ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Paper ID #35368

Development of Convective Heat Transfer Experiment for Integration into the Undergraduate Curriculum

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Development of Educational Convective Heat Transfer Experiment for Integration into the Undergraduate Curriculum

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2021 ASEE St. Lawrence Section Annual Conference

ABSTRACT:

Existing commercial educational experiments can be rather expensive. The objective of this paper is to present the development of a low-cost educational convective heat transfer experiment for integration into the undergraduate curriculum. The paper discusses the construction of experimental set-up and assembly using an existing wind tunnel and how to develop the convective heat transfer correlations using non-dimensional parameters for a heated cylinder operating at different electric power outputs (e.g., different temperature) and different velocities. In addition, uncertainty error analysis is demonstrated to teach the accuracy of the developed experimental convective heat transfer correlation as it is compared to the correlation from the textbook. Industrial Failure Modes and Effects Analysis, FMEA, is applied during the development process.

The heating rod was easily removable to permit other experiments to be conducted. With the existing wind tunnel, the overall assembly was low cost, safe and easy to operate.

INTRODUCTION:

The field of heat transfer plays a major role in the design of components within most branches of advanced technologies. Consequently, it is important to have a coverage of the three domains of conduction, convection and radiation heat transfer in the undergraduate curriculum. Convective heat transfer is an intriguing phenomenon and many experimental correlations have been developed by scientists and used by engineers in the field. A good understanding of how to generate the experimental convective heat transfer correlations will provide a stronger educational foundation for the future engineers in the field. This is the purpose of the present paper.

Forced convection is a type of heat transfer in which fluid motion is generated by an external source. Air within a wind tunnel travels at specific velocities allowing for heat to be transferred from a heated rod to the cooler air. Heat transfer and airflow are interrelated, therefore, when airflow is increased, the rate at which heat is transferred also increases. In this experiment, the heat transfer rate from the cylindrical rod to the surrounding air within the wind tunnel can be determined.

Existing commercially available educational experiments are expensive, ranging from $40,000 to $60,000. This paper discusses the development of a low-cost convective heat transfer experiment using an existing wind tunnel within the mechanical engineering laboratory environment. The device must be able to fit inside the wind tunnel and generate heat at a level that is safe for students performing the experiment. In addition, the device should be easily removable to make sure the wind tunnel is available for other fluid flow experiments. Along with the experiment, a lab manual with proper equations and values related to the experiment is developed for students' activity.

Learning Objectives:

- To conduct experiments, use measurement instrumentation and analyze data.
- To develop an understanding of error analysis for analyzing experimental data, as well as, graphical representation of data.
- To develop convective heat transfer correlations.

Outcomes:

- Calculate heat loss due to forced convection from an electric heated cylinder.
- Collect data sheets and demonstrate error analysis.
- Calculations using theoretical concepts and collected data.
- Conclusions from the calculations and data analysis.

CONSTRUCTION OF EXPERIMENT:

This section provides a procedure for the construction of experimental set-up and assembly to develop the convective heat transfer correlation.

Instrumentation and Equipment:

- Wind Tunnel (Armfield C2 Subsonic) (Figure 1)
- Heating Dernord Cartridges: (Length = 10.7″, Diameter = ¾″, Power = 120V) (Figure 3)
- Thermocouples (3 K-Types) attached at 3 different heights providing average temperature. (Figure 4)
- Thermocouple Readout (PerfectPrime TC41, 4-Channel K-Type Digital Thermometer Thermocouple Sensor, (-200 to 1372°C))
- Extech DC Regulated Power Supply (Model #382213)
- Aluminum Plate with heating rod assembly (Figure 2)
- Manual anemometer to measure the flow velocity OR use pressure measurement to calculate the local velocity

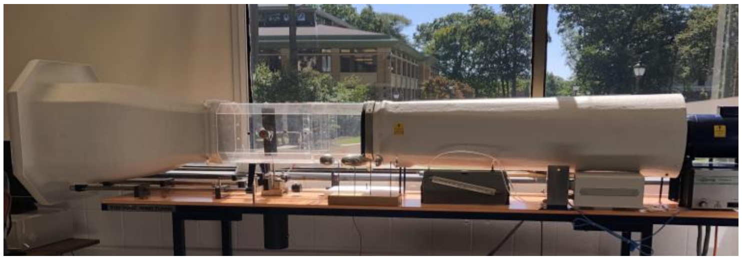

Figure 1 – Wind Tunnel

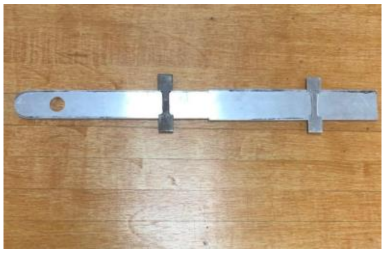

Figure 2 – Fabricated plate to hold the heating rod (through the hole) and fit into the wind tunnel

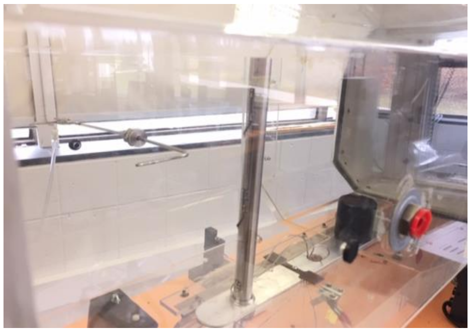

Figure 3 – Heating rod assembly installed inside the wind tunnel

Experimental Development

An electrically heating rod cartridge with slightly shorter length (=10.7″) than the wind tunnel height (=12") was procured. A similar platform to the existing airfoil device was machined to thread in the heating rod. The base of the heating rod is flush with the wind tunnel. The new heating rod-platform assembly fits inside the wind tunnel and is easily replaceable. Three thermocouples in a vertical orientation facing the direction of the flow from the wind tunnel were tack welded. Measuring from the bottom of the heating rod, the vertical alignment of the thermocouples was placed at 0.5", 4.5", 8.75" from the base. The thermocouples provided an average arithmetic mean rod temperature for the calculation. The thermocouple wires routed behind the heating rod to avoid disturbing the upstream flow field. Downstream of the flow from the wind tunnel, a hole was drilled for the thermocouples to be fed through and connected to the thermocouple readout. As the hole was downstream, this did not skew any of the readings from the heating rod because the flow encountering the face of the heating rod remained constant.

The overall cost of this development was estimated as

Heating Rod = $35
Thermocouples (3x) = $110
Power supply = $100
Thermocouple Readout = $35
Anemometer = $20

Total Cost = $300 (without cost of wind tunnel)

Cost of machining of plate assembly and thermocouples tack welding were not included.

Failure Modes and Effects Analysis (FMEA):

Shown in Table 1 below is the Failure Mode Effects Analysis (FMEA) chart for the developed experimental device. This chart illustrates the specific failures the device could experience due to potential internal and external factors. According to the chart, some functions that might fail can be considered inconsequential while others may impact the experiment's ability to function. Each failure consists of three categories: Severity, Occurrence and Control. The Severity of each failure is determined by rating the potential risk the failure produces on a scale of 1-10, with 1 being the least alarming and 10 being the most alarming. The combined ratings of these three categories results in a Risk Priority Number (RPN = Severity x Occurrence x Control), which determines whether necessary action is required. Several different issues were addressed involving all potential failures that could occur during the experiment.

An analysis of each potential failure is discussed as follows:

The first potential issue was the possibility of the power supply failing to produce safe temperatures that could cause damage to the wind tunnel or a member involved with the experiment. The power supply's purpose is to limit the amount of current and voltage that is entering the heating rod. The cause of this failure is due to a student (or teacher) setting the power output too high. To prevent this from occurring, warnings were placed in the laboratory manual notifying students not to exceed a specific voltage (V=20 V). This failure was identified as maximum severity due to the dangers that could occur. If students follow proper procedure, this failure should not occur. If this failure were to occur, mandatory action would be required; i.e., to connect the rod to a variable power supply that limits the power input preventing the rod from getting too hot. Surge control unit can be replaced with a variable power supply.

Assembly or Device Analyzed:		**Heating Rod**							
					RPN			**Total**	
Function	**Failure Mode**	**Effects**	**Cause**	**Control Method**	Severity	Occurrence	Control	**RPN Score**	**Action Plan**
Power supply used to output the maximum temperature of the heating rod (80 – 100C)	Fails to give off safe temps	Can harm the person using it. Can damage the wind tunnel, and TCs	Student sets power supply too high	Place warnings in Lab Manual notifying students not to exceed a certain voltage	10	2	6	120	Connect rod to power supply and limits the power input preventing the rod to stay below 100C
Wind tunnel to deliver steady air flow	Wind tunnel fails to function at a steady velocity	Can result in incorrect measurements for the experiment	Wind tunnel set velocity fluctuates rather than remaining constant	Check the wind tunnel to ensure the inputs are set correctly (velocity)	5	3	3	45	Run diagnostics on wind tunnel to find the problem
Plate that supports the heating rod	Plate collapses / doesn't properly hold the rod / Leaks	Unable to carry out the procedure / Flow Leakage	Loose pegs / unleveled ground / incorrect measurements or assembly	Design and construct a stable support plate	5	1	1	5	Ensure plate is properly secured in wind tunnel
The TCs read the temps of the rod	TCs fail to give reading or gives an inaccurate reading	Will result in faulty or no data	Faulty TCs or poor connections between the thermocouple and the reader	Ensure there is a good connection between TCs and rod, along with connection to the reader	4	3	1	12	Establish good connection for all TCs / TC readout functions properly
The heat given off by the heating rod is from 80-100 C	Heating rod fails to function / turn on	Rod will not heat up	Loss of power supply	Ensure all connections between power supply and necessary experimental equipment are adequate	3	2	1	6	Ensure wires from heating rod are connected to power supply. Ensure power supply is plugged into power outlet / functions properly

Table 1: Failure Mode Effects Analysis for the Experimental Device

(TC: Thermocouple)

The next potential mode of failure is if the wind tunnel fails to maintain a steady velocity. The flow is extremely important when dealing with convection and the calculation of Reynold's number. If the wind tunnel does not maintain a steady flow over the rod, the obtained values would be in errors. This however would be a very rare occurrence. If this does happen though, diagnostics on the tunnel will be run to find the source of the problem and have it repaired.

The third point in the chart discusses the possibility of the heating rod base support plate (Figure 2) assembly not securing or properly functioning as designed with resulting flow leakage. As a result, the students would not be able to proceed with the experiment. The primary cause of this occurrence is due to the supportive attachment, resulting in the plate not securing properly. In order to ensure this doesn't occur, rigid design to hold and secure the assembly into the wind tunnel and construct supportive pegs that can withstand the weight of the overall device. This failure should very rarely occur.

Another possible issue would be if the thermocouples give faulty or no readings. There are multiple ways that this could potentially happen. One of which is if the thermocouples have a poor connection to the rod, allowing for it to read a less accurate temperature. Another way this could happen is if there is a poor connection between the thermocouples and the temperature readout. To prevent this rare occurrence the user needs to ensure good connections to the rod and to the readout to guarantee a valid reading. A uniform temperature reading of all thermocouples at the beginning of each experiment should address this issue.

The last potential possibility is that the power supply fails to function properly to overheat or the connection between the wires and the power supply fails causing the heating rod not to reach expected temperatures. The issue would be that the heating rod could not reach sufficient temperatures to perform the experiment. To prevent this from happening, we must ensure all connections between power supply and necessary experimental equipment are adequate. Due to a reliable power supply and new heating rod, this failure should rarely occur.

STUDENTS' ACTIVITY

The following section describes the activity to be performed by the students. This section can be directly included into the Laboratory Manual. The section on Instrumentation and Equipment plus the Figures from the above are recommended being included for clarity and completeness.

Equipment Setup:

1. Open the wind tunnel – replace the existing aerodynamic airfoil with the electrically heated rod assembly. Make sure the base of the rod is flush with the base of the wind tunnel, as shown in Figure 3. If necessary, place a weight on the opposite end of the

assembly - downstream of heating rod - to balance the weight of the heating rod.

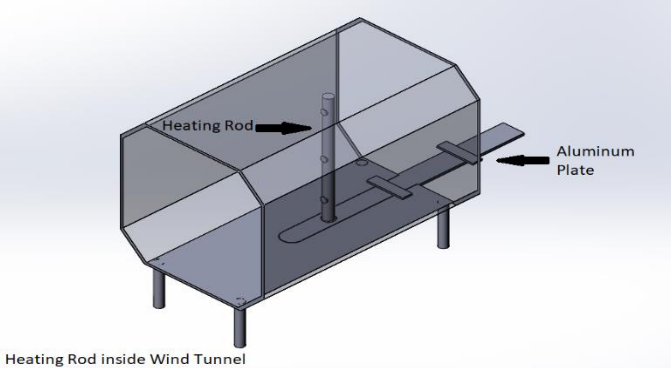

Figure 4 – Schematic of heating rod assembly inside the wind tunnel

2. Use the electrical schematic diagram (Figure 5) for the power supply and thermocouples connections.
3. Ensure that the thermocouple wires are fed through the hole in the plate so they can be attached to the readout.
4. Close the wind tunnel for minimal leakage and air loss.
5. Connect the thermocouple wires to the thermocouple readout.
6. Connect the heating rod to the power supply. Connect the power supply to the power outlet.

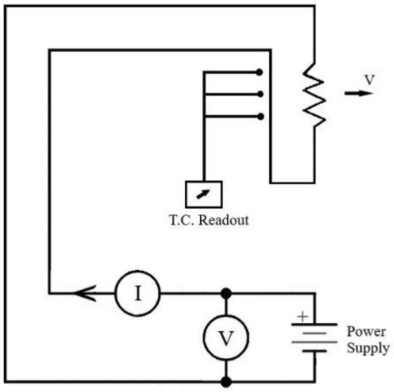

Figure 5 – Schematic of Electric Circuit Diagram

Procedure:

To run this experiment correctly an electrical heating rod was implemented. An electric current running through the element results in the heating of the rod. Through this method, the heating rod is maintained at constant temperature with electrical power at equilibrium with the convective heat loss to the surrounding.

1. Turn on the thermocouple readout and record the ambient temperature, T_∞.

2. Turn on the electric power supply. When setting the voltage, be sure that the current isn't limited.
3. Turn on airflow through the wind tunnel.
4. Set the wind tunnel speed (e.g., 4 m/s using the hand-held anemometer at the wind tunnel exhaust). Record exhaust velocity $U_{exhaust}$ (m/s) using an anemometer.
5. Set power supply voltage to V=16 V. Read the current, I (e.g., 1.2A). Record both V and I.
6. Wait approximately few minutes to allow the heating rod to reach a steady-state temperature. (Expect thermocouples temp. in the range of 80-100^{o} C)
7. Using the thermocouple readout, record the rod surface temperatures at the top, middle and bottom of the rod.
8. Repeat steps 4-7 for a constant current and voltage for $U_{exhaust}$ = 6, 8 and 10 m/s.
9. Repeat steps 4-7 for higher temperature using higher electric power level V= 19 V, I = 1.5 A. to bring the thermocouple temperatures in the range 40-60^{o} C (maintain low temperature for safety and avoid damaging the wind tunnel for exhaust velocity $U_{exhaust}$ = 4 m/s

Note:

- **Do not touch the heating cartridge when turned on. When turning off the power supply, wait a few minutes for the heating cartridge to reach a safe temperature for removal.**
- **Do not operate the wind tunnel above its recommended flow velocity.**
- **You may use a pressure gage to measure the flow velocity.**

Data to be collected:

Rod: Length, L= …… , Diameter, D = ……

Temperatures:

- Free stream room temp T_∞=……. (^{o}C)
- Heating Rod Thermocouples: T_{Top}=…… T_{Middle}= …… T_{Bottom}= ……(^{o}C)

Power Supply: Voltage V= ……. volts and Current I = ……. amps

Exhaust velocity $U_{exhaust}$ = …...m/s

Flow Rate $Q_{exhaust} = A_{exhaust} U_{exhuast}$ where $A_{exhaust}$ (m^2) is the cross sectional area at the exhaust where velocity is being measured. Flow Rate $Q_{exhaust}$ (m^3/s) is different than Heat Generated Q (J/s).

Related Equations:

Average Surface Temp, $T_s = (T_{Top} + T_{Middle} + T_{Bottom})/3$

$Power\ P = VI = Q$

$Heat\ Generated\ Q = h\,A(T_s - T_\infty)$where h is convective heat transfer coefficient and A is heating rod peripheral surface area.

$Nusselt\ number\ Nu = \frac{h\,D}{k}$ where k is air thermal conductivity

$Reynolds\ number\ Re = \frac{\rho U_\infty D}{\mu}$where ρ is air density, μ is air viscosity

$Prandtl\ number\ Pr = \frac{c_p \mu}{k}$ where c_p is specific heat of air

Calculated Data:

- Using T_∞ and your textbook/web calculate the following free stream fluid properties: ρ, μ, k and Pr
- Rod heating surface area A (m^2)= πD*L
- Power, P (Watts) = V*I
- Heat Generated, Q (Watts) = Electric Power, P
- h (W/m^2K) = Q / (πD*L($T_s - T_\infty$))
- Area at exhaust, $A_{exhaust}$ where anemometer is placed and wind tunnel flow cross section area A_∞ where the heating rod is located.
  Fluid velocity at the heating rod $U_\infty = U_{exhaust} * (A_{exhaust} / A_\infty)$
- Calculate $Nu = \frac{hD}{k}$
- Calculate $Re = \frac{\rho U_\infty D}{\mu}$

Typical Graph of Results:

A. Use the above equation to plot Nu vs. Re for two different electric power levels (see circle (red) and triangle (blue) symbols for the experimental data).
B. Use your textbook [1] for heat transfer correlation for a cylinder in cross flow, $Nu_D = 0.19\ Re_D^{0.68}\ Pr^{1/3}$ in the range of $4000 < Re_D < 40000$
    a. Using this equation, plot Nu vs Re (shown black solid line as textbook correlation) using the calculated Pr from above.
C. Change your graph to log-log scale. This will make the correlation a straight line.
D. Draw a straight line through all the experimental data. This line is of the form $Nu = c\ Re^m$
    a. Select two points and read their Nu and Re values from the graph. Using two equations and two unknowns, parameters c and m can be found. (e.g., for the above c = 0.014 and m = 0.968. This creates our proposed experimental heat transfer correlations to be $Nu_D = 0.014\ Re_D^{0.968}$ for Pr = 0.71)

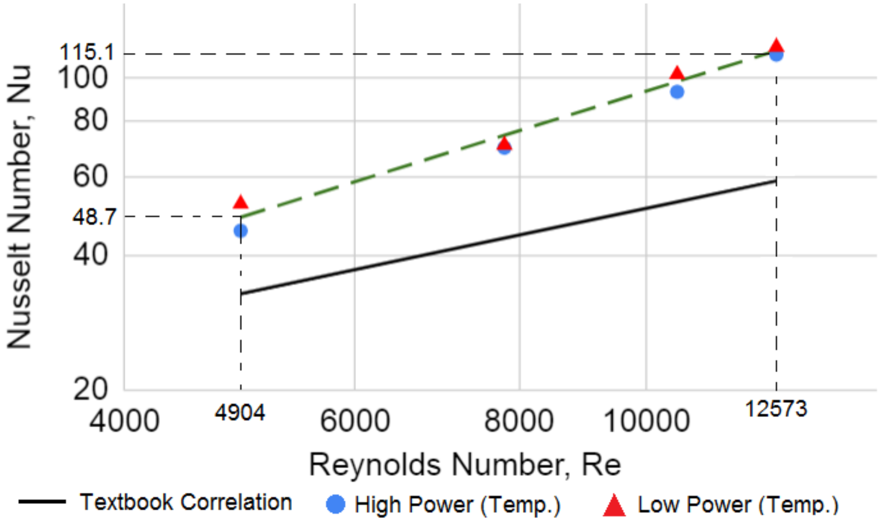

Figure 6: Typical Chart for Nusselt Number versus Reynolds Number

DISCUSSION OF RESULTS:

In this regard, a proposed experimental correlation has been generated (dashed line). Students should be able to discuss the sources of discrepancy between proposed and the textbook (solid line) correlations. The following are possible sources:

- Temperature variations along the rod as well as circumferential.
- Taking into account the Heat loss calculation from the rod end
- Flow velocity variation and calculation

In addition, the students should discuss why a log-log is used in Fig 4.

Uncertainty Error Analysis

The following section provides an error analysis and how to predict the percent uncertainty on each parameter [2]. For instance, if velocity is off by X amount, how accurate are Nusselt and Reynolds Numbers?

Assumptions:

- The test objectives are known and the measurement is a clearly defined process
- We assume a normal distribution of errors and reporting of uncertainties
- Errors are uncorrelated to each other

1. Assume an uncertainty variable for the measurement you are testing.

   Example: velocity reading has an uncertainty of ± 0.5 m/s, what is the uncertainty of Reynolds Number?

2. Take derivative of equations to find uncertainty values

   Re = $\frac{UD}{\upsilon}$

$\delta Re = \frac{dRe}{dU} * \delta U$, δU = the assumed uncertainty variable

Re (uncertainty) = Re $\pm\delta Re$

Re = $\frac{UD}{\upsilon} = \frac{(4.09)(0.01905)}{1.59*10^{-5}} = 4900$

δU = 0.5 m/s

δRe = $\frac{D}{\upsilon} * \delta U \rightarrow$ δRe = $\frac{0.01905}{1.59*10^{-5}} * 0.5 \rightarrow$ δRe = 599

Re = 4900 $\pm$ 599

3. Calculate uncertainties for Nusselt Number
   a. Present Correlation

$$Nu = 0.014Re^{0.968}$$

   b. Uncertainty Analysis

$\delta Nu = \frac{dNu}{dU} * \delta Re$, δRe = the assumed Reynolds Number uncertainty

Nu (uncertainty) = Nu ± δNu

$Nu_{present} = 0.014Re^{0.968} = 0.014(4900)^{0.968} = 52$

δRe = 599 m/s

$\delta Nu_{present} = (0.968)(0.014)Re^{-0.032}*\delta Re \rightarrow \delta Nu_{present} = (0.968)(0.014)(4900)^{-0.032}*599$

$\delta Nu_{present} = 6$

$Nu_{present} = 52 \pm 6$

4. Compare textbook correlation and present correlation to the measured results for Nusselt Number

Questions for Analysis and Conclusion:

1. Graph Reynold's number versus Nusselt number for the results from experiment, textbook correlation, and present correlation.
2. What are the sources of discrepancy (averaging temp from non-uniform heating rod temp, end heat loss, velocity reading …)?

FUTURE WORK:

Taking into account all of the information presented, several additions and/or changes are possible for this project. One addition is to create a similar cylindrical geometry with a different length and/or diameter heating rod. This would allow mechanical engineering students to understand convective heat transfer through a variety of specimens and the benefit of non-dimensional parameters to use a single correlation independent of the size. Another potential addition would be to implement other geometric shapes into the assembly for advanced use. As a result, allowing the students to calculate and analyze more complex geometries such as square, triangular, or elliptical geometries. Finally, the students can install additional thermocouples at other circumferential locations on the heating rod and generate the local circumferential correlation.

CONCLUSION:

A simple educational convective heat transfer experiment was designed and developed for integration into the undergraduate mechanical engineering program. An existing laboratory wind-tunnel (Figure 1) was used by replacing the aerodynamic unit with an electrically heated cylindrical unit. The device was easily removable, safe and easy to follow. The experiment demonstrated how to collect data and derive empirical convective heat transfer with uncertainty error analysis.

ACKNOLEDGEMENTS:

We would also to thank the members of the Hardiman Scholars Program as well as the Earl W. and Hildagunda A. Brinkman Private Charitable Foundation and Bannow-Larson foundation for their financial support.

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