Development of Heat Transfer Laboratory Experiments Utilizing Student Design Teams

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Abstract

Teams of students designed and developed experiments for a new four-credit course in heat transfer at George Fox University as a part of their initial laboratory experience. Over the past three years, students have developed eight experiments that cover a broad range of conduction, convection and radiation phenomena. The new heat transfer course consists of three hours of lecture and one three-hour laboratory per week. Teams which consisted of two students each designed and developed laboratory experiments for this new course at a fraction the cost that it would have taken to purchase similar experiments from an outside vendor. In the process, the students gained useful insights into thermal design methodology and developed a greater appreciation for the fundamentals of heat transfer, than would have been realized by simply performing “canned” experiments. Student design teams prepared a full laboratory handout as well as an operations manual as a part of their laboratory experiment design projects. Teams were given a fixed budget and were required to submit a cost analysis with their final report. Oral and written presentations were required for each of the student teams, along with the satisfactory demonstration of their working experiment. Laboratory experiment details and the design process followed by each student team will be outlined for several of the experiments developed, including: heat conduction in a tapered rod, natural convection in a vertical flat plate, forced air turbulent convection inside a heated tube, overall heat transfer coefficient in a double pipe heat exchanger, film condensation heat transfer coefficient and combined radiation and natural convection of a horizontal cylinder. Rubrics were used to evaluate the student design process, as well as written and oral presentations.

Background and Motivation

George Fox University (GFU) is a liberal arts institution which began a 3:2 dual degree engineering program in 1988. As a result of its successful operation, in the year 2000 GFU began implementing a four year engineering major, which required the development of 21 new engineering courses and hiring three additional faculty members. Currently over 80 students are pursuing a BS degree in engineering with concentrations in either electrical or mechanical engineering at George Fox. Students in the mechanical concentration take five courses dedicated to the thermal sciences, including: Thermodynamics I and II, Fluid Mechanics, Heat Transfer, and a senior elective in Combustion, Emissions and Air Pollution.
The Fundamentals of Heat Transfer (ENGM 380) is a one-semester, four-credit course consisting of three lecture hours and one three-hour laboratory session per week. Students in the mechanical engineering concentration take this course during the spring semester of their junior year. The course content is divided by subject matter emphasized in the following way: 35% conduction, 30% convection, 10% heat exchangers and 25% radiation.

In order to provide the laboratory experiences necessary for this new course, two possible options were considered. The first was to simply purchase turnkey laboratory experiments from various vendors whose products were targeted to the educational marketplace. Although this option was given serious consideration, the cost for obtaining the eight to ten different experimental apparatus necessary to cover the different thermal transport modes would have been somewhere between $80,000 and $200,000. Given the program start-up funds that were available, this was deemed too costly an approach. The other option considered was somewhat of a novel idea: that of using student design teams for the first several years the course was offered and have these teams design, build and test different experimental set-ups for investigating various heat transfer mechanisms. As this option was considered to be both less expensive and also more interesting for the students involved, it was employed.

The objectives to be realized by utilizing the student design teams for laboratory experiment development, were: (1) student teams design, develop and construct a laboratory experiment, (2) student teams must demonstrate successful operation of the laboratory apparatus, (3) student teams prepare a written report outlining their design experience, detailing equipment purchased and technical set-up and operation requirements for the experiment, and (4) student teams make an oral presentation detailing their design experience and experimental results to the class and submit a written lab report handout which will be used by future students for the purpose of conducting the experiment.

**Lab Experiment Design Process**

The new heat transfer course was structured with three one-hour lectures and one three-hour laboratory session per week for fourteen weeks (one semester). During the first year this new course was offered, students used all of the laboratory sessions as times for design review meetings with the course instructor to discuss their design progress and to set weekly objectives, as well as work times for project development and construction purposes. Student teams used the final lab session for making their oral presentations to the class. Three experiments were built by this first class. The second year this course was offered, students performed the three lab experiments developed by the prior year’s student teams (e.g. had three traditional three-hour lab experiments to perform), and used the remaining lab times for working in teams on developing their own lab experiments. After using this model for two years, six heat transfer experiments were available for students to perform as traditional three-hour laboratory experiments, and the remaining lab sessions were used to develop their own lab experiments. After using this model for three years, GFU now has eight experimental lab set-ups with written lab handouts which are available for use as traditional lab experiments for next year’s class. It is anticipated that this process will be used for one more year so that a total of eleven or twelve different heat transfer lab experiments will be available for classes to perform on a traditional basis.
three-hour basis in the future. The progression of lab experiment development and implementation are shown in Table 1.

Table 1. Progression of Lab Experiment Development and Implementation

<table>
<thead>
<tr>
<th>Year</th>
<th>Traditional 3-Hour Labs</th>
<th>Lab Development Work Sessions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>2004</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>2005</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>2006*</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>2007*</td>
<td>11 or 12</td>
<td>0</td>
</tr>
</tbody>
</table>

*Projected

The first two times this course was offered there were six students enrolled, the third time it was offered only five students were in it. These small initial class sizes permitted ample one-on-one meeting sessions between the course instructor and the student design teams. The teams typically had two members and the procedure used to develop the specific team composition was based on student interest in the lab topics suggested by the instructor at the beginning of the course. Throughout the semester, the course instructor met with each team individually for about one hour per week during the regularly scheduled lab session, at which time the student team members reported on their weekly progress and asked questions concerning their future design ideas and direction, materials purchasing decisions and machine shop requirements were also discussed. At the end of each weekly meeting, a new set of goals were agreed upon by student team members and the course instructor - to be achieved during the following week.

The design criteria for each of these laboratory experiments were: (1) to successfully demonstrate the objective of the lab, (2) cost for all parts and materials limited to $500.00, (3) lab apparatus must be user-friendly, (4) consideration given to future maintenance of the apparatus (e.g. repairability, reparability/durability), (5) ensure safe operation, and (6) be aesthetically pleasing (have professional appearance). Several labs utilized equipment which already existed (e.g. power supplies, manometers, multi-meters, etc.) and these costs were not included in the $500.00 budget. Also, inter-team coordination was employed on several occasions, such that some teams designed their apparatus with the needs of other teams in mind, so that a couple different teams could plan to share a given signal conditioning unit, flow metering device, or digital display (and thus cost-share the purchase price of the instrument and keep within their respective budgets).

Lab Experiments Developed

The lab experiments which were developed by student design teams include the following: one-dimensional conduction heat transfer in a tapered rod, forced convection heat transfer inside a heated tube, natural convection heat transfer from a vertical flat plate, overall heat transfer coefficient in a double pipe heat exchanger, film condensation heat transfer from a horizontal tube, and combined thermal radiation and natural convection from horizontal pipe surfaces. For each of these lab designs, the course instructor assisted the teams by providing the lab design
objective and a general presentation of the necessary theory to be employed, as well as those measurements which needed to be obtained experimentally in order to compare the experimental results with the thermal transport phenomena being demonstrated. A brief presentation will be made for several of the aforementioned student lab designs, including the lab objective, an abbreviated description of the procedure/theory, a diagram of the apparatus and a sample of the results obtained after conducting the experiment in Appendix 2.

Assessment and Student Feedback

Students were evaluated during the oral presentation of their lab design projects by the course instructor, as well as a group of other departmental faculty and several members of the Industrial Advisory Board using a standard set of rubric forms (maximum score of 30 points). The written documents submitted by teams (maximum score of 36 points), as well as an evaluation of the team’s design process (maximum score of 30 points) were evaluated by the course instructor, also using a set of standard rubric forms. The project grade was determined for each team in the following way:

\[
\text{Oral} \times \frac{20}{30} + \text{Written} \times \frac{30}{36} + \text{Process} \times \frac{50}{30} = \text{Project Total}
\]

The project grade for each individual team member was obtained by modifying the project total score as calculated above, by a factor derived from the self-assessment data received on the team evaluation rubric form, where among other questions, student team members were asked to rate the individual performance of themselves and their other team members contribution to the project. A copy of this Team Evaluation Rubric form is included in Appendix 1. The results of student responses obtained using this tool were averaged and are included in figure 1 (note that scores may range from 1 to 8, - indicated on the team evaluation rubric form). As shown, students assessed their team experiences in designing and developing heat transfer laboratory experiments as having been very effective. Students’ written and oral comments indicated that the design experience was very rewarding.

Concluding Remarks

After three years of using student teams to design and develop heat transfer laboratory experiments, eight new experiments have been completed and successfully implemented into the course laboratory curriculum. Experiments cover a broad range of thermal transport phenomena and their development by design teams allowed students the chance to experience the thermal design process, as well as to perform a useful service to the growing engineering department of George Fox University, by creating laboratory experiments at a fraction of their actual purchase cost. This model for lab development will be implemented for one additional year, after which a total of eleven or twelve different lab experiments will be available for future students to use in the laboratory component of ENGM 380, the newly developed heat transfer class.
Figure 1  Results of team scoring rubric forms used to assess student team effectiveness

References


Biographical Information

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Robert F. Harder is Professor of Mechanical Engineering and Chair of the Mathematics, Computer Science and Engineering Department at George Fox University. He teaches in the area of thermal engineering including thermodynamics, heat transfer, fluid mechanics and combustion. Dr. Harder has research interests in tribology, tribo-energetics (conjugate problems which involve heat transfer, wear and material phase transformation), electronic cooling and novel combustion methods. He received his B.S. in 1982 and M.S. in 1986 both in mechanical engineering from Michigan Technological University, and his Ph.D. in 1995, in materials science and engineering from the Oregon Graduate Institute of Science and Technology.
Appendix 1

Team Evaluation Rubric

Course Number and Title: ENGM 380 Fundamentals of Heat Transfer

Project Title: _____________________________________________________________

Your Name:___________________________________________Date:___________________

Directions: For each of the items below, circle the number that best represents your evaluation of your team’s effectiveness. Please put any comments about experience on the back.

1. Time Management:
   1 2 3 4 5 6 7 8
   Much time spent without purpose Got off track frequently Did well once we got our ideas clear No wasted effort without purpose frequently got our ideas clear stayed on target

2. Creativity:
   1 2 3 4 5 6 7 8
   Little done to generate ideas Ideas were imposed on by a few Friendly session but not creative Ideas were encouraged and fully explored

3. Decision Making:
   1 2 3 4 5 6 7 8
   Poor resolution of difference Let one person rule Made compromises to get the job done Genuine agreement and support

4. Productivity:
   1 2 3 4 5 6 7 8
   Did not accomplish our goal Barely accomplished the job Just did what we had to do Highly productive session

Team members were: (include your name also)

Opinion of individual contributions for this team project. (Allocate 100 points to your team members (include yourself). Base allocation on your opinion of individual performance

1. ____________________________________________________________
2. ____________________________________________________________
3. ____________________________________________________________
Appendix 2

Several of the labs designed and built by engineering student design teams in ENGM 380 Fundamentals of Heat Transfer at George Fox University are included on the following pages.

(1) One-dimensional conduction heat transfer in a tapered rod

Lab Objective: Experimentally determine the steady state temperature distribution in a tapered bar, and compare it with analytical predictions (this can also be done for a transient analysis)

Lab Apparatus:
1. Cartridge Heater Wires        2. Thermocouple Switch         3. Ice Point

Assumptions:

- 1-dimensional conduction (axial)
- Steady state conditions
- Negligible convection from the peripheral surface
- Constant properties
- No generation

Analysis:

Determine analytical temperatures for the 8 locations. Use $T_3$ from the experimental values as a boundary condition. Calculate the dimensionless temperature distribution for experimental and analytical temperatures, where:

$$\theta_x = \frac{T_x - T_{10}}{T_3 - T_{10}}$$

and:

$$T_x = \frac{-q}{k\pi} \left[ \frac{1}{0.001083 - 0.002381x} \right] + \frac{q}{k\pi(0.001083)} + T_3$$

Procedure:

1.) Connect water entrance tube to faucet and water exit tube to drain, and then turn on cold water (may need to adjust water valves in order to insure flow rate is the same). Turn on ice point and connect thermocouple connection to voltmeter. Connect cartridge heater to power supply and apply no more than 70 watts and 120 volts

2.) Take mV readings at locations 3-10 and then find corresponding temperature values from type K thermocouple correlations.

3.) Turn off power and water, and drain tubes. Once the bar has reached steady state, thermocouple outputs are read for the insulated portion of the bar.

These temperatures are then cast into a dimensionless form, and plotted against dimensionless distance $x/L$. 
Sample Results:

Figure 1 Temperature profile comparison

Comments: This lab can also be used for transient analysis of 1-D conduction heat transfer with a variable cross-sectional area.
(2) Forced convection heat transfer inside a heated tube

**Lab Objective:** The purpose of this lab is to determine the local forced convection heat transfer coefficient in a tube subjected to a uniform heat flux both experimentally and analytically.

**Lab Apparatus:** The apparatus consists of a stainless steel tube connected to a source of variable voltage supply. The tube is supplied with air from the building air supply. There are eight thermocouples. Thermocouple 1 is located in a mixing chamber at the exit of the tube and measures the temperature of air at exit. Thermocouples 2 through 7 measure the surface temperatures of the tube at 6 different locations as indicated. The final thermocouple, number 8, measures the temperature of the air at the inlet. Note that thermocouple 7 is located at a distance of 1 inch from the start of the heated tube.

The nozzle at the exit measures the mass rate of flow by using a manometer to measure the pressure difference $P_A - P_{atm}$. Then the equations derived above for steady, frictionless, incompressible flow are used to relate the condition at A (in white PVC mixing chamber) to those at B (exiting the known diameter nozzle to atmosphere at left).

![Lab apparatus - blue wires clamped to opposite ends of stainless steel tube connect to power supply giving uniform wall heat flux condition, air flow enters on right side](image)

**Analysis:**

For a system to be operating in the turbulent regime the flow needs to be great enough for $Re_D > 2300$.

For a circular tube:

$$Re_D = \frac{4\dot{m}}{\pi D \mu}$$

Therefore, in order for $Re_D > 2300$, the mass flow rate needs to be:

$$\dot{m} = \frac{2300 \pi D \mu}{4}$$

By definition the mass flow mate is:

$$\dot{m} = \rho A_b V_B$$

Therefore the velocity can be expressed as:

*Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition*  
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Experimental Approach:
Knowing this required velocity, the pressure drop that will provide such a velocity needs to be evaluated.

For steady, frictionless, incompressible flow Bernoulli’s equation simplifies to:

\[ \frac{P_A}{\rho} + \frac{V_A^2}{2} = \frac{P_B}{\rho} + \frac{V_B^2}{2} \]

From conservation of mass

\[ \rho A_A V_A = \rho A_B V_B \]

Combining these relations:

\[ \Delta P = (P_A - P_B) = \frac{\rho}{2} (V_B^2 - V_A^2) \]

Substituting \( V_B \) for \( V_A \), the equation reduces to:

\[ \Delta P = \frac{\rho}{2} \left( V_B^2 - \left( \frac{A_B}{A_A} \right)^2 \right) = \frac{\rho V_B^2}{2} \left( 1 - \left( \frac{A_B}{A_A} \right)^2 \right) \]

Since: \( \left( \frac{A_B}{A_A} \right)^2 \approx 10^{-5} \approx 0 \):

\[ \Delta P = \frac{\rho V_B^2}{2} \]

From manometry:

\[ \Delta P = \rho_{\text{fluid}} g \Delta h \]

therefore:

\[ \Delta h = \frac{\Delta P}{\rho_{\text{fluid}} g} \]

Thus an expression for the change in height of manometer fluid as a function of \( \text{Re}_D \) may be obtained:

\[ \Delta h = \frac{\left[ \frac{\text{Re}_D \pi D_{\text{tube}} \mu}{a A_B} \right]^2}{2 \rho_{\text{fluid}} \rho_{\text{air}} g} \]
Now the forced convection heat transfer coefficient must be determined.

From Ohmic heating:

\[ q = P = VI \]

\[ q'' = \frac{q}{A_s} = \frac{VI}{A_s} \]

Also, if \( q'' \) is assumed to be constant and uniform:

\[ q'' = h \left( T_{i,x} - T_{m,x} \right) \]

where:

- \( T_{i,x} \) = temperature via thermocouple location
- \( T_{m,x} \) = mean temperature

Therefore:

\[ h_x = \frac{q''}{(T_{i,x} - T_{m,x})} = \frac{VI}{A_s(T_{i,x} - T_{m,x})} \]

The mean air temperature as a function of position \( x \) must be determined. For a constant heat flux:

\[ \frac{dT_m}{dx} = \frac{q''_s P}{\dot{m}c_p} = \frac{Ph}{\dot{m}c_p}(T_s - T_m) \]

note that \( q_{\text{conv}} \) is independent of \( x \).

Integrating of a pipe from \( x = 0 \) to \( x \):

\[ \int_0^x dT_m = \int_0^x \frac{q''_s P}{\dot{m}c_p} dx \]

\[ T_m(x) - T_m(\text{in}) = \frac{q''_s P x}{\dot{m}c_p} - 0 \]

\[ T_m(x) = T_{m,\text{in}} + \frac{q''_s P x}{\dot{m}c_p} \]

Therefore the mean temperature of the air at each \( x \) location may be obtained by using the above equation.

Now the local Nusselt number can be determined for each \( x \) location using:

\[ Nu_x = \frac{h_x D}{k} \]

**Analytical Approach:**

For each flow rate a corresponding Nusselt number can be found using the correlation:
\[ \bar{Nu}_L = 0.023 \Pr^{0.4} \Re_D^{(4/5)} \]

**Procedure:**

1) Adjust the mass flow rate of the air to give \( \Re_D > 2300 \) to ensure that the system is operating in the turbulent regime.
2) Adjust the current (not to exceed 25 amps) to give a reasonable temperature of the tube surface.
3) Measure all temperatures indicated by the thermocouples and the electrical power input.
4) Determine local heat transfer coefficients for both the developing region and the fully developed region.
5) Determine the local Nusselt number and find the average Nusselt number for the flow rate.
6) Repeat for three other flow rates.
7) Calculate the Nusselt number using the correlation given for each flow rate.
8) Plot \( \bar{Nu}_L, \ Nu_x, \text{ and } \ Nu_{ave} \) versus \( \Re_D \)

**Sample Results:**

![Graph of local Nusselt number](image_url)

**Figure 2** Variation of local Nusselt number along the tube computed experimentally
Figure 3: Comparison of experimental and analytical Nusselt numbers for experiment.

Comments: Students from the second class who did this lab in the traditional fashion, realized that an assumption which was made originally, that of all wall heat flux going into the forced air flow within the tube, was incorrect. They showed with further analysis, that by insulating the exterior tube wall it would be possible to minimize the errors which resulted for higher flow rates and for locations farther away from the air flow entrance.
(3) Natural convection heat transfer from a vertical flat plate

**Lab Objective:** To measure the steady state one dimensional temperature distribution in a vertical plate exposed to atmospheric air, with one end maintained at a constant temperature.

**Lab Apparatus:** One end of a steel plate is welded to a pipe through which heat is conducted from the condensation of steam inside the pipe. Three sets of thermocouples are mounted on the plate in vertical rows, distributed evenly along the length. These thermocouples are to measure the temperature distribution in the plate. Two additional thermocouples measure the mean temperature of the base pipe, and the temperature of the ambient air.

![Figure 1 Vertical plate with condensing steam boundary condition on left and infinite tip](image)

**Analysis:** It is assumed that the plate is long enough to where the tip is at ambient air conditions. The correlation used to find the convection coefficient was

\[ h = N_u \frac{k}{L} \]

The Nusselt number is needed to find \( h \), but in order to find Nusselt, the Raleigh number is required. The Raleigh number can be found by

\[ Ra = Gr Pr = \frac{g \beta(T_s - T_8)L^3}{\nu \alpha} \]
where $\alpha$, $v$ and $\beta$ are found in standard material properties tables at the film temperature and $g$ is the acceleration due to gravity. Once the Raleigh number is calculated, it was found to fit within the correlation of $0 < Ra < 10^9$. Therefore the following equation can be used:

$$\text{Nu} = 0.68 + 0.67 \frac{Ra^{1/4}}{[1 + (0.492 / \text{Pr})^{9/16}]^{4/9}}$$

Having the Nusselt number allows the calculation of the convection coefficient $h$, by the original equation. Finally, the $h$ can be put into the equation

$$\theta(x) = \exp\left(-\frac{hx^2}{kA}\right)^{1/2}$$

where: $\theta(x) = \frac{(T(x) - T_8)}{(T_b - T_8)}$

$T_8$ is the temperature of the ambient air, and $T_b$ is the temperature of the plate base. $T(x)$ is the temperature at the prescribed distance $x$, from the base of the plate, and is the desired value.

Sample Results:

![Figure 2 Horizontal temperature profile of vertical plate](image)

Figure 2 Horizontal temperature profile of vertical plate
(4) Overall heat transfer coefficient in a double pipe heat exchanger

Lab Objective: To determine and compare the overall heat transfer coefficient in a double pipe, single-pass, counter-flow heat exchanger both experimentally and analytically.

Lab Apparatus: A single-pass counter-flow exchanger consists of two concentric straight pipes each containing a flowing fluid, the two flows entering at opposite ends of the pipe. In this case, water is used for both flows, hot water in the center pipe, and cold water in the annulus between the pipes.

![Figure 1 Counter-Flow Heat Exchanger cross section](image1)

The inner pipe is made of copper, which very efficiently transfers heat between the two flows. The outer pipe, however, does not need to conduct well. In fact, in an experimental setting, it is beneficial to stop any heat transfer to the surroundings in order to more accurately calculate the heat transfer coefficient between only the fluids in the pipe.

![Figure 2 Complete heat exchanger](image2)

Analysis:

By definition:

$$q = UA_s \Delta T_{lm}$$

Where:

- $U \equiv$ Overall Heat Transfer Coefficient
- $\Delta T_{lm} \equiv$ Log-Mean Temperature Difference
- $A_s \equiv$ Average Surface Area Between Fluid Flows
Thus, knowing $T_{lm}$ and $A_s$, we must find $q$ in order to determine $U$. So we use the following equation, which is valid for any type of heat exchanger:

$$q = \dot{m}_h c_{p,h} (T_{h,i} - T_{h,o}) = \dot{m}_c c_{p,c} (T_{c,o} - T_{c,i})$$

Where each $c_p$ is evaluated at a respective mean temperature: $T_m = \frac{T_i - T_o}{2}$

However, since in an experimental setting, this equality is not exact due to various experimental errors, we will find both values of $q$ and average them together.

$$q_1 = \dot{m}_h c_{p,h} (T_{h,i} - T_{h,o})$$
$$q_2 = \dot{m}_c c_{p,c} (T_{c,o} - T_{c,i})$$

$\Rightarrow$ $q_{ave} = \frac{q_1 + q_2}{2}$

Using average heat transfer rate ($q$) and area the overall heat transfer coefficient may be evaluated as:

$$U = \frac{q}{A_s \Delta T_{lm}}$$

Where the log mean temperature difference is for a counter flow heat exchanger is:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln (\Delta T_1 / \Delta T_2)} = \frac{(T_{hot,in} - T_{cold,out}) - (T_{hot,out} - T_{cold,in})}{\ln \left( \frac{T_{hot,in} - T_{cold,out}}{T_{hot,out} - T_{cold,in}} \right)}$$

And remembering that $A_s$ is and average surface area for the inner pipe:

$$A_s = \pi \cdot d_{ava} L = \pi \left( \frac{d_i + d_o}{2} \right) L \quad \text{Where:} \quad \left\{ \begin{array}{l} d_i = .0146m \\ d_o = .0158m \\ L = 1.864m \\ D_o = .029m \end{array} \right.$$  

In order to determine an overall heat transfer coefficient analytically, we must first know the convective coefficient for flow in the annulus between the two cylinders. To explain:

Recall by the definition of heat transfer coefficient:

$$U = \frac{1}{R_{TOT} A} \quad \Rightarrow \quad R_{TOT} = \frac{1}{h_i A} + \frac{1}{h_o A} \quad \Rightarrow \quad U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}} \quad \Rightarrow \quad U^{-1} = \frac{1}{h_i} + \frac{1}{h_o}$$

Where:

$h_i \equiv$ conv. coeff. for the hot fluid flow
$h_o \equiv$ conv. coeff. for the cold fluid flow

So we must find $h_i$ and $h_o$. To do this, we recall that $h$ is related directly to the Nusselt Number of a given flow.
\[ \text{\textit{Nu}_D} = \frac{hD}{k_f} \quad \Rightarrow \quad h = \frac{\text{\textit{Nu}_D}k_f}{D} \]

And Nusselt number can be found using the Dittus-Boelter Equation as follows:

\[ \overline{\text{\textit{Nu}}}_D = 0.023 \left( \frac{Re}{D} \right)^{0.4} \text{Pr}^\alpha \quad \text{Where: } \alpha = \begin{cases} 0.3, & \text{For Cooling} \\ 0.4, & \text{For Heating} \end{cases} \]

It must be remembered, however, that the Dittus-Boelter equation is only applicable for situations in which there is fully developed turbulent flow. So we recall the approximation of \( Re_D \geq 10^4 \) for ensuring turbulent flow. It is critical to check that each flow is turbulent. To do this, use the equation:

\[ Re_D = \frac{4\dot{m}}{\pi D \mu} \quad \text{for flow in a circular pipe.} \]

For this application:

\[ Re_{D,h} = \left( \frac{4\dot{m}}{\pi d_i \mu_{h}} \right)_{\text{hot}} \quad \text{Re}_{D,c} = \left( \frac{4\dot{m}}{\pi D_H \mu_{c}} \right)_{\text{cold}} \]

\( D_H \) is the hydraulic diameter defined as: \( D_H = D_o - d_i \)

Where \( \mu \) is evaluated at \( T_{lm} \):

\[ T_{lm,hot} = \frac{(T_{\text{hot,in}} - T_{\text{hot,out}})}{\ln\left(\frac{T_{\text{hot,in}}}{T_{\text{hot,out}}}\right)} \quad T_{lm,hot} = \frac{(T_{\text{cold,in}} - T_{\text{cold,out}})}{\ln\left(\frac{T_{\text{cold,in}}}{T_{\text{cold,out}}}\right)} \]

Therefore in order to satisfy the turbulent condition the mass flow rate must be:

\[ \dot{m}_h = \frac{2300 \pi \cdot d_i \mu}{4} \quad \dot{m}_c = \frac{2300 \pi \cdot D_H \mu_c}{4} \]

If however, \( Re_D \) is not fully developed another Nusselt number relationship, called the Gnielinski method must be used:

\[ \text{\textit{Nu}}_D = \frac{(f/8)(Re_D - 1000) \text{Pr}}{1 + 12.7(f/8)^{1/2}(\text{Pr}^{5/3} - 1)} \quad \text{Where: } \begin{cases} 0.5 < \text{Pr} < 2000 \\ 3000 < Re_D < 5 \times 10^6 \end{cases} \]

Remember: All properties for both Nusselt number equations are found at \( T_{lm} \).

Also, \( f \) is defined as the moody friction factor found using figure 8.3 in Fundamentals of Heat and Mass Transfer, Fifth Edition. This can be avoided however if a smooth tube surface is assumed. Both copper and PVC have a very low roughness and are both virtually smooth so this assumption can be made. The friction factor equations are:
\[ f = 0.316 \text{Re}_{D}^{-1/4} \quad \text{Re}_{D} \leq 2 \cdot 10^4 \]
\[ f = 0.184 \text{Re}_{D}^{-1/5} \quad \text{Re}_{D} \geq 2 \cdot 10^4 \]

Now individually, \( h_i \) and \( h_o \) must be found. For each case, use properties found at the film temperature for that flow. It should be noted, however, that for the case of the outer annulus, the hydraulic diameter is required:

\[ D_H = D_o - d_i \]

Finally, having values for both \( h_i \) and \( h_o \), we can find \( U_{\text{analytical}} \):

\[
U_{\text{analytical}}^{-1} = \left( \frac{1}{h_i} + \frac{1}{h_o} \right)_{\text{analytical}}
\]

Procedure:

1.) Turn on temperature bath, set temperature to 40°C and flow rate appropriate to ensure turbulence.
2.) Turn on cold water from faucet adjust flow rate to ensure turbulent flow.
3.) Record mass flow rate for hot and cold tubes once flow is steady.
4.) Wait for steady state, when achieved record temperature values from thermocouples.
5.) Repeat for five different cold water flow rates.

Sample Results:
(5) Film condensation heat transfer from a horizontal tube

Lab Objective: For a system consisting of a copper tube with internally flowing cold water and steam condensation on the outer surface, determine the overall heat transfer coefficient both analytically and experimentally for the system.

Lab Apparatus:

Figure 1 Condensation heat transfer lab experiment

Analysis: In simplified form the system presented in this lab experiences two methods of heat transfer. One is the internal convection due to the cold water flowing through the copper pipe. The other is the film condensation due to the steam atmosphere surrounding the pipe. Once at steady state, it is found through an energy balance that all the heat that enters the copper tube from the condensate leaves the copper tube to the flowing water. Mathematically:

\[ h_o \left(T_{\text{steam}} - T_{\text{wall}}\right) = h_i \left(T_{\text{wall}} - T_{\text{bulk}}\right) \]  

(1)

where:

\[ T_{\text{bulk}} = \frac{T_{\text{inlet}} + T_{\text{exit}}}{2} \]  

(2)

and:

\[ h_o = \text{film condensation coefficient} \]

\[ h_i = \text{internal flow convection coefficient} \]
Equation (1) is useful, but cannot stand alone. First, to find $h_i$, the Reynolds number must be obtained. If certain properties, which may be functions of $T_{\text{bulk}}$, are known about the internal flow then the Reynolds number can be found as:

$$Re_D = \frac{\rho V D}{\mu} = \frac{Q \rho D}{\mu A} = \frac{4Q \rho}{\pi \mu D_i}$$  \hspace{1cm} (3)$$

In this case, both the density and the viscosity are dependent on the value of $T_{\text{bulk}}$. The volumetric flow rate $Q$ will be given directly from a flow meter mounted on the apparatus. With the Reynolds number a Nusselt number for internal flow can now be calculated provided that the Prandtl number for water at $T_{\text{bulk}}$ has been obtained. The following equation was best suited for this experiment and states:

$$Nu_D = \frac{\left(\frac{f}{8}\right)(Re_D - 1000) \Pr}{1 + 12.7 \left(\frac{f}{8}\right) \left(\Pr^{2/3} - 1\right)} = \frac{h_{\text{water}} D_i}{k_{\text{water}}}$$  \hspace{1cm} (4)$$

where:

$$f = \text{friction factor from the Moody Chart}$$

or:

$$f_{\text{smooth}} = (0.79 \ln(Re_D) - 1.64)^2$$  \hspace{1cm} (5)$$

Both equations (4) and (5) require a Reynolds number between 3000 and 5 million. Notice that $h_i = h_{\text{water}}$ which can be solved for simply by rearranging terms.

Secondly, an expression for $h_o$ is needed. From an analysis performed on a horizontal tube with external laminar film condensation it is found that the average heat transfer coefficient is:

$$h_o = 0.729 \left[ \frac{\rho_{\text{water}} (\rho_{\text{water}} - \rho_{\text{steam}}) g h_{fg} }{D \mu_{\text{water}} (T_{\text{steam}} - T_{\text{wall}})} \right]^{1/4}$$  \hspace{1cm} (6)$$

where:

$$h_{fg} = h_{fg} + \frac{3}{8} c_{p_{\text{water}}} (T_{\text{steam}} - T_{\text{wall}})$$  \hspace{1cm} (7)$$

The water properties are all functions of the steam temperature. Notice that $T_{\text{wall}}$ is not given, but must be approximated to solve equation (6) and (7). After calculating a value for $h_o$ it is possible to rearrange equation (1) and resolve for $T_{\text{wall}}$ in the following fashion:

$$T_{\text{wall}} = \frac{h_i T_{\text{bulk}} + h_o T_{\text{steam}}}{h_i + h_o}$$  \hspace{1cm} (9)$$
This yields a new approximation for the copper surface temperature which can then be used to find corrected water properties and then a new condensation coefficient \( h_o \). Several iterations of this process would prove to be enough to converge upon an acceptable \( h_o \) value.

Now the analytical value of the overall heat transfer coefficient can be obtained simply from:

\[
\frac{1}{U_{th}} = \frac{1}{h_i} + \frac{1}{h_o} \quad (10)
\]

An experimental value of the overall heat transfer coefficient can be found with relative simplicity using the following relationship:

\[
(T_{steam} - T_{water})_{exit} = (T_{steam} - T_{water})_{inlet} e^{-\frac{UA}{mc_p}} \quad (11)
\]

If equation (11) were to be rearranged to solve for \( U \), then it would appear in the following form:

\[
U_{exp} = \left[ \frac{mc_p \ln \left( \frac{T_{steam} - T_{water, exit}}{T_{steam} - T_{water, inlet}} \right)}{A_s} \right] \quad (12)
\]

Now the analytical and experimental values of the overall coefficient can be compared and possible reasons for error can be discussed. Note that equation (6) is used assuming that condensation occurs evenly over the surface of the tube. This assumption is necessary for simplicity, but the results may be questionable.

**Procedure:** The cold water source enters at the left end of the chamber where it passes thermocouple #1. It exits the chamber, passes around the back through a flow meter and then a regulation valve. If the constant temperature bath is used, then the return water will be routed back through the bath. Consult the technical manual for more information on the constant temperature bath. If the sink faucet is the chosen source then the return water is drained in the sink.

**Step 1:** Connect both the thermocouple display meter and the flow display meter to the apparatus. For instructions and setup information concerning either meter display, consult the technical manual.
Step 2: Connect the steam generator via small flexible tubes to both ends of the chamber. Flip the power switch and make sure the generator selector knob is pointing to ‘high.’

Note: Before each trial refill the steam generator to ¾ full to ensure that it will not run dry before the system reaches steady state.

Step 3: Once the chamber fills with steam, allow water to flow though the copper tube at a pre-selected rate. Remember that three trials will be performed each at different flow rates.

Note: Make sure to keep the volumetric flow rate between 0.28 - 2.4 gal/min (1 - 9 L/min) as required by the turbine flow meter.

Step 4: As soon as the average steam temperature (thermocouples #1 – #3) and the exit water temperature (thermocouple #2) reaches steady state, record the temperature of the inlet and exit temperature and also the water flow rate.

Step 5: Check the steam generator’s water level and then change the flow rate for the next trial.

Note: It may be useful to confirm the accuracy of the flow meter by using another measurement method. It is likely to have some deviation of the flow meter measurement at higher flow values.

Step 6: Once all necessary values have been obtained, turn off the water and the steam generator.

Comments: The results from this lab were not very good and the experiment is currently under investigation for possible sources of error or incorrect assumptions and/or analysis.