T_s_2-T[3])))

{-----------------------Third Air Heater-------------------------}
{T_3rd_inlet =T[4]}
To_3 = 249.9 [C]                              {Assumed} "----"
{T_dp_3rd_inlet = T_dp[3]}
T_m_3 = (T[4]+To_3)/2

{V_dot_3 = 0.7 [ft^3/min]}
    u_3 = V_dot_3 *convert(ft^3/min,m^3/s) / A_3
    A_3 = pi *(d_3/2)^2
m_dot_3 = V_dot_3*convert(ft^3/min,m^3/s) * rho_3

" Properities"
rho_3=density(AirH2O, T=T_m_3 ,D=T_dp[3],P=P1)
cp_3=cp(AirH2O,T=T_m_3,D=T_dp[3],P=P1)
mu_3=viscosity(AirH2O,T=T_m_3,D=T_dp[3],P=P1)
mu_s_3=viscosity(AirH2O,T=T_s_3,D=T_dp[3],P=P1)                        { mu at
Surface Temp}
Pr_3=prandtl(AirH2O,T=T_m_3,D=T_dp[3],P=P1)
k_3=conductivity(AirH2O,T=T_m_3,D=T_dp[3],P=P1)


"Constatn Surface Temp Tube"
d_3 = 10*convert(mm,m)
L_3 = 89 *convert(mm,m)
{T_s_3 = 537 [C]}
A_s_3 = pi * d_3 *L_3
```

```
{Heat Transfer Eq}
{m_dot * cp * (T[2]-T[1]) = h * A_s * DELTAT_Lm}
m_dot_3 * cp_3 *convert(kJ/kg-K,J/kg-K) * (T[5] - T[4]) =  h_3 * A_s_3 *  (T[4] - T[5]) / (ln((T_s_3-T[5])/(
T_s_3-T[4])))
   Re_D_3 = (rho_3* u_3 * d_3)/mu_3
   L_e_3 = 0.05 * Re_D_3 * Pr_3 * d_3
   N_u_3 = 1.86 * (Re_D_3 * Pr_3 * d_3 / L_3)^(1/3) * (mu_3 / mu_s_3)^(0.14)
   h_3=N_u_3 * k_3 / d_3
Q_dot[3] = h_3 * A_s_3 *  (T[4] - T[5]) / (ln((T_s_3-T[5])/(T_s_3-T[4])))
```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

A = 0.00007854 [m^2]
A_s = 0.002796 [m^2]
cp = 1.019 [kJ/kg-K]
d = 0.01 [m]
h_1 = 27.82 [W/m^2-K]
k = 0.02678 [W/m-K]
L = 0.089 [m]
L_e = 0.8865 [m]
μ = 0.00001924 [kg/m-s]
μ_s = 0.00002652 [kg/m-s]
$\dot{m}$ = 0.0003687 [kg/s]
N_u = 10.39
P1 = 101.3 [kPa]
Pr_3 = 0.7605
$Re_{D,3}$ = 1094 [-]
ρ_2 = 0.8285 [kg/m^3]
To_3 = 249.9 [C]
$T_{m,3}$ = 204.1 [C]
$T_{s,2}$ = 530 [C]
u_2 = 4.206 [m/s]
$\dot{V}_1$ = 0.0003304 [m^3/s]
A_2 = 0.00007854 [m^2]
$A_{s,2}$ = 0.002796 [m^2]
cp_2 = 1.412 [kJ/kg-K]
d_2 = 0.01 [m]
h_2 = 30.81 [W/m^2-K]
k_2 = 0.03283 [W/m-K]
L_2 = 0.089 [m]
$L_{e,2}$ = 0.6187 [m]
μ_2 = 0.00002185 [kg/m-s]
$\mu_{s,2}$ = 0.00002635 [kg/m-s]
$\dot{m}_2$ = 0.0002737 [kg/s]
$N_{u,2}$ = 9.387 [-]
Pr = 0.7269
Re_D = 2439
RH = 0.4
ρ_3 = 0.6686 [kg/m^3]
T_m = 41.72 [C]
T_o = 60.11 [C]
$T_{s,3}$ = 530 [C]
u_3 = 4.206 [m/s]
$\dot{V}_2$ = 0.7 [ft^3/min]
A_3 = 0.00007854 [m^2]
$A_{s,3}$ = 0.002796 [m^2]
cp_3 = 1.435 [kJ/kg-K]
d_3 = 0.01 [m]
h_3 = 32.07 [W/m^2-K]
k_3 = 0.04006 [W/m-K]
L_3 = 0.089 [m]
$L_{e,3}$ = 0.4159 [m]
μ_3 = 0.00002571 [kg/m-s]
$\mu_{s,3}$ = 0.00003757 [kg/m-s]
$\dot{m}_3$ = 0.0002209 [kg/s]
$N_{u,3}$ = 8.005 [-]
Pr_2 = 0.7758
$Re_{D,2}$ = 1595 [-]
ρ = 1.116 [kg/m^3]
To_2 = 158.4 [C]
$T_{m,2}$ = 112 [C]
T_s = 220 [C]
u = 4.206 [m/s]
$\dot{V}$ = 0.7 [ft^3/min]
$\dot{V}_3$ = 0.7 [ft^3/min]

No unit problems were detected.
EES suggested units (shown in purple) for A_2 A_3 A_s_2 A_s_3 cp_2 cp_3 .

Arrays Table: Main

	T_i [C]	$\dot{Q}_i$ [W]	$T_{dp,i}$ [C]	h_i [kJ/kg]
1	23.33	13.82	8.983	41.55
2	60.11	35.87		
3	65.56	29.02	65.56	
4	158.4			
5	249.9			

Test Section - Finned Tube


```
"assumption" {Delete}

{P1 = 101.3 [kPa]}
V_dot_a_1 = 0.7 [ft^3/min]
V_dot_a = V_dot_a_1*convert(ft^3/min,m^3/s)
  A = pi *(d_5/2)^2
{m_dot_a =V_dot_a * rho_a}

{State 5: Test Section}

"Hot Gas tube"
d_o = 0.5 * convert('in', 'm')                 {Tube Diameter}
d_wall = 0.016 * convert('in', 'm')            {Tube wall thickness}
d_5 = d_o - d_wall                             {Inner diameter}
L = 18.64 * convert('in', 'm')                 {Tube length}
A_s = pi * d_5 * L                             {Surface area}

T[4] = 260 [C]                                 {Max dry-bulb -- 500F}
T[5] = 32.22 [C]                               {Min dry-bulb -- 90F}
T_m_a = (T[4] + T[5]) / 2                      {Mean Temperature}

T_dp[4] = 65.56 [C]                            {Max dewpoint --150F}
T_dp[5]= 32.22 [C]                             {Min dewpoint -- 90F}
T_dp_m = (T_dp[4] + T_dp[5]) / 2               {Mean Temperature}
  "Properties"
  cp_a=specheat(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
  rho_a=density(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
  mu_a=viscosity(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
  Pr_a=prandtl(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
  k_a=conductivity(AirH2O,T=T_m_a,D=T_dp_m,P=P1)

"Cold Air"
T_c_i = 23.33 [C]                              {68F}
T_c_o_A = 50 [C]                               {Assumed -- ##F}
T_m_c = (T_c_i + T_c_o_A) /2
RH_c = 0.384                                   {Room RH}
Tdp_c_i=dewpoint(AirH2O,T=T_c_i,R=RH_c,P=P1)
Tdp_c_o = Tdp_c_i

 "Properties"
  rho_c=density(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)
  mu_c=viscosity(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)
  cp_c =specheat(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)
  k_c=conductivity(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)


V_dot_c = 90 [ft^3/min]
m_dot_c = V_dot_c*convert(ft^3/min,m^3/s) * rho_c
mu_s = mu_c

" Fins"
" Fins"
d_d = 19*convert(in,m)
k_st = 15.1 [W/m-K]
{N = ## [-]}
t = 0.002 [m]
L_f = 0.010 [m]
{L = 18.64 *convert(in,m)}

r_1 = 0.5/2* convert(in,m)
r_2 = r_1 + L_f
```

```
S = L / N

r_11 = (0.5/2)* convert(in,m)

{ Solution }
T_s = 260 [C]
T_amb =  23 [C]
h_c= 2.3

Q_dot_HEX = N * eta_f * h_c * A_f * (T_s - T_amb) + N * h_c * A_b * (T_s - T_amb)
    A_f = 2 * pi * (r_2^2 - r_1^2) + 2 * pi *r_2 * t
    A_b = 2 * pi * r_1* (S - t)

    r_2_c = r_2 + (t/2)
    L_c = L_f + t/2
    A_p = L_c * t
    rf = r_2_c / r_1

    epslon = L_c^(3/2) * ( h_c / (k_st*A_p))^(1/2)
    Re_D_c = 4*m_dot_c / (mu_c*pi*d_d)
    eta_f = 0.94


{LMTD: Q_dot_HEX = m_dot_c*cp_c*(T_c,o - T_c,i )=  m_dot_h*cp_h*(T_h,i - T_h,o) = F*U*A_s*deltaT_lm}

Q_dot_HEX = m_dot_a * cp_a * convert(kJ/kg-K, J/kg-K) *(T[4] - T[5])
Q_dot_HEX = m_dot_c*cp_c * convert(kJ/kg-K, J/kg-K) * (T_c_o - T_c_i )

{Q_dot_HEX = UA_s*DELTAT_lm
    DELTAT_2 = T[5] - T_c_i
    DELTAT_1 = T[4] - T_c_o
    DELTAT_lm = ( DELTAT_2 - DELTAT_1 ) / ln(DELTAT_2/DELTAT_1)}

Re_a = 4 * m_dot_a / (pi * d_5 *   mu_a)                    {Laminar}
    L_t = 0.05 * Re_a * Pr_a * d_5
    {If L_t > L --> entrance region & mu_b/mu_s = 0.029 --> use the following N_u:}
    N_u_a = 1.86 * (Re_a * Pr_a * d_5 / L)^(1/3) * (mu_a / mu_s)^(0.14)
    h_a = N_u_a * k_a / d_5

{   Re_c = 4 * m_dot_w / (pi * (d_w+d_5) *mu_w )          {Laminar}
    {For concentric annulus, use the following equations:}
    N_u_w = 7.42 {N_u for fully developed laminar flow in circular annulas @ Di/Do = 0.242}}
Q_dot_HEX = 70.9 [W]
    {h_w = N_u_a * k_w  / (d_w - d_5)}
{   h_c = 2.378                                          [W/m^2-K]}
{1/(U*A_s) = 1/(h_a * A_s) + 1/(h_c * A_s)}


"-----------------------------------------------------------------Extra-----------"
```

SOLUTION

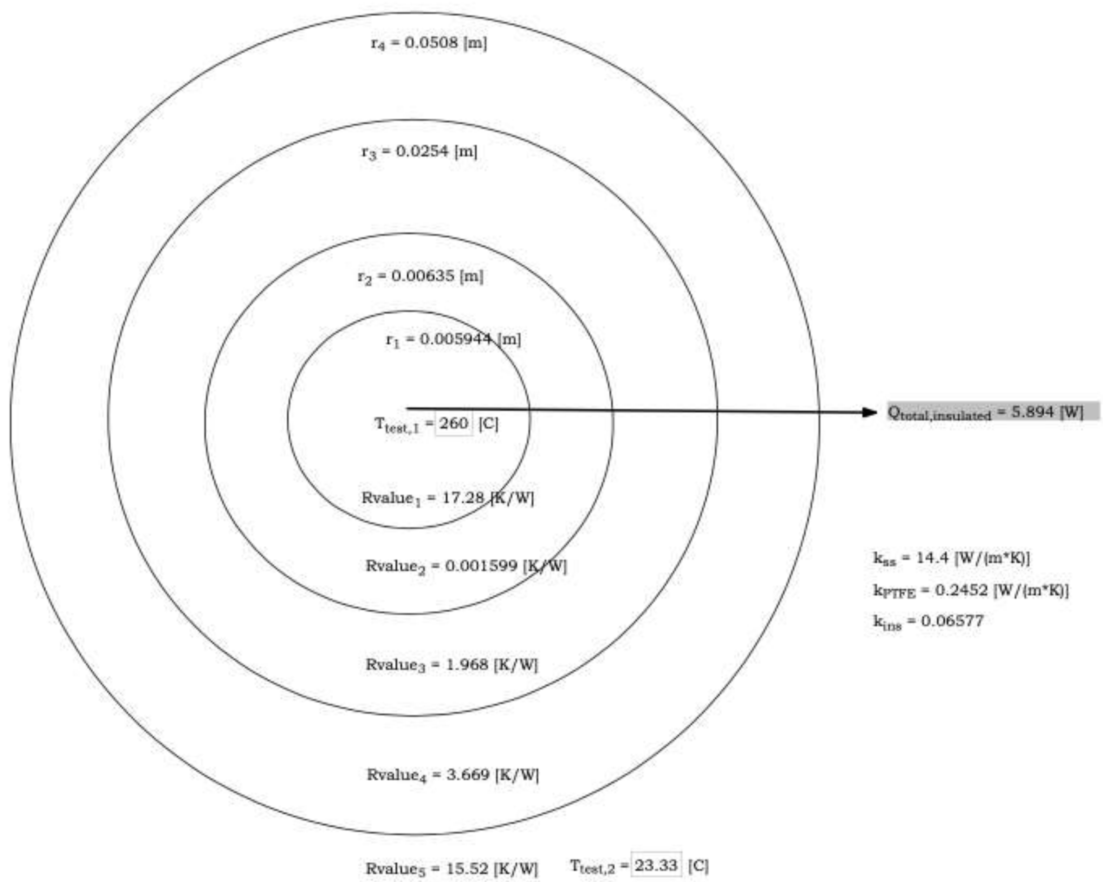
Unit Settings: SI C kPa kJ mass deg

A = 0.0001187 [m^2]	A_b = 0.0001673 [m^2/dim]	A_f = 0.001632 [m^2]
A_p = 0.000022 [m^2]	A_s = 0.01829 [m^2]	cp_a = 1.171 [kJ/kg-K]
cp_c = 1.018 [kJ/kg-K]	d_5 = 0.01229 [m]	d_d = 0.4826 [m]
d_o = 0.0127 [m]	d_{wall} = 0.0004064 [m]	epslon = 0.096
η_f = 0.94	h_a = 15.29 [W/m^2-K]	h_c = 2.3 [W/m^2-K]
k_a = 0.03488 [W/m-K]	k_c = 0.02641 [W/m-K]	k_{st} = 15.1 [W/m-K]

$L = 0.4735$ [m]
$L_c = 0.011$ [m]
$L_f = 0.01$ [m]
$L_t = 0.5254$ [m]
$\mu_a = 0.0000236$ [kg/m-s]
$\mu_c = 0.00001901$ [kg/m-s]
$\mu_s = 0.00001901$ [kg/m-s]
$\dot{m}_a = 0.0002659$ [kg/s]
$\dot{m}_c = 0.04818$ [kg/s]
$N = 76.46$ [-]
$Nu_{u,a} = 5.388$
$P1 = 101.3$ [kPa]
$Pr_a = 0.7327$
$\dot{Q}_{HEX} = 70.9$ [W]
$Re_a = 1167$
$Re_{D,c} = 6686$
$rf = 2.732$
$\rho_a = 0.805$ [kg/m^3]
$\rho_c = 1.134$ [kg/m^3]
$RH_c = 0.384$
$r_1 = 0.00635$ [m]
$r_{11} = 0.00635$
$r_2 = 0.01635$ [m]
$r_{2,c} = 0.01735$ [m]
$S = 0.006192$ [m/dim]
$t = 0.002$ [m]
$Tdp_{c,i} = 8.381$ [C]
$Tdp_{c,o} = 8.381$ [C]
$T_{amb} = 23$ [C]
$T_{c,i} = 23.33$ [C]
$T_{c,o} = 24.78$ [C]
$T_{c,o,A} = 50$ [C]
$T_{dp,m} = 48.89$ [C]
$T_{m,a} = 146.1$ [C]
$T_{m,c} = 36.67$ [C]
$T_s = 260$ [C]
$\dot{V}_a = 0.0003304$ [m^3/s]
$\dot{V}_{a,1} = 0.7$ [ft^3/min]
$\dot{V}_c = 90$ [ft^3/min]

No unit problems were detected.
EES suggested units (shown in purple) for A_b A_f A_p cp_a cp_c h_a .

KEY VARIABLES
$\dot{Q}_{HEX} = 70.9$ [W] *Heat Transfer @ Test Section*


r4 = 0.0508 [m]
r3 = 0.0254 [m]
r2 = 0.00635 [m]
r1 = 0.005944 [m]
Ttest,1 = 260 [C]
Qtotal,insulated = 5.894 [W]
Rvalue1 = 17.28 [K/W]
Rvalue2 = 0.001599 [K/W]
Rvalue3 = 1.968 [K/W]
Rvalue4 = 3.669 [K/W]
Rvalue5 = 15.52 [K/W]
Ttest,2 = 23.33 [C]
kss = 14.4 [W/(m*K)]
kPTFE = 0.2452 [W/(m*K)]
kins = 0.06577

```
{P1 = 101.3 [kPa]}
"Volumetric Flow Rate of Hot Gas"
V_dot_a_1 = 0.7                                  [ft^3/min]
V_dot_a =  V_dot_a_1*convert(ft^3/min,m^3/s)
   A = pi *(d_5/2)^2
   m_dot_a =V_dot_a * rho_a
Vel_a = V_dot_a / A                              {Velocity of Hot Gas}

{State 5: Test Section}


"Hot Gas tube"
d_o = 0.5 * convert('in', 'm')                   {Tube Diameter}
d_wall = 0.016 * convert('in', 'm')              {Tube wall thickness}
d_5 = d_o - d_wall                               {Inner diameter}
L = 18.64 * convert('in', 'm')                   {Tube length}
A_s = pi * d_5 * L                               {Surface area}

T_4 = 249.9 [C]                                  "-for calculation window-"
T_5 = 32.22 [C]                                  "-for calculation window-"

T[4] = 249.9 [C]                                 {dry-bulb of heater -- 500F}
T[5] = 32.22 [C]                                 {Min dry-bulb -- 90F}
T_m_a = (T[4] + T[5]) / 2                        {Mean Temperature}

T_dp[4] = 65.56 [C]                              {Max dewpoint --150F}
T_dp[5]= 32.22 [C]                               {Min dewpoint -- 90F}
T_dp_m = (T_dp[4] + T_dp[5]) / 2                 {Mean Temperature}
   "Properties"
   cp_a=specheat(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
   rho_a=density(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
   mu_a=viscosity(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
   Pr_a=prandtl(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
   k_a=conductivity(AirH2O,T=T_m_a,D=T_dp_m,P=P1)

"Cold Air"
T_c_i = 23.33 [C]                                {Room Temperature -- 74F}
T_c_o_A = 38.89 [C]                              {Assumed -- 102F}
T_m_c = (T_c_i + T_c_o_A) /2                     {Mean Temperature}
RH_c = 0.384                                     {Room reletive humidity}
Tdp_c_i=dewpoint(AirH2O,T=T_c_i,R=RH_c,P=P1)
Tdp_c_o = Tdp_c_i

 "Properties"
   cp_c =specheat(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)
   rho_c=density(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)
   mu_c=viscosity(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)
   Pr_c=prandtl(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)
   k_c=conductivity(AirH2O,T=T_m_c,D=Tdp_c_i,P=P1)


V_dot_c = 90 [ft^3/min] {2 fans will be controlled to deliver 90 CFM}
```

```
id_test_tube = od_test_tube - (t_tube_wall * 2) {Inner diameter of test tube}

"PTFE Fitting Dimensions"
L_PTFE=4 * convert(in,m) {inch to meter}        {Length of PTFE fitting}
od_PTFE=2 * convert(in,m) {inch to meter}       {Outer diameter of PTFE fitting}

"Insulation Dimensions"
Ins_wall_t = 1 * convert(in,m) {inch to meter}  {Insulation wall thickness}
id_ins = 2 * convert(in,m) {inch to meter}      {Insulation pipe size}
od_ins = id_ins + (2*ins_wall_t)                {Outer diameter of insulation}

"Horizontal insulated pipe"
L_c_ins = od_ins                                {Characteristic length of natural convection}

"radius of various surfaces"
r_1=id_test_tube/2                              {inner test tube wall - radius}
r_2=od_test_tube/2                              {outer test tube wall ... inner PTFE wall - radius}
r_3=od_PTFE/2                                   {outer PTFE wall ... inner insulation wall - radius}
r_4= od_ins / 2                                 {outer insulation wall - radius}

"Surface areas"
A_r4 = L_PTFE*2*3.14159*r_4
A_r1 = L_PTFE*2*3.14159*r_1

"Temperatures"
{T_test_1=260}                                  {inner gas temperature}
{T_test_2=23.33}                                {outer ambient temperature}
DELTA_ins=T_test_1-T_test_2                     {delta T from hot to cold}

"Coefficient of expansion for ideal gas"
T_test_2K = converttemp(C,K,T_test_2)           {inner gas temperature - Kelvin}
bravo_ig = 1/T_test_2K                          {Coefficient of expansion}


{T_s_ins = T_test_2}


"Grashof Number of ambient air"
gravity = 9.81                                  {Gravitational constant}
nu_ambair=kinematicviscosity(AirH2O,T=T_c_i,R=RH_c,P=P1) {Kinematic Viscosity}
Gr_ambair = (gravity * bravo_ig * (T_s_ins-T_c_i) * (L_c_ins^3)) / (nu_ambair^2) {Grashof}
Pr_ambair=prandtl(AirH2O,T=T_c_i,R=RH_c,P=P1)                                  {Prandtl
Number of ambient air}

"Raleigh Number"
Ra_D = Gr_ambair * Pr_ambair

"Naturally convective heat transfer coefficient around insulation"
Nusselt_ambair = (0.6*((0.387*(Ra_D^(1/6))) / ((1+(0.559/Pr_ambair)^(9/16))^(8/27))))^2 {Nusselt of the
condition}
```

```
k_ambair=conductivity(AirH2O,T=T_c_i,R=RH_c,P=P1)                          {conductivity of ambient air}
h_2 = (Nusselt_ambair*k_ambair)/L_c_ins      {convection heat transfer coefficient}      {[W/m^2*K]}

h_1 = h_a

"Conductivities of materials"
{k_ss=0}    {BTU * in / ft^2 * hr * degF}      {stainless steel 304 conductivity = 99.84}
{k_PTFE=0} {BTU * in / ft^2 * hr * degF}       {PTFE conductivity = 1.70}
{k_ins=.456} {BTU * in / ft^2 * hr * degF}     {ins conductivity = .456}
k_ins = 0.038 * convert(Btu/(h*ft*R), W/(m*K))                             {W/m*K}
k_PTFE = 0.14167 * convert(Btu/(h*ft*R), W/(m*K))                          {W/m*K}
k_ss = 8.32 * convert(Btu/(h*ft*R), W/(m*K))                               {W/m*K}

"Thermal Resistance Calculations"
Rvalue_4=ln(r_4/r_3)/(2*pi*L_test*k_ins)       {Resistance of conduction in ins}
Rvalue_3=ln(r_3/r_2)/(2*pi*L_test*k_PTFE)      {Resistance of conduction in PTFE fitting}
Rvalue_2=ln(r_2/r_1)/(2*pi*L_test*k_ss)        {Resistance of conduction in SS tube}
Rvalue_1=1/(h_1*A_r1)                          {Resistance of convection on inner surface}
Rvalue_1_4 = Rvalue_1 + Rvalue_2 + Rvalue_3 + Rvalue_4

Q_total_insulated = (T[4] - T_r1) / Rvalue_1
Q_total_insulated = (T[4] - T_r2) / (Rvalue_1 + Rvalue_2)                  {Qtotal of system}
Q_total_insulated = (T[4] - T_r3) / (Rvalue_1 + Rvalue_2 + Rvalue_3)
Q_total_insulated = (T[4] - T_s_ins) / (Rvalue_1 + Rvalue_2 + Rvalue_3 + Rvalue_4)
Q_total_insulated = (T[4] - T_c_i) / (Rvalue_1 + Rvalue_2 + Rvalue_3 + Rvalue_4 + Rvalue_5)
Rvalue_5=1/(h_2*A_r4)
                                               {Resistance of convection on outer surface}

"Heat transfer"
Q_total_insulated = DELTA_ins / Rvalue_total  {Total heat loss}
```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

A = 0.0001187 [m^2]	aa_{duct} = 0.254 [m]
a_{duct} = 0.3328 [m]	A_{r1} = 0.003794 [m^2]
A_{r4} = 0.03243 [m^2]	A_s = 0.01829 [m^2]
bb_{duct} = 0.4826 [m]	$bravo_{ig}$ = 0.003373 [K^{-1}]
cp_a = 1.17 [kJ/kg-K]	cp_c = 1.018 [kJ/kg-K]
ΔT_1 = 225.2 [C]	ΔT_2 = 8.89 [C]
ΔT_{lm} = 66.93 [C]	Δ_{ins} = 236.7 [K]
d_i = 0.01229 [m]	d_o = 0.0127 [m]
d_{wall} = 0.0004064 [m]	F = 1
f_f = 0.03147	gravity = 9.81 [m/s^2]
Gr_{ambair} = 1.318E+07	h_1 = 15.25 [W/m^2-K]
h_2 = 1.987 [W/m^2-K]	h_a = 15.25 [W/m^2-K]
h_c = 2.378 [W/m^2-K]	id_{ins} = 0.0508 [m]
$id_{test,tube}$ = 0.01189 [m]	$Ins_{wall,t}$ = 0.0254 [m]
k_a = 0.03451 [W/(m*K)]	k_{ambair} = 0.02542 [W/(m*K)]
k_c = 0.026 [W/(m*K)]	k_{ins} = 0.06577 [W/(m*K)]
k_{PTFE} = 0.2452 [W/(m*K)]	k_{ss} = 14.4 [W/(m*K)]

$L = 0.4735$ [m]
$L_{duct} = 0.3328$ [m]
$L_t = 0.5373$ [m]
$\mu_a = 0.00002339$ [kg/(m*s)]
$\mu_b = 0.00001876$ [kg/(m*s)]
$\dot{m}_c = 0.04906$ [kg/s]
$\nu_{ambair} = 0.00001552$ [m^2/s]
$Nu_c = 30.44$
$od_{PTFE} = 0.0508$ [m]
$P1 = 101.3$ [kPa]
$Pr_{ambair} = 0.7312$
$\dot{Q}_{HEX} = 68.56$ [W]
$Ra_D = 9.639E+06$
$Re_c = 10007$
$\rho_c = 1.155$ [kg/(m^3)]
$Rvalue_1 = 17.28$ [K/W]
$Rvalue_2 = 0.001599$ [K/W]
$Rvalue_4 = 3.669$ [K/W]
$Rvalue_{total} = 40.15$ [K/W]
$r_2 = 0.00635$ [m]
$r_4 = 0.0508$ [m]
$Tdp_{c,o} = 8.381$ [C]
$T_h = 32.22$ [C]
$T_{c,o} = 24.7$ [C]
$T_{dp,m} = 48.89$ [C]
$T_{m,c} = 31.11$ [C]
$T_{r2} = 148$ [C]
$T_{s,ins} = 114.8$ [C]
$T_{test,2} = 23.33$ [C]
$t_{tube,wall} = 0.0004064$ [m]
$Vel_a = 2.783$ [m/s]
$\dot{V}_{a,1} = 0.7$ [ft^3/min]

$L_{c,ins} = 0.1016$ [m]
$L_{PTFE} = 0.1016$ [m]
$L_{test} = 0.4572$ [m]
$\mu_c = 0.00001876$ [kg/(m*s)]
$\dot{m}_a = 0.0002692$ [kg/s]
$Nusselt_{ambair} = 7.944$ [-]
$Nu_a = 5.432$
$od_{ins} = 0.1016$ [m]
$od_{test,tube} = 0.0127$ [m]
$Pr_a = 0.7335$
$Pr_c = 0.7293$
$Q_{total,insulated} = 5.894$ [W]
$Re_a = 1192$
$\rho_a = 0.8148$ [kg/m^3]
$RH_c = 0.384$
$Rvalue_{1,4} = 22.92$ [K/W]
$Rvalue_3 = 1.968$ [K/W]
$Rvalue_5 = 15.52$ [K/W]
$r_1 = 0.005944$ [m]
$r_3 = 0.0254$ [m]
$Tdp_{c,i} = 8.381$ [C]
$T_a = 249.9$ [C]
$T_{c,i} = 23.33$ [C]
$T_{c,o,A} = 38.89$ [C]
$T_{m,a} = 141.1$ [C]
$T_{r1} = 148$ [C]
$T_{r3} = 136.4$ [C]
$T_{test,1} = 260$ [C]
$T_{test,2K} = 296.5$ [K]
$UA_a = 1.024$ [W/K]
$\dot{V}_a = 0.0003304$ [m^3/s]
$\dot{V}_c = 90$ [ft^3/min]

No unit problems were detected.

KEY VARIABLES
$\dot{Q}_{HEX} = 68.56$ [W] *Heat Transfer @ Test Section – Calculated based on hot air side (inlet tube)*
$cp_a = 1.17$ [kJ/kg-K]
$cp_c = 1.018$ [kJ/kg-K]
$\dot{m}_c = 0.04906$ [kg/s]
$T_h = 32.22$ [C]
$T_{c,i} = 23.33$ [C]
$T_{c,o} = 24.7$ [C]
$T_a = 249.9$ [C]
$\dot{m}_a = 0.0002692$ [kg/s]

Test Section - Water Cooled


```
"assumption" {Delete}

{P1 = 101.3 [kPa]}
V_dot_a_1 = 0.7 [ft^3/min]
V_dot_a =  V_dot_a_1*convert(ft^3/min,m^3/s)
  A = pi *(d_5/2)^2
m_dot_a =V_dot_a * rho_a


{State 5: Test Section}


"Hot Gas tube"
d_o = 0.5 * convert('in', 'm')            {Tube Diameter}
d_wall = 0.016 * convert('in', 'm')       {Tube wall thickness}
d_5 = d_o - d_wall                        {Inner diameter}
L = 18.64 * convert('in', 'm')            {Tube length}
A_s = pi * d_5 * L                        {Surface area}

T[4] = 220.2 [C]                          {Max dry-bulb -- 500F}
T[5] = 32.22 [C]                          {Min dry-bulb -- 90F}
T_m_a = (T[4] + T[5]) / 2                 {Mean Temperature}

T_dp[4] = 65.56 [C]                       {Max dewpoint --150F}
T_dp[5]= 32.22 [C]                        {Min dewpoint -- 90F}
T_dp_m = (T_dp[4] + T_dp[5]) / 2          {Mean Temperature}
  "Properties"
  cp_a=specheat(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
  rho_a=density(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
  mu_a=viscosity(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
  Pr_a=prandtl(AirH2O,T=T_m_a,D=T_dp_m,P=P1)
  k_a=conductivity(AirH2O,T=T_m_a,D=T_dp_m,P=P1)

"Cold Water"
d_w = 2*convert('in','m')
T_w_i = 23 [C]                            {68F}
T_w_o_A = 50 [C]                          {Assumed -- ##F}
T_m_w = (T_w_i + T_w_o_A) /2
 "Properties"
  rho_w=density(Water,T=T_m_w,P=P1)
  mu_w=viscosity(Water,T=T_m_w,P=P1)
  cp_w =specheat(Water,T=T_m_w,P=P1)
  k_w=conductivity(Water,T=T_m_w,P=P1)
```

```
V_dot_w = 3 [L/hr]
V_dot_w_cfm = V_dot_w *convert(L/hr , ft^3/min)
m_dot_w = V_dot_w_cfm*convert(ft^3/min,m^3/s) * rho_w
mu_s = mu_w


{ Solution }

{LMTD: Q_dot_HEX = m_dot_c*cp_c*(T_c,o - T_c,i )=  m_dot_h*cp_h*(T_h,i - T_h,o) =
F*U*A_s*deltaT_lm}

Q_dot_HEX = m_dot_a * cp_a * convert(kJ/kg-K, J/kg-K) *(T[4] - T[5] )
Q_dot_HEX = m_dot_w*cp_w * convert(kJ/kg-K, J/kg-K) * (T_w_o - T_w_i )

Q_dot_HEX = UA_s*DELTAT_lm
   DELTAT_2 = T[5] - T_w_i
   DELTAT_1 = T[4] - T_w_o
   DELTAT_lm = ( DELTAT_2 - DELTAT_1 ) / ln(DELTAT_2/DELTAT_1)

Re_a = 4 * m_dot_a / (pi * d_5 *   mu_a){Laminar}
   L_t = 0.05 * Re_a * Pr_a * d_5
   {If L_t > L --> entrance region & mu_b/mu_s = 0.029 --> use the following N_u:}
   N_u_a = 1.86 * (Re_a * Pr_a * d_5 / L)^(1/3) * (mu_a / mu_s)^(0.14)
   h_a = N_u_a * k_a  / d_5

   Re_w = 4 * m_dot_w / (pi * (d_w+d_5) *mu_w )                              {Laminar}
   {For concentric annulus, use the following equations:}
   N_u_w = 7.42 {N_u for fully developed laminar flow in circular annulas @ Di/Do =
0.242}
   h_w = N_u_a * k_w  / (d_w - d_5)

1/(U*A_s) = 1/(h_a * A_s) + 1/(h_w * A_s)
```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

A = 0.0001187 [m^2]	A_s = 0.01829 [m^2]	cp_a = 1.167 [kJ/kg-K]
cp_w = 4.179 [kJ/kg-K]	ΔT_1 = 179.5 [C]	ΔT_2 = 9.22 [C]
ΔT_{lm} = 57.35 [C]	d_5 = 0.01229 [m]	d_o = 0.0127 [m]
d_w = 0.0508 [m]	d_{wall} = 0.0004064 [m]	h_a = 9.065 [W/m^2-K]
h_w = 54.02 [W/m^2-K]	k_a = 0.03342 [W/m-K]	k_w = 0.6238 [W/m-K]
L = 0.4735 [m]	L_t = 0.5743 [m]	μ_a = 0.00002278 [kg/m-s]
μ_s = 0.0006983 [kg/m-s]	μ_w = 0.0006983 [kg/m-s]	$\dot{m}_a$ = 0.0002792 [kg/s]
$\dot{m}_w$ = 0.0008279 [kg/s]	$N_{u,a}$ = 3.335	$N_{u,w}$ = 7.42
P1 = 101.3 [kPa]	Pr_a = 0.7359	$\dot{Q}_{HEX}$ = 61.27 [W]
Re_a = 1270	Re_w = 23.93	ρ_a = 0.8451 [kg/m^3]
ρ_w = 993.5 [kg/m^3]	$T_{dp,m}$ = 48.89 [C]	$T_{m,a}$ = 126.2 [C]

$T_{m,w}$ = 36.5 [C]	$T_{w,i}$ = 23 [C]	$T_{w,o}$ = 40.71 [C]
$T_{w,o,A}$ = 50 [C]	U = 7.762 [W/m^2-K]	UA_s = 1.068 [W/K]
$\dot{V}_a$ = 0.0003304 [m^3/s]	$\dot{V}_{a,1}$ = 0.7 [ft^3/min]	$\dot{V}_w$ = 3 [L/hr]
$\dot{V}_{w,cfm}$ = 0.001766 [ft^3/min]		

No unit problems were detected.
EES suggested units (shown in purple) for cp_a DELTAT_1 DELTAT_2 DELTAT_lm h_a h_w .

KEY VARIABLES
$\dot{Q}_{HEX}$ = 61.27 [W] *Heat Transfer @ Test Section*

Test Section - Conduction Heat Transfer

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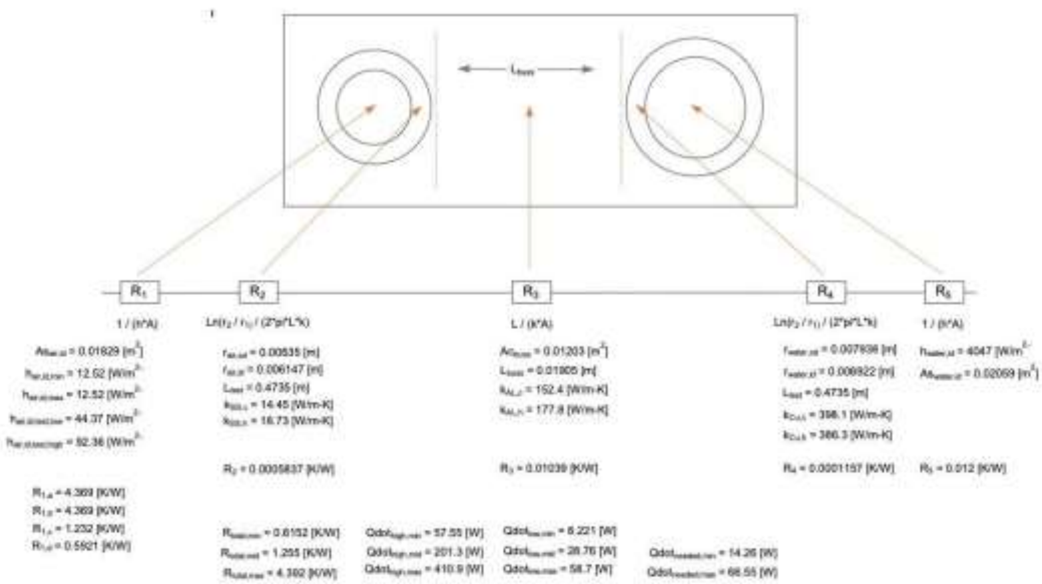
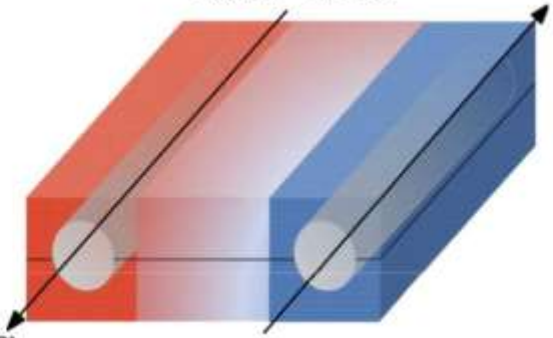
EES Ver. 10.835: #1867: For use by students and faculty, College of Engineering, University of Oklahoma, Stillwater, OK





0.7 cfm without Turbulator :

$Re_{air,id,max}$ = 1139

$h_{air,id,max}$ = 12.52 [W/m^2

$R_{total,max}$ = 4.392 [K/W]

0.15 cfm without Turbulator :

$Re_{air,id,min}$ = 244.1

$h_{air,id,min}$ = 12.52 [W/m^2

$R_{total,max}$ = 4.392 [K/W]

0.7 cfm with Turbulator :

$Re_{air,id,test,high}$ = 10000

$h_{air,id,test,high}$ = 92.36 [W/m^2

$R_{total,min}$ = 0.6152 [K/W]

$Qdot_{high,max}$ = 410.9 [W]

```
P1 = 14.67 * convert(psia, kPa)
   {Atmospheric Pressure}

"------------------------Test tube properties----------------------------"

D_air_id = 0.484 * convert(in,m)                    {Air - Inner Diameter}
r_air_id = D_air_id / 2                             {Air - Inner Radius}
D_air_od = 0.5 * convert(in,m)                      {Air - Outer Diameter}
r_air_od = D_air_od / 2                             {Air - Outer Radius}
L_test = 18.64 * convert(in,m)                      {Air - Length of Test Section}

As_air_od = pi * D_air_od * L_test                  {Air - Outer surface area}
As_air_id = pi * D_air_id * L_test                  {Air - Inner surface area}
A_air_diff = As_air_od - As_air_id                  {Air - Difference in Surface Area}
A_air_perc_diff = A_air_diff / As_air_od            {Air - Percent difference in surface area}

Ac_air_id = pi* .25 * (D_air_id^2)                  {Air - Inner cross sectional area}
Ac_air_od = pi* .25 * (D_air_od^2)                  {Air - Outer cross sectional area}
Ac_air_tube = Ac_air_od - Ac_air_id                 {Air - Area of tube cross section}

"---------------------Water tube properties-----------------------------"

D_water_od = 0.625 * convert(in,m)                  {Water - OD}
r_water_od = D_water_od / 2                         {Water - Outer radius}
D_water_id = 0.545 * convert(in,m)                  {Water - ID}
r_water_id = D_water_id / 2                         {Water - Inner radius}

As_water_od = pi * D_water_od * L_test              {Water - Outer surface area}
```

```
As_water_id = pi * D_water_id * L_test                                  {Water -
Inner surface area}
A_water_diff = As_water_od - As_water_id                                 {Water -
 Difference in Surface Area}
A_water_perc_diff = A_water_diff / As_water_od                          {Water - %
difference in surface area}

Ac_water_id = pi * .25 * (D_water_id^2)                                 {Water -
Inner cross sectional area}
Ac_water_od = pi * .25 * (D_water_od^2)                                  {Water -
 Outer cross sectional area}
Ac_water_tube = Ac_water_od - Ac_water_id                                {Water -
 Area of tube cross section}

"--------------------------Water Properties @ Inlet----------------------------"

T_water_inlet = converttemp(F,C,45)                                     {Water
inlet temp}

Pr_water_id=prandtl(Water,T=T_water_inlet,P=P1)                         {Prandtl
Number of water in}
rho_water_id=density(Water,T=T_water_inlet,P=P1)                        {Density of
water in}
v_water_id=volume(Water,T=T_water_inlet,P=P1)                           {Specific
volume of water in}
k_water_id=conductivity(Water,T=T_water_inlet,P=P1)
   {Conductivity of water in}
cp_water_id=cp(Water,T=T_water_inlet,P=P1)
   {Specific heat of water in}
mu_water_id=viscosity(Water,T=T_water_inlet,P=P1)                       {Dynamic
Viscosity of water in}
nu_water_id=kinematicviscosity(Water,T=T_water_inlet,P=P1)              {Kinematic
Viscosity of water in}

"-------------------Water Extensive Properties @ inlet---------------------------"

Vdot_water_id = 0.22 * convert(L/s,m^3/s)
   {Volumetric flow rate of water}
mdot_water_id = Vdot_water_id * rho_water_id                             {Mass
flow rate of water}

Vel_water_id = Vdot_water_id / Ac_water_id
   {Velocity of water}

C_water = mdot_water_id * cp_water_id                                   {Heat
```

```
capacity rate of water}

"------------------------Hot Air Properties @ Inlet-------------------------------"

Tdb_air_h_id = converttemp(F,C,500)                                          {Drybulb
temp at hot air inlet}
Tdp_air_h_id = converttemp(F,C,150)                                          {Dewpoint
at hot air inlet}

Pr_air_h_id = prandtl(AirH2O,T=Tdb_air_h_id,D=Tdp_air_h_id,P=P1)             {Prandtl
Number of air}
k_air_h_id = conductivity(AirH2O,T=Tdb_air_h_id,D=Tdp_air_h_id,P=P1)
   {Conductivity of air}
nu_air_h_id = kinematicviscosity(AirH2O,T=Tdb_air_h_id,D=Tdp_air_h_id,P=P1)
   {Kinematic Viscosity of air}
mu_air_h_id = viscosity(AirH2O,T=Tdb_air_h_id,D=Tdp_air_h_id,P=P1)           {Dynamic
Viscosity of air}
cp_air_h_id = cp(AirH2O,T=Tdb_air_h_id,D=Tdp_air_h_id,P=P1)                  {Specific
Heat of hot air inlet}
v_air_h_id = volume(AirH2O,T=Tdb_air_h_id,D=Tdp_air_h_id,P=P1)               {Specific
volume of hot air inlet}
rho_air_h_id=density(AirH2O,T=Tdb_air_h_id,D=Tdp_air_h_id,P=P1)              {Density of
hot air inlet}

"-------------------------Hot Air Properties @ outlet--------------------------"

Tdb_air_h_o = converttemp(F,C,110)                                           {Drybulb
at hot air outlet}
Tdp_air_h_o = converttemp(F,C,90)                                            {Dewpoint
at hot air outlet}

Pr_air_h_o = prandtl(AirH2O,T=Tdb_air_h_o,D=Tdp_air_h_o,P=P1)                {Prandtl
Number of air}
k_air_h_o = conductivity(AirH2O,T=Tdb_air_h_o,D=Tdp_air_h_o,P=P1)
   {Conductivity of air}
nu_air_h_o = kinematicviscosity(AirH2O,T=Tdb_air_h_o,D=Tdp_air_h_o,P=P1)
   {Kinematic Viscosity of air}
mu_air_h_o = viscosity(AirH2O,T=Tdb_air_h_o,D=Tdp_air_h_o,P=P1)              {Dynamic
Viscosity of air}
cp_air_h_o = cp(AirH2O,T=Tdb_air_h_o,D=Tdp_air_h_o,P=P1)                     {Specific
Heat of hot air inlet}
v_air_h_o = volume(AirH2O,T=Tdb_air_h_o,D=Tdp_air_h_o,P=P1)                  {Specific
volume of hot air inlet}
rho_air_h_o=density(AirH2O,T=Tdb_air_h_o,D=Tdp_air_h_o,P=P1)                 {Density of
```

```
hot air outlet}

"------------------------Bulk Mean fluid temperature - hot gas---------------------------"

Tdb_air_h_b = (Tdb_air_h_id + Tdb_air_h_o) / 2                          {Drybulb
hot air bulk mean}
Tdp_air_h_b = (Tdp_air_h_id + Tdp_air_h_o) / 2                          {Dewpoint
hot air bulk mean}

Pr_air_h_b = prandtl(AirH2O,T=Tdb_air_h_b,D=Tdp_air_h_b,P=P1)          {Prandtl
Number of air}
k_air_h_b = conductivity(AirH2O,T=Tdb_air_h_b,D=Tdp_air_h_b,P=P1)
   {Conductivity of air}
nu_air_h_b = kinematicviscosity(AirH2O,T=Tdb_air_h_b,D=Tdp_air_h_b,P=P1)
   {Kinematic Viscosity of air}
mu_air_h_b = viscosity(AirH2O,T=Tdb_air_h_b,D=Tdp_air_h_b,P=P1)        {Dynamic
Viscosity of air}
cp_air_h_b = cp(AirH2O,T=Tdb_air_h_b,D=Tdp_air_h_b,P=P1)               {Specific
Heat of hot air}
v_air_h_b = volume(AirH2O,T=Tdb_air_h_b,D=Tdp_air_h_b,P=P1)            {Specific
volume of hot air}
rho_air_h_b=density(AirH2O,T=Tdb_air_h_b,D=Tdp_air_h_b,P=P1)

"--------------------------Air Extensive Properties-------------------------------"

Vdot_air_id_min = 0.15 * convert(ft^3,m^3) / convert(min,s)             {Air -
volumetric flow min}
Vdot_air_id_max = 0.7 * convert(ft^3,m^3) / convert(min,s)              {Air -
volumetric flow max}

Vel_air_id_min = Vdot_air_id_min / Ac_air_id                             {Air -
velocity flow min}
Vel_air_id_max = Vdot_air_id_max / Ac_air_id                             {Air -
velocity flow max}

mdot_air_id_min = Vdot_air_id_min * rho_air_h_b                          {Air - Mass
flow rate min}
mdot_air_id_max = Vdot_air_id_max * rho_air_h_b                          {Air - Mass
flow rate max}

C_air_min = mdot_air_id_min * cp_air_h_b                                 {Air - Heat
capacity rate min}
C_air_max = mdot_air_id_max * cp_air_h_b                                 {Air - Heat
capacity rate max}
```

```
"-------------------------------Heat transfer-----------------------------------"

Qdot_needed_min = mdot_air_id_min * cp_air_h_b * (Tdb_air_h_id - Tdb_air_h_o)
  {Heat transfer needed at minimum conditions}
Qdot_needed_max = mdot_air_id_max * cp_air_h_b * (Tdb_air_h_id - Tdb_air_h_o)
  {Heat transfer needed at maximum conditions}

delta_T_max = Tdb_air_h_id - T_water_inlet                    {Delta T
between both inlets}
delta_T_min = Tdb_air_h_o - T_water_inlet                     {Delta T
between air outlet and water inlet}
Qdot_max_min = C_air_min * delta_T_max                        {Heat
transfer max at minimum conditions}
Qdot_max_max = C_air_max * delta_T_max                        {Heat
transfer max at maximum conditions}

"----------------Convection heat transfer coefficient of air side--------------"

Re_air_id_min = Vel_air_id_min * D_air_id / nu_air_h_b        {Air -
Reynolds min flow}
Re_air_id_max = Vel_air_id_max * D_air_id / nu_air_h_b        {Air -
Reynolds max flow}
Re_air_id_test_low = 4000                                     {Test
number for unknown turbulator - low}
{Re_air_id_test_high = 20000}                                 {Test
number for unknown turbulator - high}

Nusselt_air_id_min = 4.36                                     {Nusselt
for non-turbulator tube}{Laminar}
Nusselt_air_id_max = 4.36                                     {Nusselt
for non-turbulator tube}{Laminar}
Nusselt_air_id_test_low = 0.023 * (Re_air_id_test_low ^0.8) * (Pr_air_h_b^(0.4))
  {Nusselt for low test value}{Turbulent}
Nusselt_air_id_test_high = 0.023 * (Re_air_id_test_high^0.8) * (Pr_air_h_b^(0.4))
  {Nusselt for high test value}{Turbulent}

h_air_id_min = Nusselt_air_id_min * k_air_h_b / D_air_id
h_air_id_max = Nusselt_air_id_max * k_air_h_b / D_air_id
h_air_id_test_low = Nusselt_air_id_test_low * k_air_h_b / D_air_id
h_air_id_test_high = Nusselt_air_id_test_high * k_air_h_b / D_air_id

"--------------Convection heat transfer coefficient of water side------------"

Re_water_id = Vel_water_id * D_water_id / nu_water_id         {Water -
Reynolds}
```

```
Nusselt_water_id = 0.023 * (Re_water_id^0.8) * (Pr_water_id^(0.3))          {Water -
Nusselt}
h_water_id = Nusselt_water_id * k_water_id / D_water_id          {Water -
Heat xfer coeff}

"--------------------------Conduction Path Properties-----------------------------------"

t_buss = 1 * convert(in,m)
L_buss = 0.75 * convert(in,m)
Ac_buss = t_buss * L_test
k_AL_c = conductivity(Aluminum_6061, T=T_water_inlet)
k_AL_h = conductivity(Aluminum_6061, T=Tdb_air_h_id)

k_Cu_c = conductivity(Copper, T=T_water_inlet)
k_Cu_h=conductivity(Copper, T=Tdb_air_h_id)

k_SS_c=conductivity(Stainless_AISI304, T=T_water_inlet)
k_SS_h=conductivity(Stainless_AISI304, T=Tdb_air_h_id)
k_SS_316=conductivity(Stainless_AISI316, T=T_water_inlet)

{k_paste = 8.5
L_paste = 0.01}

R_1_a = 1 / (h_air_id_min * As_air_id)
R_1_b = 1/ (h_air_id_max * As_air_id) {Equals to R_1_a}
R_1_c = 1/(h_air_id_test_low * As_air_id)
R_1_d = 1/(h_air_id_test_high * As_air_id)

R_2 = ln(r_air_od / r_air_id) / (L_test * 2 * pi * k_SS_h)
{R_3 = ln((r_air_od + (L_paste * convert(in,m)))/r_air_od) / (L_test * 2 * pi * k_paste)}
R_3 = L_buss / (Ac_buss * k_AL_c) {Changed from R_4 to R_3}
{R_5 = ln((r_water_od + (L_paste * convert(in,m)))/r_water_od)/ (L_test * 2 * pi * k_paste)
}
R_4 = ln(r_water_od / r_water_id) / (L_test * 2 * pi * k_Cu_c) {Changed from R_6 to R_4}
R_5 = 1 / (h_water_id * As_water_id) {Changed from R_7 to R_5}

{R_2_7 = R_2 + R_3 + R_4 + R_5 + R_6 + R_7}
R_2_7 = R_2 + R_3 + R_4 + R_5
R_total_min = R_2_7 + R_1_d
R_total_mid = R_2_7 + R_1_c
R_total_max = R_2_7 + R_1_a

"-----------------------------Maximum heat transfer---------------------------------"
```

```
Qdot_high_max = delta_T_max / R_total_min
Qdot_high_mid = delta_T_max / R_total_mid
Qdot_high_min = delta_T_max / R_total_max

Qdot_low_max = delta_T_min / R_total_min
Qdot_low_mid = delta_T_min / R_total_mid
Qdot_low_min = delta_T_min / R_total_max


"---------------------------- Foam insulation test ---------------------------------"
L_buss_left = 0.5 * convert(in,m)
Ac_buss_left = L_buss_left * L_test
R_3left = L_buss_left / (Ac_buss_left * k_AL_c)
K_foam_left = 0.022 [W/m-K]
t_foam =  0.125 * convert(in,m)
No_layers = 4 [-]
A_c_leftside = 1 * convert(in,m) * 18.5 * convert(in,m)
R_foam = No_layers * t_foam / (K_foam_left * A_c_leftside)

R_left_total = R_foam + R_3left + R_2 + R_1_a
T_ambiant = 24 [C]

Q_dot_loss = (Tdb_air_h_id  - T_ambiant) / R_left_total
```

SOLUTION

Unit Settings: SI C kPa J mass deg

$Ac_{air,id}$ = 0.0001187 [m²]	$Ac_{air,od}$ = 0.0001267 [m²]
$Ac_{air,tube}$ = 0.000007978 [m²]	Ac_{buss} = 0.01203 [m²]
$Ac_{buss,left}$ = 0.006013 [m²]	$Ac_{water,id}$ = 0.0001505 [m²]
$Ac_{water,od}$ = 0.0001979 [m²]	$Ac_{water,tube}$ = 0.00004743 [m²]
$As_{air,id}$ = 0.01829 [m²]	$As_{air,od}$ = 0.01889 [m²]
$As_{water,id}$ = 0.02059 [m²]	$As_{water,od}$ = 0.02361 [m²]
$A_{air,diff}$ = 0.0006045 [m²]	$A_{air,perc,diff}$ = 0.032
$A_{c,leftside}$ = 0.01194 [m²]	$A_{water,diff}$ = 0.003022 [m²]
$A_{water,perc,diff}$ = 0.128	$cp_{air,h,b}$ = 1172 [J/kg-K]
$cp_{air,h,id}$ = 1454 [J/kg*K]	$cp_{air,h,o}$ = 1064 [J/kg*K]
$cp_{water,id}$ = 4200 [J/kg*K]	$C_{air,max}$ = 0.3072 [J/s-K]
$C_{air,min}$ = 0.06582 [J/s-K]	C_{water} = 923.9 [J/s-K]
$\delta_{T,max}$ = 252.8 [K]	$\delta_{T,min}$ = 36.11 [K]
$D_{air,id}$ = 0.01229 [m]	$D_{air,od}$ = 0.0127 [m]
$D_{water,id}$ = 0.01384 [m]	$D_{water,od}$ = 0.01588 [m]
$h_{air,id,max}$ = 12.52 [W/m²-K]	$h_{air,id,min}$ = 12.52 [W/m²-K]
$h_{air,id,test,high}$ = 92.36 [W/m²-K]	$h_{air,id,test,low}$ = 44.37 [W/m²-K]
$h_{water,id}$ = 4047 [W/m²-K]	$k_{air,h,b}$ = 0.03529 [W/m-K]
$k_{air,h,id}$ = 0.0444 [W/m-K]	$k_{air,h,o}$ = 0.02702 [W/m-K]
$k_{AL,c}$ = 152.4 [W/m-K]	$k_{AL,h}$ = 177.8 [W/m-K]
$k_{Cu,c}$ = 398.1 [W/m-K]	$k_{Cu,h}$ = 386.3 [W/m-K]
$K_{foam,left}$ = 0.022 [W/m-K]	$k_{SS,316}$ = 13.08 [W/m-K]
$k_{SS,c}$ = 14.45 [W/m-K]	$k_{SS,h}$ = 18.73 [W/m-K]

$k_{water,id}$ = 0.5728 [W/m-K]
$L_{buss,left}$ = 0.0127 [m]
$mdot_{air,id,max}$ = 0.0002621 [kg/s]
$mdot_{water,id}$ = 0.22 [kg/s]
$\mu_{air,h,id}$ = 0.00002792 [kg/m-s]
$\mu_{water,id}$ = 0.001417 [kg/m-s]
$Nusselt_{air,id,max}$ = 4.36
$Nusselt_{air,id,test,high}$ = 32.17
$Nusselt_{water,id}$ = 97.81
$\nu_{air,h,id}$ = 0.00004672 [m^2/s]
$\nu_{water,id}$ = 0.000001418 [m^2/s]
$Pr_{air,h,b}$ = 0.7319
$Pr_{air,h,o}$ = 0.7357
$Qdot_{high,max}$ = 410.9 [W]
$Qdot_{high,min}$ = 57.55 [W]
$Qdot_{low,mid}$ = 28.76 [W]
$Qdot_{max,max}$ = 77.64 [W]
$Qdot_{needed,max}$ = 66.55 [W]
$\dot{Q}_{loss}$ = 4.474 [W]
$Re_{air,id,min}$ = 244.1
$Re_{air,id,test,low}$ = 4000
$\rho_{air,h,b}$ = 0.7932 [kg/m^3]
$\rho_{air,h,o}$ = 1.093 [kg/m^3]
$R_{1,a}$ = 4.369 [K/W]
$R_{1,c}$ = 1.232 [K/W]
R_2 = 0.0005837 [K/W]
R_3 = 0.01039 [K/W]
R_4 = 0.0001157 [K/W]
$r_{air,id}$ = 0.006147 [m]
R_{foam} = 48.37 [K/W]
$R_{total,max}$ = 4.392 [K/W]
$R_{total,min}$ = 0.6152 [K/W]
$r_{water,od}$ = 0.007938 [m]
$Tdb_{air,h,id}$ = 260 [C]
$Tdp_{air,h,b}$ = 48.89 [C]
$Tdp_{air,h,o}$ = 32.22 [C]
t_{buss} = 0.0254 [m]
$T_{water,inlet}$ = 7.222 [C]
$Vdot_{air,id,min}$ = 0.00007079 [m^3/s]
$Vel_{air,id,max}$ = 2.783 [m/s]
$Vel_{water,id}$ = 1.462 [m/s]
$v_{air,h,id}$ = 2.028 [m^3/kg]
$v_{water,id}$ = 0.0010001 [m^3/kg]

L_{buss} = 0.01905 [m]
L_{test} = 0.4735 [m]
$mdot_{air,id,min}$ = 0.00005616 [kg/s]
$\mu_{air,h,b}$ = 0.00002383 [kg/m-s]
$\mu_{air,h,o}$ = 0.00001926 [kg/m-s]
No_{layers} = 4 [-]
$Nusselt_{air,id,min}$ = 4.36
$Nusselt_{air,id,test,low}$ = 15.46
$\nu_{air,h,b}$ = 0.00003004 [m^2/s]
$\nu_{air,h,o}$ = 0.00001762 [m^2/s]
P1 = 101.1 [kPa]
$Pr_{air,h,id}$ = 0.7545
$Pr_{water,id}$ = 10.39
$Qdot_{high,mid}$ = 201.3 [W]
$Qdot_{low,max}$ = 58.7 [W]
$Qdot_{low,min}$ = 8.221 [W]
$Qdot_{max,min}$ = 16.64 [W]
$Qdot_{needed,min}$ = 14.26 [W]
$Re_{air,id,max}$ = 1139
$Re_{air,id,test,high}$ = 10000
$Re_{water,id}$ = 14274
$\rho_{air,h,id}$ = 0.5975 [kg/m^3]
$\rho_{water,id}$ = 1000 [kg/m^3]
$R_{1,b}$ = 4.369 [K/W]
$R_{1,d}$ = 0.5921 [K/W]
$R_{2,7}$ = 0.02309 [K/W]
R_{3left} = 0.01386 [K/W]
R_5 = 0.012 [K/W]
$r_{air,od}$ = 0.00635 [m]
$R_{left,total}$ = 52.75 [K/W]
$R_{total,mid}$ = 1.255 [K/W]
$r_{water,id}$ = 0.006922 [m]
$Tdb_{air,h,b}$ = 151.7 [C]
$Tdb_{air,h,o}$ = 43.33 [C]
$Tdp_{air,h,id}$ = 65.56 [C]
$T_{ambient}$ = 24 [C]
t_{foam} = 0.003175 [m]
$Vdot_{air,id,max}$ = 0.0003304 [m^3/s]
$Vdot_{water,id}$ = 0.00022 [m^3/s]
$Vel_{air,id,min}$ = 0.5964 [m/s]
$v_{air,h,b}$ = 1.363 [m^3/kg]
$v_{air,h,o}$ = 0.9431 [m^3/kg]

No unit problems were detected.
EES suggested units (shown in purple) for Ac_buss_left rho_air_h_b R_3left R_left_total R_total_max R_total_mid .

Detailed Cost Breakdown

Heat Exchanger Purchase List					
4PC92	Humidifier	Circulation Pump	1	184.34	$ 184.34
EXS1F1HR7	Humidifier	Air Bubblers	1	12	$ 12.00
2KGW4	Humidifier	Flange Kit for Pumps	1	15.08	$ 15.08
4TCR8	Humidifier	Humidifier Heater	1	56.42	$ 56.42
B00JYIO34S	Humidifier	Thermometer for manual readings	1	24.95	$ 24.95
3ACV6	Humidifier	Stainless tube for high temperature area	1	25.34	$ 25.34
1079PK17	Humidifier	Sight glass for humidifier	1	32.49	$ 32.49
1FBH7	Humidifier	RTV silicone for sealing high temperature connections	1	4.41	$ 4.41
40PN96	Humidifier	Insulation	1	11.72	$ 11.72
40PP02	Humidifier	Insulation	1	14.23	$ 14.23
1VEV8	Humidifier	Pipe for humidifier	1	157.3	$ 157.30
6MZ11	Humidifier	Pipe for spray bar	1	20.94	$ 20.94
6MZ13	Humidifier	Pipe for pump circulation line	1	42.12	$ 42.12
2PLP9	Humidifier	Reducer for spray bar	1	9.18	$ 9.18
22FL80	Humidifier	PVC Tee	1	3.3	$ 3.30
22FL93	Humidifier	PVC 90 elbow	2	2.02	$ 4.04
22FJ13	Humidifier	1-1/4" Male Adapter	2	0.66	$ 1.32
22FJ25	Humidifier	3/4" Male Adapter	1	0.3	$ 0.30
1VFG7	Humidifier	3" coupling for humidifier	3	15	$ 45.00
22FJ44	Humidifier	1-1/4" pvc coupling	5	0.66	$ 3.30
22FJ53	Humidifier	3/4" pvc coupling	3	0.3	$ 0.90
21TF21	Humidifier	Pipe thread sealant tape	1	1.11	$ 1.11
1VGG6	Humidifier	PVC Reducing Tee	6	63.16	$ 378.96
2PLP2	Humidifier	PVC Reducing Coupling	4	26.57	$ 106.28
2PLN4	Humidifier	PVC Reducing Coupling	4	21.56	$ 86.24
2PLR1	Humidifier	PVC Reducer Bushing	4	16	$ 64.00
6MZ15	Humidifier	2" PVC Pipe	2	80	$ 160.00
6MZ14	Humidifier	1-1/2" PVC Pipe	2	58.42	$ 116.84
6NF20	Humidifier	1/2" PVC Pipe	4	3.5	$ 14.00
3TPV1	Humidifier	1/4" PVC Pipe	4	8.01	$ 32.04
6NF25	Humidifier	2" PVC Pipe	4	18.41	$ 73.64
6579T42	Instrumentation	200 ft. of 24 gauge K-type thermocouple wire	1	204	204
6CTY4	Instrumentation	RTDs for water temperature measurements at 3 locations	3	19.78	59.34
21TP27	Instrumentation	0.2 to 10ml. Plastic Graduated Cylinder, Clear, Height: 14.5 cm / 5.7 in	1	$4.63	$4.63
N/A	Instrumentation	Breadboard for low voltage electrical connections	1	10.99	10.99
N/A	Instrumentation	Arduino Board for controlling inputs and outputs	3	15.99	47.97
N/A	Instrumentation	Breadboard jumpers for low voltage connections	2	10.99	21.98
N/A	Instrumentation	Thermocouple Modules for temperature sensor K-Type thermocouples	20	7.99	159.8
N/A	Instrumentation	6-ft. long USB cable for Arduino connection	1	7.95	7.95
N/A	Instrumentation	RTD temperature sensor amplifier	3	10.99	32.97
AHP-3742	Heating section	316 SS Inline Duct Heater up to 1000°F and .75 kW Power 50/200W	3	$98.41	$295.23
SFM3100-VC	Heating section	ANALOG AIR FLOW SENSOR	1	$161.60	$161.60
1LRY6	Heating section	1/4" SS coupling	1	3.21	3.21
2UB91	Heating section	1/2" SS 90 elbow	3	17.26	$ 51.78
1LTP2	Heating section	Stainless reducer for heaters	4	5.26	21.04
1LRY6	Heating section	1/4" coupling for heater connections	1	3.21	3.21
1XAV7	Heating section	1/2" stainless steel pipe for connection to the water tank and test sections	2	5.73	11.46
6MN32	Heating Section	Shut off valve for inlet to system	1	11.06	$ 11.06
1MNC7	Heating Section	High temperature union for heating section	3	15.67	$ 47.01
4DHU7	Heating Section	Check Valve	1	19.86	$ 19.86
6C891	Controls	Relays for on/off controls	6	7.7	46.2
41D405	Controls	Control transformer for controls circuit	1	73.37	73.37
5ZDH3	Controls	Low voltage control circuits	1	30.45	30.45
5ZDH2	Controls	Low voltage control circuits	1	30.45	30.45
4NHV8	Controls	Thumb screw for mounting PCBs	2	2.59	5.18

52XC59	Controls	Back panel for wall of enclosure - lessens number of screws protruding through back of panel	1	25.7	25.7
3KH18	Controls	Cable ties for cable management	1	28	28
5NB54	Controls	Screws to mount panel to enclosure	1	2.85	2.85
2FUJ4	Controls	Nylon locknut for panel mounting screws	1	10.15	10.15
3XYY5	Controls	Spacer for panel standoff distance	1	1.92	1.92
31JJ43	Controls	Screws for fastening cable management ties	1	6.12	6.12
6C890	Controls	Relay for various components	6	9.22	55.32
Lowes	Controls	15A 125v 2 wire black	2	3.08	6.16
Lowes	Controls	15A 125v 2 wire black	2	1.97	3.94
Lowes	Controls	disconnect 22-18 awg	1	3.98	3.98
22XH78	Test Section	Hosing for water bath pump	1	31.49	31.49
39R512	Test Section	1/2" x 1/4" reducing bushing for RTD mounting	2	6.25	12.5
5P098	Test Section	1/2" tee for water sensors	2	2.62	5.24
2HNN3	Test Section	Pump for water section of heat exchanger	1	57.89	57.89
6AFN9	Test Section	Fitting for hose connection	2	3.19	6.38
5P023	Test Section	Fitting for hose barb fitting connection	2	5.58	11.16
742T08	Test Section	Hose for water side circuit	1	19.37	19.37
2DPF7	Test Section	PG7 connector	5	2.25	11.25
2DZH4	Test Section	PG7 locknut	5	0.51	2.55
3XYN5	Test Section	Standoffs for PCBs	2	3.9	7.8
4AGJ5	Test Section	Standoff nuts for PCBs	1	3.53	3.53
52XA43	Test Section	Enclosure for PCBs	1	131.25	131.25
1VLV5	Test Section	1/2 male adapter for copper pipe to reducer connection.	2	1.63	3.26
9137795	Test Section	Ball End Mill bit for SS tube	1	65.46	65.46
41117177	Test Section	Ball End Mill bit for copper tube	1	45.14	45.14
2EZX3	Test Section	Bar stock for conduction buss	1	77.52	$ 77.52
4LFH8	Test Section	2 in Thick, Hinged with Self Sealing Lap Fiberglass Pipe Insulation, 3 ft Insulation Length	1	$29.40	$29.40
497Y19	Test Section	Rod Stock, White, 2" dia., 2 ft.	1	$136.17	$136.17
3/6/2021	Test Section	Aluminum Sheet Stock, 0.016 in Thickness, 4 in x 10 in W x L, Alloy 3003	1	$9.54	$9.54
2TY68	Test Section	316 Stainless Steel Union, Socket Weld, 1/2 in Pipe Size - Pipe Fitting	1	$26.60	$26.60
4WTN9	Test Section	Copper tubing for water tube	1	5.89	$ 5.89
DDNV0012	Test Section	Unions for disconnecting water lines on test section	2	9.89	$ 19.78
ECMF-100	Test Section	4" Inline Duct Fan with 0-100% Speed Controlled EC Motor	2	$72.99	$145.98
Lowes	Fittings	1/4in x 6in pipe nipple	1	9.38	9.38
Lowes	Fittings	3/8in hex nipple	1	3.38	3.38
Lowes	Fittings	1/4in x 1/4in fip coupler	3	4.68	14.04
Lowes	Fittings	1/4in x 1/4in fip elbow	3	6.08	18.24
Lowes	Fittings	1/2in od fip adapter	1	6.98	6.98
Lowes	Fittings	1/2in fip x 1/4in fip c	1	7.18	7.18
Lowes	Fittings	1/2in ftgxm cpr st adapt	1	7.38	7.38
Lowes	Fittings	1-1/4in sch40 bushing	2	1.2	2.4
Lowes	Fittings	1-1/4in sch40 bushing	2	1.49	2.98
Lowes	Fittings	1/2in ftgxf st adapt	1	5.98	5.98
Lowes	Fittings	1/2in cxc cpr coup stop	2	0.67	1.34
Lowes	Fittings	1-1/4x 3/4in sch40 bsn	1	1.28	1.28
Lowes	Fittings	1-1/4in sch40 tee	1	1.97	1.97
Lowes	Fittings	1/2in fip x 1/2in fip c	1	7.18	7.18
Lowes	Fittings	3/4in sch40 cap	1	0.63	0.63
Lowes	Fittings	1-1/4in sch40 elbow	2	1.87	3.74
Lowes	Fittings	3/8in x 1/4in fip coupler	1	5.58	5.58
Lowes	Fittings	3/4in sch40 plug	1	1.2	1.2
Lowes	Fittings	1/2in od x 1/2in mip ad	1	7.86	7.86
Lowes	Fittings	1/4in mip x 4in nipple	2	8.88	17.76
Lowes	Fittings	1/2in x 3/8in cxc cpr c	1	2.08	2.08
Lowes	Fittings	1/4in mip x 1-1/2in nip	1	4.78	4.78
Lowes	Fittings	1/4in mip x 4in nipple	1	8.88	8.88
Lowes	Fittings	1/4in x 1in ss	15	0.13	1.95
Lowes	Fittings	1/4in zinc flat	1	2.71	2.71
Lowes	Fittings	3/8in threaded retainter	1	8.09	8.09
Lowes	Fittings	1/4in mip x 1-1/2in nip	1	4.78	4.78
Lowes	Fittings	1/4in mini ball valve	1	7.88	7.88
Lowes	Hardware	hose clamp assortment	1	18.96	18.96
Lowes	Hardware	unistrut corner	3	3.72	11.16

Detailed Cost Breakdown (Continued)

Lowes	Hardware	unistruc 12ga channel	2	27.47	54.94
Lowes	Hardware	unistrut 3/8 spring	2	5.1	10.2
Lowes	Hardware	1-1/2in galv split ring h	3	2.48	7.44
Lowes	Hardware	18in cable ties	1	6.98	6.98
Lowes	Hardware	1-1/4in galv split ring H	5	2.28	11.4
Lowes	Hardware	sigma 3/4in emt 2hl stra	1	4.48	4.48
Lowes	Hardware	1/2in rwa fmc 25ft	1	24.06	24.06
Lowes	Hardware	sigma 1/2in emt 2hl stra	1	1.18	1.18
Lowes	Hardware	unistrut corner	2	3.72	7.44
Lowes	Hardware	KOB 3/8in x 50ft rubber	1	35.98	35.98
Lowes	Hardware	3/8in zinc nut	100	0.12	12
Lowes	Hardware	3/8x 1-1/4 bolt	50	0.21	10.5
Lowes	Hardware	5/16 flat washer	100	0.13	13
Lowes	Hardware	1/4 industry connectors	1	10.96	10.96
Lowes	Hardware	1/4in industry coupler	1	4.18	4.18
Lowes	Tools	bh hwh self drill 10x3/4 50	1	5.98	5.98
Lowes	Tools	1/4in air tool filter	1	17.48	17.48
Lowes	Tools	Tools	1	112.83	112.83
Misc	Misc	Shipping	1	42.72	42.72

Total Spent	$ 4,663.32

External Heater Datasheet

FLEXIBLE HEATERS

ULTRA-HIGH TEMPERATURE HEATING TAPES

STH, SST, SWH Series

- **Maximum Exposure Temperature up to 760°C (1400°F)**
- **Premium Quality**
- **Samox™ Insulated**
- **Integrally Molded Separate Plug**
- **Available with Leads Same End†**

Standard tapes are made from fine gage stranded resistance wires that are double insulated with braided Samox and knitted into flat tapes for maximum flexibility. A heavy insulated tape is made by taking a standard tape and braiding it between layers of Samox yarn. Wide tapes are made from two or more standard tapes that are sewn between two layers of Samox cloth.

SPECIFICATIONS

Heating Elements: 36-40 gage stranded resistance wire
Heating Elements Insulated: Double braided Samox
Dielectric Strength: In excess of 2000V
Lead Wires: Emerge from opposite ends into separate sides of integrally molded separate plug. Maximum temperature for lead wires is 260°C (500°F).

Laboratory: Wide and Heavy Insulated tapes are good for direct contact on conductive surfaces. Do not use standard insulated tapes on a metal or conductive surface.

To Order

Watts	W/in.²	Volts	Size	Heavy Insulated Tapes Model No.	Standard Insulated Tapes Model No.	Total Watts
156	13	120	½" x 2'	STH051-020	SST051-020	160
313	13	120	½" x 4'	STH051-040	SST051-040	310
470	13	120	½" x 6'	STH051-060	SST051-060	470
627	13	120	½" x 8'	STH051-080	SST051-080	620
783	13	240	½" x 10'	STH052-100*	SST052-100*	780
940	13	240	½" x 12'	STH052-120*	SST052-120*	940
313	13	120	1" x 2'	STH101-020	SST101-020	310
627	13	120	1" x 4'	STH101-040	SST101-040	620
940	13	240	1" x 6'	STH102-060*	SST102-060*	940
1245	13	240	1" x 8'	STH102-080*	SST102-080*	1250

Watts	W/in.²	Volts	Size	Wide Heavy Insulated Tapes Model No.
313	7.5	120	1¾" x 2'	SWH171-020
627	7.5	120	1¾" x 4'	SWH171-040
940	7.5	120	1¾" x 6'	SWH171-060
1254	7.5	120	1¾" x 8'	SWH171-080
1570	7.5	240	1¾" x 10'	SWH172-100*
470	7.8	120	2¼" x 2'	SWH251-020
940	7.8	120	2¼" x 4'	SWH251-040
1411	7.8	120	2¼" x 6'	SWH251-060
1881	7.8	120	2¼" x 8'	SWH251-080*
2351	7.8	240	2¼" x 10'	SWH252-100*
627	8.0	120	3¼" x 2'	SWH351-020
1254	8.0	120	3¼" x 4'	SWH351-040
1881	8.0	120	3¼" x 6'	SWH351-060*
2508	8.0	120	3¼" x 8'	SWH351-080*
3135	8.0	240	3¼" x 10'	SWH352-100*

Comes with instruction sheet.

† To order heaters with power leads exiting the same end of the tape, add suffix "-LSE" to model number. Call Sales for prices. To order 240V version change the "1" before the "-" in model number to "2". All 240V versions are supplied without plugs. Call sales for prices.

** Does not come with plug.*

CAUTION AND WARNING!
Fire and electrical shock may result if products are used improperly or installed or used by non-qualified personnel. See inside back cover for additional warning.

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