Session T4B4

Laboratory/Demonstration Experiments in Heat Transfer: Laminar and Turbulent Forced Convection Inside Tubes

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Abstract

Laboratory exercises or demonstrations which are designed to compare experimental data with literature correlations are excellent methods for reinforcing course content. As part of the requirements for CHEG 3143, Heat Transport, and CHEG 3232, Laboratory II, junior level chemical engineering students were required to (1) perform simple heat transfer experiments using inexpensive materials that are readily available in most engineering departments and (2) compare the experimental results with literature correlations. The design, implementation and analysis of two of these experiments are described in this presentation.

Laminar flow heat transfer coefficients were measured for the flow of ethylene glycol through 11 ft x 3/16 in i.d. coiled copper tubing by heating the coil in an agitated water bath at about 150ºF. The temperature of the exiting ethylene glycol was recorded as a function of flow rate and was used to determine the duty of the copper coil and the experimental heat transfer coefficient. Finally, the experimental results were compared to results from the Seider-Tate equation.

Similarly, turbulent flow heat transfer coefficients were measured for the flow of air through an 18 in x ¼ in i.d. copper tube as the air was heated by immersing the tube into an agitated water bath at about 140°F. As in the laminar flow experiments, the temperature of the exiting air was recorded as a function of flow rate and was used to detemine the duty and the experimental heat transfer coefficient. Finally, the experimental results were compared to results from the Dittus-Boelter equation.

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Introduction

A number of papers have been written recently on methods for improving or supplementing the teaching of heat transfer including the use of spreadsheets to solve two-dimensional heat transfer problems[1], a new transport approach to teaching turbulent thermal convection[2], the use of computers to evaluate view factors in thermal radiation[3], and a new computational method for teaching free convection[4]. Supplemental experiments for use in the laboratory or classroom have also been presented including rather novel experiments such as the drying of a towel[5] and the cooking of French fry-shaped potatoes[6]. As part of the combined requirements for CHEG 3143, Heat Transport, and CHEG 3232, Laboratory II, junior level chemical engineering students at the University of Arkansas were required to perform simple heat transfer experiments using inexpensive materials that are readily available in most engineering departments and to compare their experimental results with literature correlations. The design, implementation and analysis of two of these experiments describing laminar and turbulent flow heat transfer through tubes are described below.

Laminar Flow, Forced Convection Inside a Coiled Tube

Objective

Convection is one of the primary modes of heat transport. It can occur as either free or forced convection in either the laminar or turbulent flow regimes. In this experiment, laminar flow heat transfer coefficients were measured for the flow of ethylene glycol inside a 3/16 in coiled copper tube. The ethylene glycol was heated by immersing the copper coil inside an agitated hot water bath. The objectives of this experiment were to:

1. Determine experimental heat transfer coefficients for laminar flow inside a coiled tube, and
2. Compare the experimental coefficients with those predicted by the Seider-Tate equation, which is applicable for laminar tube flow.

Experimental Equipment List

- Coiled copper tubing (¼ in o.d. x 3/16 in i.d. x 11 ft long). There were six coils, each having a diameter of 7 in. The cross-sectional diameter of the tubing was 0.0039 in^2, the surface area was 103.7 in^2 and l_c/d_i = 528.
- 6 ft of 5/8 in i.d. Tygon® tubing.
- One thermocouple reader (Omega Model HH12).
- One 1 kW immersion heater (Fisher Automerse, 115V, 7.5A) with variable temperature control.
- One VWR thermocouple reader (Serial 221109742).
- One Arrow Engineering variable speed agitator drive (1/10 hp, 6,000 rpm max).

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- One 4 in diameter six-blade disk impeller operated at about 200 rpm.
- One 5 gal polyethylene pail.
- One 1 liter collection beaker.
- 4 gal of hot water.
- 2 gal of ethylene glycol (commercial automotive antifreeze).
- Two 1 gal containers
- One stopwatch.
- One TEEL Centrifugal Pump (Model 1P676A, 1630 rpm, 1/55 hp, 115V, 0.85A).
- One Baldor variable speed motor (0.5 hp, 1750 rpm).
- One Micropump positive displacement pump (Model 21056C).

Experimental Procedure

1. Assemble the experimental apparatus as shown in the schematic of Figure 1 and the photograph of Figure 2.
2. Fill the polyethylene pail with about 4 gal of hot water and set the agitator drive to about 500 rpm.
3. Insert the 1 kW immersion heater into the vessel.
4. Adjust the variable temperature knob on the heater until the water temperature reaches a steady 150°F.
5. Prime the pump by manually filling the inlet tube from the ethylene glycol tank to the pump with ethylene glycol.
6. Turn on the pump and allow the ethylene glycol to flow through the coil and into the 1gal collection container.
7. After about ½ gal of ethylene glycol has flowed through the system, which is sufficient to reach steady-state, collect a 500 ml sample of the ethylene glycol exiting the coil. Record the collection time in order to calculate the volumetric flow rate.
8. Immediately measure the sample temperature with the thermocouple and also measure the temperature of the ethylene glycol in the ethylene glycol feed tank.
9. Repeat the experiment at several different ethylene glycol flow rates.

Safety Concerns

1. Wear safety glasses at all times.
2. Avoid skin exposure to ethylene glycol. Should exposure occur, wash the affected area with soap and water.

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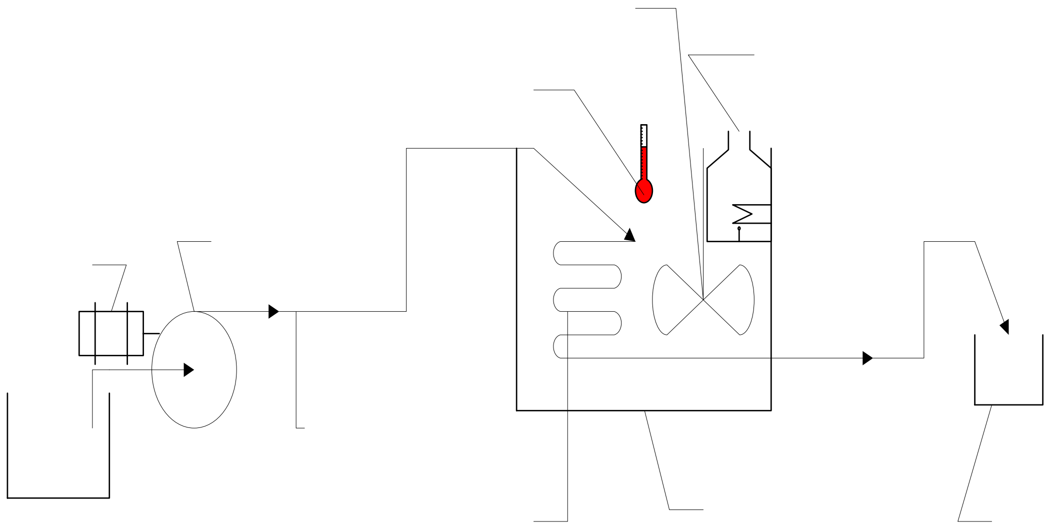

Figure 1. Schematic of Experimental Apparatus

Figure 2. Photograph of Experimental Apparatus

Pum

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70F Ethylene

Data Reduction (NOTE: tube wall and outside tube resistances were ignored)

1. Calculate the duty of the copper coil:

$$q_{out} = \dot{m}\ C_p\ (T_{out} - T_{in}) \tag{1}$$

2. Calculate the surface area of heat transfer:

$$A_s = \pi\ d_i\ l_c \tag{2}$$

3. Calculate the LMTD:

$$LMTD = \left(\frac{(T_s - T_{in}) - (T_s - T_{out})}{\ln\left(\frac{(T_s - T_{in})}{(T_s - T_{out})} \right)} \right) \tag{3}$$

4. Calculate the experimental heat transfer coefficient:

$$q_{in} = q_{out}$$

$$q_{in} = h_e * A_s * LMTD \tag{4}$$

$$\therefore h_e = \left(\frac{q_{out}}{A_s * LMTD} \right)$$

5. Calculate the experimental Nusselt number:

$$Nu_e = \frac{h_e * d_i}{k} \tag{5}$$

6. Calculate the ethylene glycol velocity:

$$v = \dot{m} * \left(\frac{1}{\rho * A_c * l_c} \right) \tag{6}$$

7. Calculate the Reynolds number:

$$\mathrm{Re} = \frac{d_i * v * \rho}{\mu} \tag{7}$$

8. Calculate the experimental Nusselt number from the Seider-Tate equation[7]:

$$Nu_c = 1.86 \left(\frac{\mathrm{Re} * \mathrm{Pr} * d_i}{l_c} \right)^{1/3} * \left(\frac{\mu}{\mu_s} \right)^{0.14} \tag{8}$$

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9. Calculate the correlational heat transfer coefficient:

$$h_c = \frac{Nu_c k}{d_o} \tag{9}$$

Comparison of Experimental Results with Correlation

Table 1 presents the experimental data and Table 2 presents the calculated correlated and experimental values. The maximum experimental error was 24%, which is very reasonable for these experiments.

Table 1. Experimental Results

$\dot{m}$, lb/hr	T_s, °F	T_{in}, °F	T_{out}, °F	q, BTU/hr	$LMTD$, °F
83.5	148	69.6	126	9143	43.8
59.4	139	69.6	123	6153	36.4
93.8	126	69.6	108	6934	34.1
63.6	125	69.6	109	4812	32.3
31.3	123	69.6	114	2694	24.8
45.9	121	69.6	105	3191	29.6

Table 2. Calculated Correlated and Experimental Data

v, ft/s	Re	Nu_e	Nu_c	h_e, BTU/hrft^2 °F	h_c, BTU/hrft^2 °F	% Error
1.66	360	12.5	10.0	376	302	19.7
1.16	182	10.3	8.1	304	240	21.1
1.86	287	12.3	9.4	366	280	23.7
1.26	195	9.0	8.3	268	246	8.5
0.62	96	6.6	6.3	196	186	4.9
0.91	141	6.5	7.1	194	211	8.9

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Turbulent Flow, Forced Convection Inside a Tube

Objective

In this experiment, turbulent flow heat transfer coefficients were measured for the flow of air through a ¼ in copper tube. As in the previous experiment, the air was heated by immersing flexible tubing that led to the copper tube inside an agitated hot water bath. The objectives of this experiment were to:

1. Determine experimental heat transfer coefficients for turbulent flow through the copper tube, and
2. Compare the experimental coefficients with those predicted by the Dittus-Boelter equation, which is applicable for turbulent tube flow.

Experimental Equipment List

- One 5 gal polyethylene pail.
- Two ¼ in o.d. Tygon® tubes.
- One King Instrument Company rotameter (0-8 scfm of atmospheric air).
- One thermocouple reader (Omega Model HH12).
- One 3/8 in o.d. x ¼ in i.d. x 18 in long copper U-tube.
- One Arrow Engineering variable speed agitator drive (1/10 hp, 6,000 rpm max).
- One 4 in diameter six-blade disk impeller operated at about 500 rpm.
- 4 gal of hot water.

Thus, the reservoir for heating the air and temperature measuring devices were the same as described in the previous experiment.

Experimental Procedure

The following experimental procedure was used to obtain the necessary data for calculating the experimental heat transfer coefficients:

1. Assemble the experimental apparatus as shown in the schematic of Figure 3 and the photograph of Figure 4.
2. Use a Tygon® tube to connect the laboratory air to the tube inlet.
3. Fill the pail with tap water at approximately 140°F until the copper tube is completely submerged. Take care not to allow water to enter the copper tube.
4. Start the agitator and slowly increase the speed to 200 rpm.
5. Increase the air flow rate to 8 cfm. Measure the inlet air temperature, allowing 1-2 min for the apparatus to reach steady state. When measuring air temperatures, be careful not to allow the thermocouple to come into contact with the Tygon® tube walls or the temperature reading will not be accurate.

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6. Measure the water bath temperature.
7. Disconnect the Tygon® tube from the rotameter, measure the exit air temperature, and reconnect the tube to the rotameter.
8. Repeat steps 4-6 for flow rates in increments of 1 cfm, and then duplicate the runs at 2, 4, 6, and 8 cfm to check experimental accuracy.

Safety Concerns

1. Wear safety glasses at all times.
2. Use caution when handling hot water.

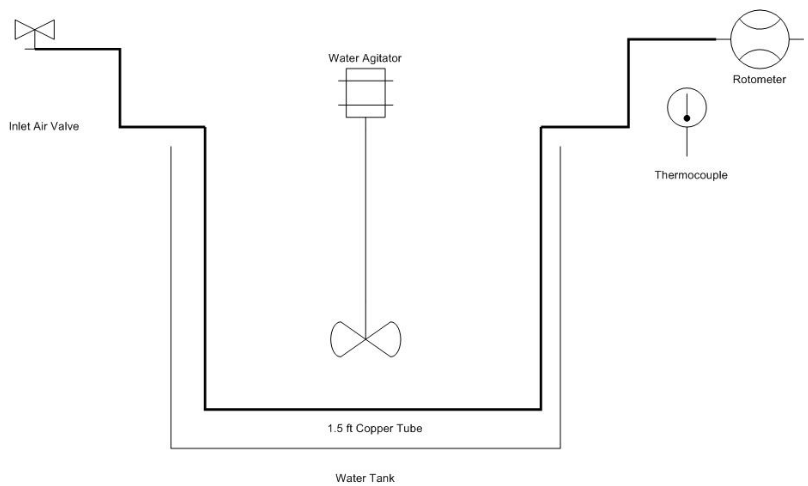

Figure 3. Schematic of Experimental Apparatus

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Figure 4. Photo of Experimental Apparatus
NOTE: This figure features a circular coil, which is much longer than the 18 inch copper U-tube used for this experiment.

Data Reduction

The experimental coefficient, Nusselt number and Reynolds number were calculated as detailed in Equations 1-7 above. The correlational Nusselt number was calculated from the Dittus-Boelter equation[7]:

$$Nu_c = 0.023\, Re^{0.8}\, Pr^{0.4} \tag{10}$$

and the correlational heat transfer coefficient was calculated as in Equation 9.

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Comparison of Experimental Results with Correlation

Table 3 presents the experimental data and Table 4 presents the experimental and correlational heat transfer coefficients. The experimental results were very close to the correlated results, with an average error of about -5.4%. Lower volumetric flow rates (2 cfm and below) resulted in experimental heat transfer coefficients below the correlational values and higher flow rates (above 2 cfm) resulted in experimental coefficients greater than the correlational values.

Table 3. Experimental Results

$\dot{m}$, lb/hr	T_s, °F	T_{in}, °F	T_{out}, °F	q, BTU/hr	$LMTD$, °F
34.6	132	75.2	108	273	38.1
30.3	130	75.2	107	231	36.6
26.0	129	75.2	108	205	34.9
21.7	128	75.2	107	166	34.5
17.3	127	75.2	107	132	33.4
13.0	125	75.2	107	99	31.2
8.7	125	75.2	106	64	32.0
4.3	124	75.2	106	32	30.9
8.7	123	75.2	105	62	30.5
17.3	122	75.2	104	120	30.1
26.0	121	75.2	103	174	29.8
30.3	120	75.2	102	195	29.4
34.6	119	75.2	100	207	29.7

Table 4. Calculated Correlated and Experimental Data

v, ft/s	Re	Nu_e	Nu_c	h_e, BTU/hrft^2 °F	h_c, BTU/hrft^2 °F	% Error
252	37374	101	92	58.6	53.1	-9.4
220	32702	90	83	51.9	47.7	-8.2
189	28031	81	73	46.8	42.1	-9.9
157	23359	70	63	40.3	36.4	-9.7
126	18687	58	53	33.3	30.5	-8.6
94	14015	44	42	25.6	24.2	-5.3
63	9344	29	30	17.0	17.5	2.9
31	4672	15	17	8.6	10.1	17.3
63	9344	30	30	17.2	17.5	1.7
126	18687	58	53	33.7	30.5	-9.5
189	28031	82	73	47.5	42.1	-11.3
220	32702	92	83	53.2	47.7	-10.4
252	37374	101	92	58.5	53.1	-9.2

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Conclusions

Two simple experiments were developed for obtaining forced convection heat transfer coefficients inside tubes under laminar and turbulent flow conditions. The experiments are easily adapted for in-class demonstration or as a laboratory exercise to illustrate important heat transfer principles. In both cases, the experimental data obtained by the students compared well with literature correlations.

Nomenclature

A_c	-	Tube cross-sectional area, ft^2.
A_s	-	Surface area for heat transfer, ft^2.
C_p	-	Heat capacity of fluid, BTU/lb·°F (at T_m).
d_i	-	Inside diameter of copper coil of tube, ft
h_c	-	Correlational heat transfer coefficient, BTU/hr·ft^2·°F.
h_e	-	Experimental heat transfer coefficient, BTU/hr·ft^2·°F.
k	-	Thermal conductivity of fluid, BTU/hr·ft·°F (at T_m).
l_c	-	Length of coil, ft.
$LMTD$	-	Log mean temperature difference, °F.
$\dot{m}$	-	Mass flow rate, lb/hr.
q_{in}	-	Heat transferred to fluid, BTU/hr.
q_{out}	-	Duty of the copper coil or tube, BTU/hr.
T_{in}	-	Temperature of the inlet stream, °F.
T_m	-	Average temperature of T_{in} and T_{out}, °F.
T_{out}	-	Temperature of the outlet stream, °F.
T_s	-	Temperature of water bath (surroundings), °F.
v	-	Velocity of fluid, ft/s.

Dimensionless Numbers

Nu	-	Nusselt number.
Pr	-	Prandtl number (at T_m).
Re	-	Reynolds number.

Greek Symbols

μ	-	Viscosity of fluid, lb/ft·s (at T_m).
μ_s	-	Viscosity of fluid, lb/ft·s (at T_s).
ϱ	-	Density of fluid, lb/ft^3 (at T_m).

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Mr. Dorman, Mr. Fluornoy, Ms. Keogh and Ms. Leach are junior-level chemical engineering students at the University of Arkansas. All four students participated with their classmates (in groups of two) in performing experimental exercises as part of the requirements for CHEG 3143, Heat Transport, and CHEG 3232, Laboratory II.

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