Laboratory/Demonstration Experiments in Heat Transfer: Forced Convection

**Edgar C. Clausen, W. Roy Penney, Alison N. Dunn, Jennifer M. Gray,
Jerod C. Hollingsworth, Pei-Ting Hsu, Brian K. McLelland,
Patrick M. Sweeney, Thuy D. Tran, Christopher A. von der Mehden,
Jin-Yuan Wang**

**Ralph E. Martin Department of Chemical Engineering
University of Arkansas**

Abstract

Laboratory exercises or demonstrations which are designed to compare experimental data with data or correlations from the literature 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 perform simple heat transfer experiments using inexpensive materials that are readily available in most engineering departments. The design, implementation and analysis of three of these experiments are described.

Experimental forced convection heat transfer coefficients were determined by flowing air over an upward facing horizontal plate, past the bulb of a mercury/glass thermometer and through an annulus. In each case, the apparatus (the plate, cylinder or inner cylinder) was allowed to cool or heat in the flowing air, while recording temperature as a function of time. The experimental heat transfer coefficients were then determined from a heat balance over the heat transfer surface. Finally, the experimental coefficients were compared to those obtained from appropriate literature correlations.

The experimental forced convection heat transfer coefficients for parallel flow over flat plate were 2.2-3.5 times higher than literature correlation coefficients, most likely resulting from the high turbulence generated by the fan. The experimental forced convection heat transfer coefficient for two different sizes of mercury/glass thermometer bulbs, were within 20% of the literature correlation coefficients. The experimental forced convection coefficients from flow of hot air over a brass rod centered in an annulus were 1.6-2.2 times higher than literature correlation coefficients, most likely resulting from the the hair dryer jet velocity being 3.6 times higher than the annulus velocity.

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 or demonstrations using inexpensive materials that are readily available in most engineering departments. The design, implementation and analysis of three of these experiments, forced convection heat transfer coefficients by flowing air over an upward facing horizontal plate, past the bulb of a mercury/glass thermometer and through an annulus, are described below. This exercise has several benefits:

- It provides an opportunity for students to have additional “hands-on” experience;
- It demonstrates a physical application of correlations found in the textbook; and,
- It helps to develop an appreciation for the limitations of the correlations.

Experiment 1. Forced Convection Heat Transfer by Air Flowing Over the Top Surface of a Horizontal Plate

Objective

Forced convection heat transfer occurs when the fluid surrounding a surface is set in motion by an external means such as a fan, pump or atmospheric disturbances. This study was concerned with forced convection heat transfer from a fluid (air) flowing parallel to a flat plate at varying velocities. The objectives of this experiment were to:

1. Determine the experimental forced convection heat transfer coefficient for parallel flow over a flat plate.
2. Compare the experiment heat transfer coefficient with the coefficient calculated from the correlations presented by Cengel[7].

Experimental Equipment List

- Four mill finish aluminum plates (1.5 in x 12 in x 18 in)
- Four 13 in x 19 in sheets of ½ in thick Styrofoam® insulation
- Thermocouple reader (Omega HH12)
- 1/8 in diameter x 12 in long, Type K, sheathed thermocouple
- Anemometer-thermometer (Kane-May, model KM4107, serial # 34095)
- 1,600 W hair dryer (Hartman Protec 1600)
- Styrofoam® insulated heating box (13 in x 20 in x 23 in)
- Stopwatch, graduated in 0.01 s time intervals
- 3-speed Black & Decker window fan, model DTS50D/B

Experimental Procedure

The schematic drawings of experimental apparatus are presented as Figures 1 and 2 and photographs are presented as Figures 3 and 4.

Setup/Testing

1. Weigh each of the aluminum plates on an electronic balance. The average weight was 14.35 kg.
2. After placing two aluminum plates inside the insulated heating box, place the nozzle of the hair dryer into the hole in the lid, and heat the plates to ~150°F.
3. Place Styrofoam® insulation on a tabletop.
4. Place a heated plate in the first position on the Styrofoam® insulation, with the long (i.e., 18 in) dimension in the flow direction (see Figures 2 and 4).
5. Place two additional cold plates end-to-end (again, see Figures 2 and 4), along the 18 in dimension, and wrap the two 12 in x 1 ½ in and three 18 in x 1 ½ in vertical faces with insulation. Leave a 1cm space between plates to avoid conduction between the plates.
6. Connect the sheathed thermocouples to the thermocouple reader and insert them into the first plate.
7. Start the fan and choose one of three fan speeds.
8. Start the stopwatch as soon as the temperature changes 0.5°C from its original temperature.
9. Record the time at each successive 0.5°C change in temperature.
10. Use the anemometer to measure the air velocity over the plate at five different lateral positions to determine the average air velocity.
11. Repeat the above procedure for the two other fan speed settings.
12. Remove the second heated plate from the heating box and place it in the fourth and last position from the first plate (once again, see Figures 2 and 4).
13. Repeat the above procedures for the fourth plate.
14. Use the anemometer to measure the air velocity over the fourth plate at five different lateral positions to determine the average air velocity.

Safety Concerns

1. Wear safety glasses at all times.
2. Be very careful when handling the aluminum plates since they each weigh 32 lb (14.35 kg), and can break bones if dropped.
3. Always wear gloves when handling the hot aluminum plates.
4. Keep fingers away from the guard around the fan blades.

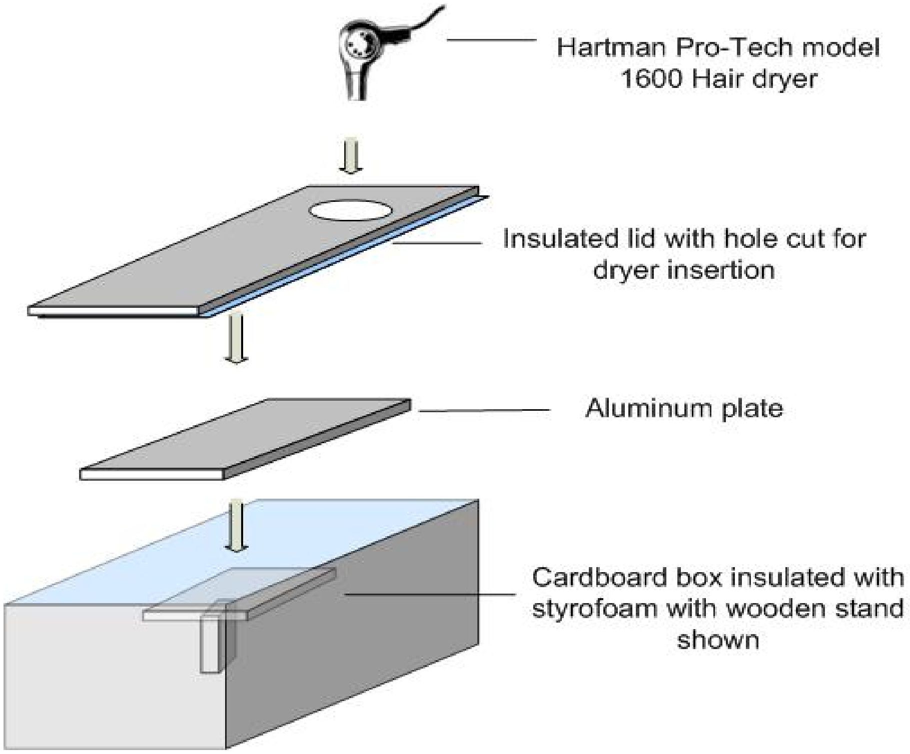

Figure 1. Insulated Wooden Box for Heating the Aluminum Plates

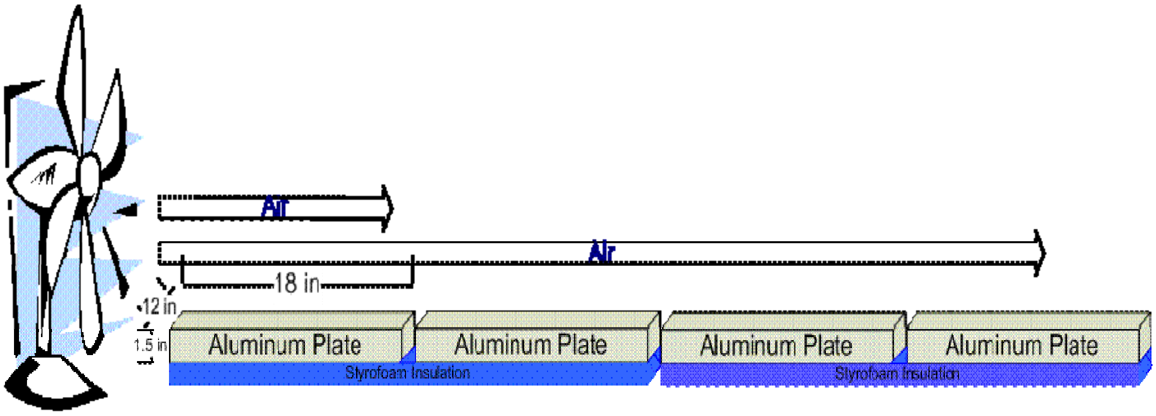

Figure 2. Location of Plates for Flat Plate Heat Transfer Experiment

Figure 3. Photograph of Insulated Wood Box used to Heat the Aluminum Plates

Figure 4. Photograph of Experimental Horizontal Plate Heat Transfer Experiment

Data Reduction

1. A heat balance on the cooling plate, with no heat generation, yields:

$$-q_{Out} = q_{Acc} \tag{1}$$

2. The plate is cooled by free convection and radiation as follows:

$$q_{Out} = q_{Conv} + q_{Rad} = hA_s(T_s - T_a) + \varepsilon\sigma A_s(T_s^4 - T_a^4) \tag{2}$$

3. The plate accumulates heat as it cools towards room temperature as follows:

$$q_{ACC} = -M\left(C_p\right)\frac{dT}{dt} = -\rho V\left(C_p\right)\frac{dT}{dt} \tag{3}$$

4. Thus, the heat balance of Equation 1 becomes:

$$\left(hA_s(T_s - T_a) + \varepsilon\sigma A_s(T_s^4 - T_a^4)\right) = -\rho V\left(C_P\right)\frac{dT}{dt} \tag{4}$$

   Although small, the heat balance was also corrected for the heat flow by conduction from the aluminum plate through the insulation to the table as $q_{Cond} = k_I As(T_s - T_a)/\Delta x_I$.

5. The experimental data of plate temperature vs. time (in Table 3) were plotted using TK Solver and were curve fitted using a second order polynomial (i.e., $T_s = a + bt + ct^2$). This equation was differentiated to determine $dT/dt = b + 2ct$.

6. Cengal[7] gives the following correlations for ***local*** heat transfer coefficients for forced convection flow over a horizontal plate:

$$Nu_x = h_x x / k = 0.332\,\mathrm{Re}_x^{0.5}\,\mathrm{Pr}^{1/3} \text{ for laminar conditions, i.e., } \mathrm{Re} < 500{,}000 \tag{5}$$

$$Nu_x = h_x x / k = 0.0296\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \text{ for turbulent conditions, i.e., } 5\text{x}10^5 < \mathrm{Re} < 10^7 \tag{6}$$

   The integrated ***average*** coefficients are given by

$$Nu = hx / k = 0.332\,\mathrm{Re}_x^{0.5}\,\mathrm{Pr}^{1/3} \text{ for laminar conditions, i.e., } \mathrm{Re} < 500{,}000 \tag{7}$$

$$Nu = hx / k = (0.037\,\mathrm{Re}^{0.8} - 871)\,\mathrm{Pr}^{1/3} \text{ turbulent conditions, } 5\text{x}10^5 < \mathrm{Re} < 10^7 \tag{8}$$

Comparison of Experimental Results with Values from the Literature

Table 1 gives all of the experimental data of temperature vs. time for the six experiments. Figure 5 presents a plot of T_s vs. time for the first plate at V = 4.82 m/s. All of the data were curve fitted, as shown in Figure 4, and the slope of all six of the individual plots was determined at the fifth data point. This slope was used in Equation 4 to determine the experimental heat transfer coefficient.

Table 1. Experimental Data for Cooling of Flat Plates with Parallel Flow of Air

1st Plate		1st Plate		1st Plate		4th Plate		4th Plate		4th Plate	
V = 4.92 m/s		V = 6.00 m/s		V = 7.24 m/s		V = 3.75 m/s		V = 4.63 m/s		V = 5.54 m/s	
Time (s)	T_s (°C)	Time (s)	T_s (°C)	Time (s)	T_s (°C)	Time (s)	T_s (°C)	Time (s)	T_s (°C)	Time (s)	T_s (°C)
0	69.4	0	60.6	0	52.8	0	72.4	0	66.7	0	60.5
29	68.8	31	60.0	30	52.2	91	71.5	45	66.1	38	60.0
60	68.2	61	59.4	63	51.7	161	70.8	87	65.5	81	59.5
67	68.1	92	58.9	98	51.1	175	70.6	127	64.9	122	58.9
113	67.2	124	58.3	132	50.5	224	70.1	167	64.5	180	58.2
143	66.6	156	57.8	167	50.0	267	69.5	210	63.9	211	57.8
171	66.1	187	57.2	204	49.4	309	69.0	255	63.3	254	57.3
202	65.5	220	56.7	237	48.9	351	68.4	293	62.8	301	56.7
235	65.0	254	56.1	277	48.3	400	67.7	339	62.2	345	56.1
263	64.5	286	55.6	316	47.8	436	67.1	384	61.6	389	55.6

Table 2 presents the experimental and reduced data for all of the experiments. For the first plate, the ratio of h_{Exp}/h_{Corr} was 2.72, 3 and 3.29 for air velocities of 4.82, 6 and 7.24 m/s, respectively, and, for the fourth plate, the respective values were 1.71, 2.36, 2.25 for air velocities of 3.75, 4.64 and 5.54 m/s, respectively. Thus, for the first plate the average ratio of h_{Exp}/h_{Corr} was 3 and for the fourth plate the average ratio was 2.1.

Table 2. Reduced Data for All Experiments – Air Flow over Flat Plate

Plate	V	Re	Nu_x	h_{CORR}	T_s	dT/dt	q	F_{CONV}	F_{RAD}	F_{COND}	h_{EXP}
1st	4.82	1.3E5	212	12.1	67.2	-.019	245	0.83	0.09	0.08	33
1st	6.00	1.5E5	234	13.3	58.3	-.018	228	0.85	0.08	0.07	40
1st	7.24	1.8E5	257	14.6	50.5	-.016	209	0.88	0.06	0.06	48
4th	3.75	3.3E5	73	9.9	70.1	-.012	157	0.71	0.16	0.13	17
4th	4.63	4.1E5	192	11.0	64.5	-.015	190	0.79	0.11	0.10	26
4th	5.54	4.9E5	210	12.0	58.2	-.013	164	0.80	0.11	0.09	27

Figure 5. Temperature vs. Time Experimental Data from the First Plate
at an Air Velocity of 4.82 m/s

These results indicate that the experimental apparatus did not come close to producing laminar flow over the plate. This is not very surprising, considering that the fan produces significant turbulence. The fan acts like an agitator in a mechanically-agitated vessel. It produces turbulence in addition to producing directed flow along the plate. In fact, it must produce a great deal of turbulence for the measured coefficients to be 200-300% higher than those which would be produced by non-turbulent laminar flow.

Experiment 2. Forced Convection Cooling on a Mercury/Glass Column

Objective

This second study was concerned with forced convection heat transfer from a fluid (air) flowing past the cylindrical bulb of a mercury/glass thermometer. The objectives of this experiment were:

1. Determine the experimental forced convection heat transfer coefficient for two different bulb sizes at two different air velocities, and
2. Compare the experiment heat transfer coefficient with the Churchill/Bernstein correlation for forced convection over a circular cylinder[8].

Experimental Equipment List

- Two mercury thermometers, one with a bulb diameter of 6 mm and a length of 1.5 cm and the other with a bulb diameter of 4.1 mm and a length of 1.4 cm
- Hot tap water
- Stop watch, graduated in 0.01 s time intervals
- Fan with two speed settings
- Anemometer

Experimental Procedure

1. Heat the thermometer by holding its bulb under hot tap water until the temperature stabilized at about 70°C.
2. Remove the thermometer from the tap water and quickly wipe it dry with a paper towel.
3. Position the thermometer horizontally in front of an operating fan, using a laboratory ring stand and clamp.
4. Record thermometer with time as the thermometer cools towards room temperature.

Safety Concerns

1. Wear safety glasses at all times.
2. Be careful not to drop the thermometers or to get burned by the hot water.
3. Keep fingers away from the fan guard.

Data Reduction

Equations 1-4 were once again used to calculate the experimental heat transfer coefficients as in the previous experiment. The heat transfer coefficient from the literature was determined using the Churchill/Bernstein correlation for forced convection over a circular cylinder[8]:

$$Nu = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(0.4/\mathrm{Pr}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{282{,}000}\right)^{5/8}\right]^{4/5} \qquad \textbf{(9)}$$

In Equation 9, all properties are evaluated at the film temperature, T_{Fiilm}, which is defined as:

$$T_{Film} = \frac{T_s + T_a}{2} \qquad \textbf{(10)}$$

Comparison of Experimental Results with Values from the Literature

Figures 6-9 show plots of experimental temperature profiles for the 4.1 mm bulb at air velocities of 500 and 920 ft/min and the 6 mm bulb at air velocities of 500 and 920 ft/min, respectively. A transient TK Solver Model was developed to calculate the transient profiles using a heat transfer coefficient calculated from Equation 9, but the coefficient was ratioed to give the best fit to the experimental data. The ratios of h_{exp}/h_{corr} to best fit the experimental data are given in Table 3.

Table 3. Ratio of h_{exp}/h_{corr} to Produce the Best Fit to the Experimental Data for the Cooling of 4.1 and 6 mm Thermometer Bulbs in Front of a Fan Blowing Room Air

Bulb Diameter (mm)	Air Velocity (ft/min)	h_{EXP}/h_{CORR}	Re	Nu	h_{CORR}
4.1	500	1.00	667	13.0	80
4.1	920	1.00	1,225	18.0	108
6.0	500	1.25	975	16.0	66
6.0	920	1.05	1,410	19.3	79

These ratios are likely a bit low because radiation effects were assumed to be negligible. Even with some radiation effects, the literature correlation (Equation 9) yields results which are quite close to the experimental coefficient. The small sizes of the thermometer bulbs relative to the turbulent eddy size produced by the fan are most likely the reason that the literature correlation better fits the experimental data for the thermometer bulbs than for the flat plate for which $h_{exp}h_{corr}$ varied from 2 to 3. For the flat plate, the turbulent eddy size is likely smaller than the dimensions of the flat plate and the turbulence in the flow field is very different than the laminar flow over a flat plate.

Figure 6. Thermometer Temperature vs. Time for the 4.1 mm Bulb at an Air Velocity of 500 ft/min (2.54 m/s). LEGEND: (+) 1st Experiment; (o) 2nd Experiment; Solid Curve – Predicted Profile with Ratio h_{EXP}/h_{CORR} = 1.

Figure 7. Thermometer Temperature vs. Time for the 4.1 mm Bulb at an Air Velocity of 920 ft/min (4.67 m/s). LEGEND: (+) 1st Experiment; (o) 2nd Experiment; Solid Curve – Predicted Profile with Ratio $h_{EXP}/h_{CORR} = 1$.

Figure 8. Thermometer Temperature vs. Time for the 4.1 mm Bulb at an Air Velocity of 500 ft/min (2.54 m/s). LEGEND: (+) 1st Experiment; (o) 2nd Experiment; Solid Curve – Predicted Profile with Ratio $h_{EXP}/h_{CORR} = 1.15$

Figure 9. Thermometer Temperature vs. Time for the 6 mm Bulb at an Air Velocity of 920 ft/min (4.67 m/s). LEGEND: (+) 1st Experiment; (o) 2nd Experiment; Solid Curve – Predicted Profile with Ratio $h_{EXP}/h_{CORR} = 1.25$

Experiment 3. Forced Convection Heat Transfer from Hot Air in An Annulus to the Inner Cylinder

Objective

Another important geometry for forced convection heat transfer is the heating or cooling of a fluid flowing through an annulus between an outer pipe and an inner cylinder. The objectives of this experiment were to:

1. Determine the experimental forced convection heat transfer coefficient for the heating of a brass rod, contained in an annulus, as air flows through the annulus, and
2. Compare these results with the heat transfer coefficient from the Dittus-Boelter equation[7].

Experimental Equipment List

- 3 in inside diameter x 72 in long PVC tube
- 1 in diameter x 42.5 in long oak dowel
- 1 in diameter x 8.1 in long brass rod with a 1/8 in diameter x 3 in long center hole
- Omega HH12 thermocouple reader
- 1/8 in diameter by 12 in long sheathed thermocouple
- Hair dryer (Hartman Protec 1600)
- Stopwatch, graduated in 0.01 s time intervals
- Window Fan (3-speed Black & Decker, model number DTS50D/B)
- Anemometer (Kane-May, model number KM4107)

Experimental Procedure

The experimental apparatus is shown in the schematic of Figure 10 and the photograph of Figure 11.

1. Determine the weight (0.88 kg) of the brass rod and its dimensions (1in dia. x 8.1 in long) .
2. Use ice to cool the rod until it is cooled below room temperature.
3. Place the wood and brass rods into the PVC tube as shown in Figure 7. *NOTE: The wood rod is used to provide an inside cylinder which is much longer than the brass rod, so that fully established turbulent flow exists prior to the hot air reaching the brass rod.*
4. Insert the thermocouple into the 1/8 in center hole in the brass rod.
5. Turn on the hair dryer at its highest speed, and immediately start the stopwatch.
6. Record the time for each successive 1^{o}C change in temperature of the rod.
7. At a point after the air flow has reached steady state, record the velocity and ambient air temperature of the air exiting the annulus.
8. Repeat this procedure as necessary, with the same or different hair dryer speeds.

Safety Concerns

1. Wear safety glasses at all times.
2. Be on guard when the fan is used.
3. Be extra careful that the PVC outer tube is held firmly vertical against a supporting structure.

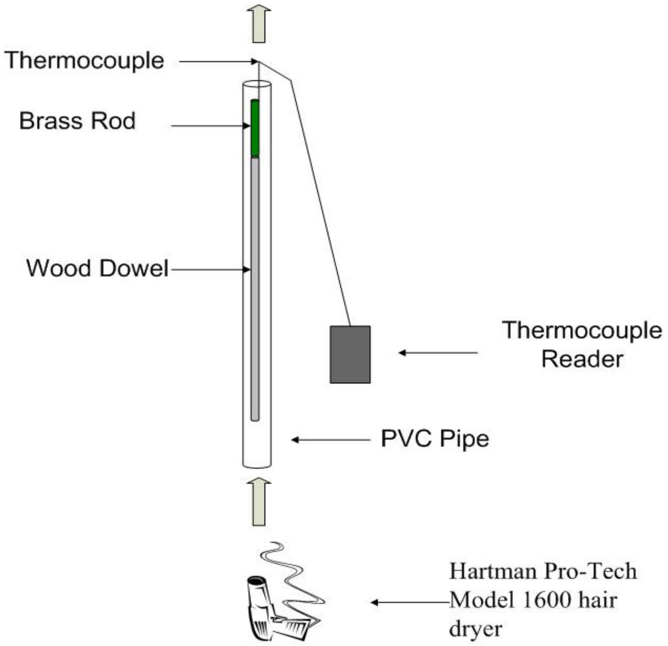

Figure 10. Schematic of Annulus Heating Apparatus

Figure 11. Schematic of Annulus Heating Apparatus

Experimental Data

Table 4. Experimental Data of Brass Rod Temperature vs. Time for Heating of the Rod with a Hair Dryer Inserted into a Pipe with the Rod in its Center

Run #1 V_{air} = 4.22 m/s $T_{air,out}$ = 62°C		Run #2 V_{air} = 2.56 m/s $T_{air,out}$ = 44.72°C		Run #3 V_{air} = 4.43 m/s $T_{air,out}$ = 64.2°C	
Time (s)	T_r (°C)	Time (s)	T_r (°C)	Time (s)	T_r (°C)
0	12	0	10	0	13
9.6	13	47.6	11	10.9	14
27.3	14	75.9	12	24.0	15
43.6	15	103	13	46.1	16
59.1	16	130	14	62.2	17
73.6	17	160	15	77.7	18
89.1	18	187	16	92.9	19
105	19	214	17	107	20
120	20	270	18	122	21
135	21	299	19	137	22

152	22	330	20	151	23
167	23	360	21	166	24
183	24	393	22	181	25
198	25	426	23	196	26

Data Reduction

1. A heat balance on the rod with no heat generation yields:

$$q_{In} - q_{Out} = q_{Acc} \tag{11}$$

2. The brass rod is heated by forced convection from below room temperature, thorough room temperature and to above room temperature. The heat transfer coefficient is determined when the rod temperature is equal to the room temperature when heat transfer by radiation to/from the pipe walls is either 0 or negligible. Thus, Equation 11 becomes

$$q_{In} = hA(T_a - T_s) \tag{12}$$

3. The brass rod accumulates heat as follows:

$$q_{Acc} = m(C_p)\frac{dT_s}{dt} \tag{13}$$

4. Therefore, the heat balance reduces to:

$$hA(T_a - T_s) = m(C_p)\frac{dT_s}{dt} \tag{14}$$

5. Equation 14 may be solved for the heat transfer coefficient:

$$h = \frac{m(C_p)\dfrac{dT_s}{dt}}{A(T_a - T_s)} \tag{15}$$

6. The experimental data, presented in Table 4, were plotted as T_s vs. time and the data were curve-fitted with a second order polynomial fit using TK Solver; i.e., $T_s = a + bt + ct^2$. The slope of the curve was determined at room temperature for insertion into Equation 15. The plot of T_s vs t, for Run # 1, is presented in Figure 12. For this run, the quadratic curve fit was $T_s = 12.168 + 0.06594(t) - 6.346E\text{-}6(t^2)$, giving $dT_s/dt = 0.0638$ ºC/s.

7. The heat transfer coefficient from the literature was determined using the Dittus-Boelter equation[7] for turbulent flow through tubes with the hydraulic diameter of the

annulus ($D_h = D_{pipe} - D_{rod}$) used as the characteristic length in both Re (= $vD_h\rho/\mu$) and Nu (= $h_{cCORR}D_h/k$).

$$Nu = 0.023\, Re^{0.8}\, Pr^{\,0.4} \tag{16}$$

8. Finally, the heat transfer coefficient from the literature correlation is calculated as follows

$$h_{Corr} = \frac{kNu}{D_h} \tag{17}$$

Figure 12. T_s vs. Time for Experiment # 1 with the 1 in Diameter x 8.1 in Long Brass Rod Heated by a 62°C, 81 ft/min (4.22 m/s) Air Stream in a 3 in Pipe.

Results from the annulus heat transfer experiments are summarized in Table 5.

Table 5. Reduced Data for All Experiments – Air Flow through an Annulus

Run	V (m/s)	Re	T_a (°C)	T_s (°C)	dT_s/dt	q	Nu	h_{CORR}	h_{EXP}	h_{CORR}/h_{EXP}
1	4.22	12,586	62.0	23	0.064	21.3	38.5	33.4	20.2	1.65
2	2.56	7,874	44.7	23	0.032	10.7	26.5	30.0	13.7	2.20
3	4.44	13,230	64.2	23	0.067	22.3	40.1	33.0	21.0	1.57

Comparison of Experimental Results with Values from the Literature

The experimental coefficients are significantly higher than the correlation predicted coefficients. This result is not surprising considering: (1) the flow from the hair dryer is quite turbulent, (2) the velocity profile from the hair dryer is not flat, and (3) the jet exiting the hair dryer is only 1 ½ in diameter; whereas, the outside annulus pipe diameter is 3 in. The exit velocity from the hair dryer is 3.6 times the annulus velocity; this high jet velocity entering the outside annulus pipe is probably the major reason that the experimental heat transfer coefficient is so much higher than the predicted value. This entering jet would produce considerable turbulence as shear layers reduce the high jet velocity to an annulus velocity, which is only 28% of the jet velocity.

Conclusions

Three simple forced convection heat transfer experiments were developed for:

1. Air flowing over an upward facing cooling horizontal plate
2. Air flowing over the cooling bulb of a mercury/glass thermometer.
3. Hot air from a hair dryer flowing over a heating brass rod within an annulus.

The experimental heat transfer coefficients were compared with literature correlation predicted values.

The experimental coefficients for the flat plate in parallel flow were 2.2-3.5 times higher than the literature correlation coefficients, primarily because the flow from the fans was highly turbulent and the literature correlations were for laminar conditions. The experimental coefficients for the bulb of the mercury/glass thermometer in parallel flow were 1-1.25 times higher than the literature correlation coefficients. This good agreement between experiment and correlation was most likely a result of the bulb dimensions being significantly smaller than the scale of turbulence produced by the fan.

The experimental coefficients for the rod within an annulus were 1.6 to 2.2 higher than the literature correlation predictions. This finding likely results from the entering jet velocity from the hair dryer being 3.6 times the annulus velocity. This high velocity jet produces considerable turbulence as shear layers reduce the entering jet velocity to an annulus velocity which is only 28% of the jet velocity.

Although the effects of these experiments on student learning has not yet been quantified, anecdotally students remarked, *after* the completion of the exercise, that they really learned a lot from these assignments. It is planned to offer this exercise again this fall, at which time the students will be surveyed relative to the value of the exercise.

Nomenclature

A_S	heat transfer area, m^2
C_p	specific heat, J/kg K
D	cylinder diameter, m
F_{CONV}	fraction of total heat transfer by convection
F_{COND}	fraction of total heat transfer by conduction
F_{RAD}	fraction of total heat transfer by radiation
h	area average convection heat transfer coefficient, W/m^2 K
h_{CORR}	heat transfer coefficient from literature correlations, W/m^2 K
h_{EXP}	heat transfer coefficient from experimental data, W/m^2 K
h_x	local heat transfer coefficient at length x along a flat plate, W/m^2 K
k	fluid thermal conductivity, W/mK
M	mass of the plate or cylinder, kg
Nu	area average Nusselt number, hx/k or hD/k
Nu_x	local Nusselt number at location x along flat plate, hx/k
Pr	Prandtl number of the fluid
q_{In}	heat transfer into the system, W
q_{Out}	heat transfer from the system, W
q_{Acc}	heat accumulated within the system, W
q_{conv}	heat transfer by convection, W
q_{Rad}	heat transfer by radiation, W
Re	Reynolds number, = $VD\rho/\mu$ for cylinder & $Vx\rho/\mu$ for a flat plate
T_a	ambient temperature of surroundings, K
T_{Film}	film temperature = $(T_s + T_a)/2$, K
T_s	surface temperature, K
v	fluid velocity, m/s
V	volume of plate or cylinder, m^3
x	length along flat plate in flow direction, m
ε	surface emissivity
ρ	fluid density, kg/m^3
σ	Stefan-Boltzmann constant, W/m^2K^4

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EDGAR C. CLAUSEN
Dr. Clausen currently serves as Adam Professor of Chemical Engineering at the University of Arkansas. His research interests include bioprocess engineering (fermentations, kinetics, reactor design, bioseparations, process scale-up and design), gas phase fermentations, and the production of energy and chemicals from biomass and waste. Dr. Clausen is a registered professional engineer in the state of Arkansas.

W. ROY PENNEY
Dr. Penney currently serves as Professor of Chemical Engineering at the University of Arkansas. His research interests include fluid mixing and process design. Professor Penney is a registered professional engineer in the state of Arkansas.

ALISON N. DUNN, JENNIFER M. GRAY, JEROD C. HOLLINGSWORTH, PEI-TING HSU, BRIAN K. MCLELLAND, PATRICK M. SWEENEY, THUY D. TRAN, CHRISTOPHER A. VON DER MEHDEN, JIN-YUAN WANG
Ms. Dunn, Ms. Gray, Mr. Hollingsworth, Ms. Hsu, Mr. McLelland, Mr. Sweeney, Ms. Tan, Mr. von der Mehden and Mr. Wang are either current or former 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.