CHEG 3143 Forced Convection Heat Transfer To Horizontal CHEG 3342
Heat Transport Plate From/To Air Flowing Over the Plates Chem. Eng. Lab. II
Fall 2004 By Jennifer Gray and Thuy Tran Fall 2004
Professor Penney December 3, 2004 Professor Clausen

Introduction and Purposes:

Forced convection occurs when the fluid is set in motion by the external means such as a fan, pump or atmospheric disturbances. This study is concerned with forced convection heat transfer from a fluid flowing parallel to a flat plate.

The purposes of this experiment are:

1. Determine the experimental forced convection heat transfer coefficient for the flat plate in parallel flow over the flat plate.
2. Compare the experiment heat transfer coefficient with the coefficient calculated from the literature correlations.

EQUIPMENT:

1. Four mill finish aluminum plates (18'' x 12'' x 1.5'')
2. Four 19'' by 13'' sheets of ½" thick Styrofoam insulation
3. Omega HH12 thermocouple reader
4. 1/8" diameter by 12" long sheathed thermocouple (Kane-May, model KM4107, serial # 34095)
5. Hairdryer (Hartman Protec 1600)
6. Styrofoam insulated heating box (20'' x 23'' x 13''), with ½" insulation thickness
7. Stopwatch
8. 3-speed Black & Decker window fan with model of DTS50D/B
9. Anemometer

SCHEMATIC OF EXPERIMENTAL APPARATUS:

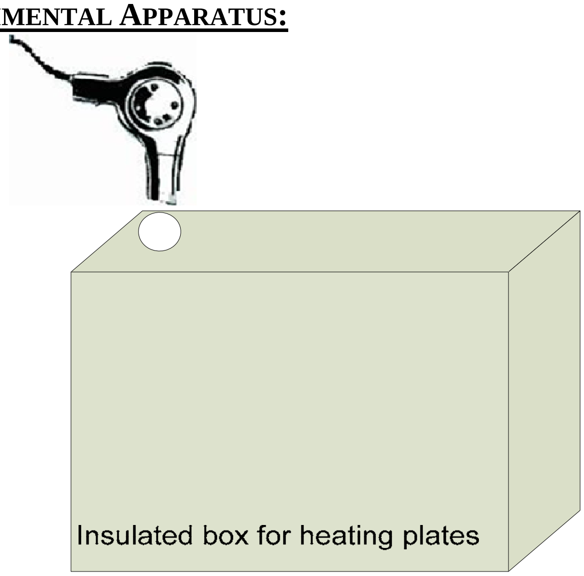

Figure 1. Schematic of Experimental Apparatus for Heating Aluminum Plate.

Figure 2. Photo of Experimental Apparatus for Heating the Aluminum Plates

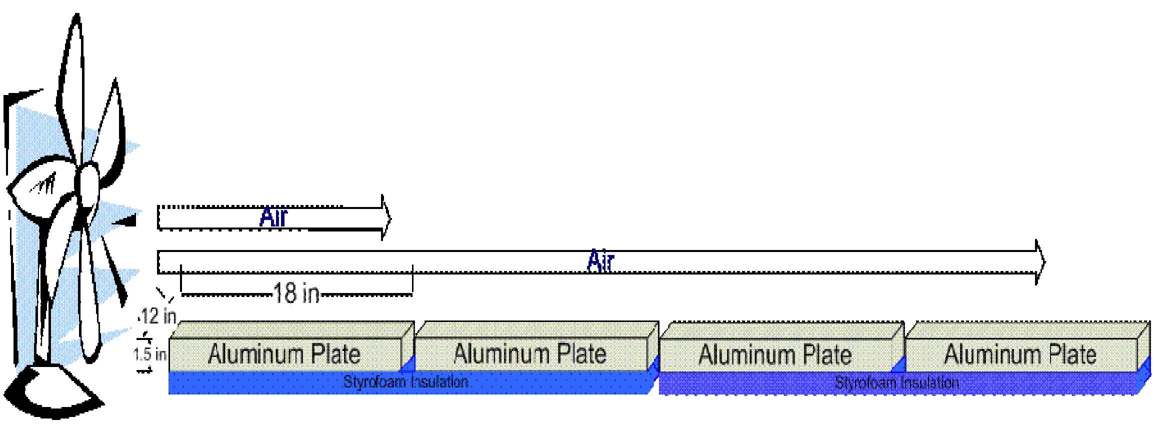

Figure 3: Schematic of Experimental Apparatus for determining the Heat Transfer Coefficient

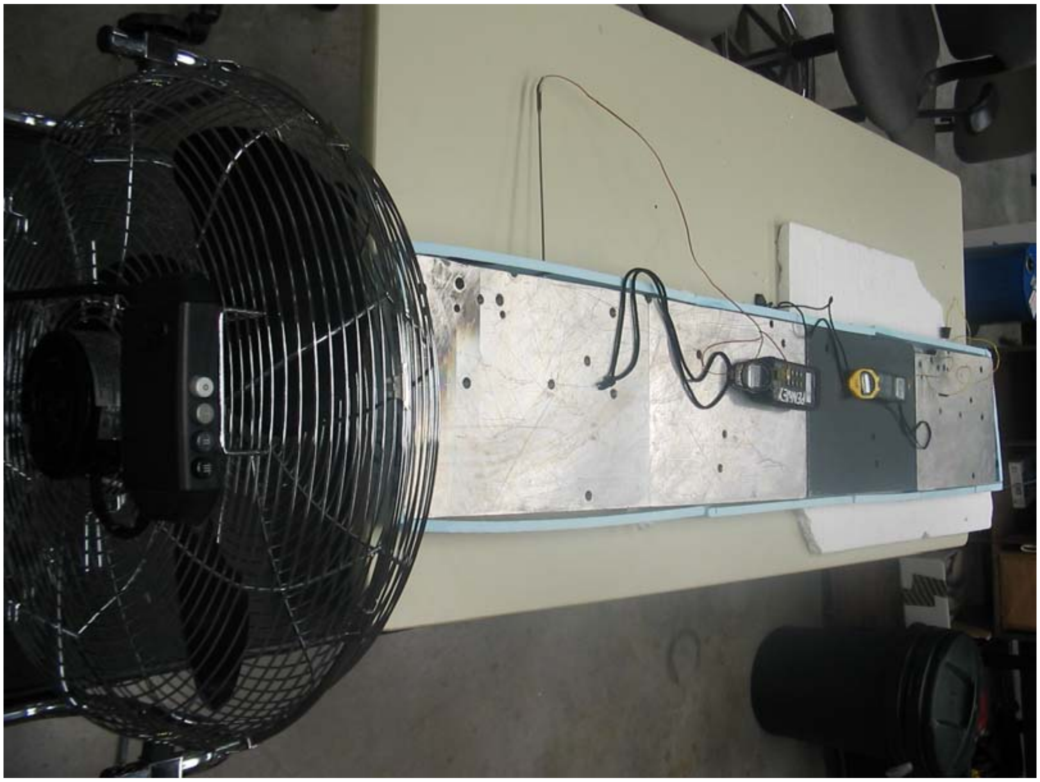

Figure 4. Experimental Apparatus for Determining the Heat Transfer Coefficients.

Experimental procedure:

1. Place two aluminum plates in the insulating box and close the lid.
2. Insert the sheath thermocouple into the plate.
3. Heat the insulating box by the hair dryer until the plate temperature is approximately 150F.
4. Remove one of the plates from the box and place it over the Styrofoam insulation.
5. Quickly put Styrofoam insulation around the hot plate except the top surface of the plate.
6. Air is forced to flow over that plate by the fan at 1100, 1500, or 1900 ft/min.
7. By using the thermocouple and the stopwatch, measure the change in temperature of plate vs. time.
8. Use the Anemometer to measure the speed of air over the plate at five different positions so that the average air speed can be computed.
9. Repeat those steps above for another two different speeds of the fan.
10. Remove the other plate from the insulating box and place it at fourth position counting from the first plate. Be sure there must be a 1cm between each plate to avoid conduction between the plates.
11. Again measure the change in temperature vs. time of the fourth plate with the thermocouple and the stopwatch at three difference fan speeds of 1100, 1500 and 1900 ft/min.
12. Also record the air speed over the fourth plate at five different positions for three different fan speeds.

Safety:

1. Wear the appropriate insulated gloves when touching the aluminum plates or removing out of the heating box.
2. Wear the safety glasses at all times when in the laboratory.
3. Be on guard when the fan is used.
4. Be extra careful not to drop the plates. They could severely damage a foot.

Data reduction procedure:

1. From the first law of thermo the heat balance over the entire plate is on the surface of the plate is

$$-q_{out} = q_A \quad (1)$$

2. In the process of cooling the plate, both radiation and convection occur from the surface of the plates. With both included, the overall energy balance becomes

$$mC_p\left(\frac{dT}{dt}\right) = h_{\exp}A_s(T_s - T_{sur}) + \varepsilon\delta A_s(T_s^4 - T_{sur}^4) \quad (2)$$

3. The polynomial regression analysis in TK Solver was used to create a graph of plate temperature vs. time and also obtain the coefficients b_1, b_2, and b_3. The equation that describes the relationship between the plate temperature and time is

$$T_s = b_1 + b_2 Time + b_3 Time^2 \quad (3)$$

4. The slope of the graph (dT/dt) is the derivative of plate temperature with respect to time. Figures 5 & 6 represent the TK program solving for the experimental heat transfer coefficient.

$$\frac{dT}{dt} = b_2 + 2b_3 Time \quad (4)$$

5. The mass of the plate is calculated from

$$m = \rho_{Al} * V_p = \rho_{Al} * l * w * H \quad (5)$$

6. The surface area of the plate is calculated from

$$A_s = l * w \quad (6)$$

The experimental heat transfer coefficient is determined from

$$h_{\exp} = \frac{mC_p\left(\frac{dT}{dt}\right) - \varepsilon\delta A_s(T_s^4 - T_{sur}^4)}{A_s(T_s - T_{sur})} \quad (7)$$

7. The Reynolds number varies along the length of the flat plate and at the end of the plate it becomes

$$\mathrm{Re} = \frac{\rho_{Air} VL}{\mu} \quad (8)$$

8. The following correlations, from equations from pages 373 and 374 in *Heat Transfer: A Practical Approach* by Yunus Cengel, are used to calculate the Nusselt number.

a. For laminar flow, the average Nusselt number over the entire plate is determined by the following equation

$$Nu = 0.664\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{1/3} \quad \text{where } \mathrm{Re} < 5*10^5 \tag{9}$$

b. For turbulent flow, the Nusselt number is equal to

$$Nu = 0.037\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \text{ where } 5*10^5 < \mathrm{Re} < 10^7 \;\&\; 0.6 \le \mathrm{Pr} \le 60 \tag{10}$$

9. The theoretical heat transfer coefficient is calculated from

$$h_{theor} = \frac{Nu * k}{l} \tag{11}$$

TK Figures of 1st plate and 4th plate

First plate

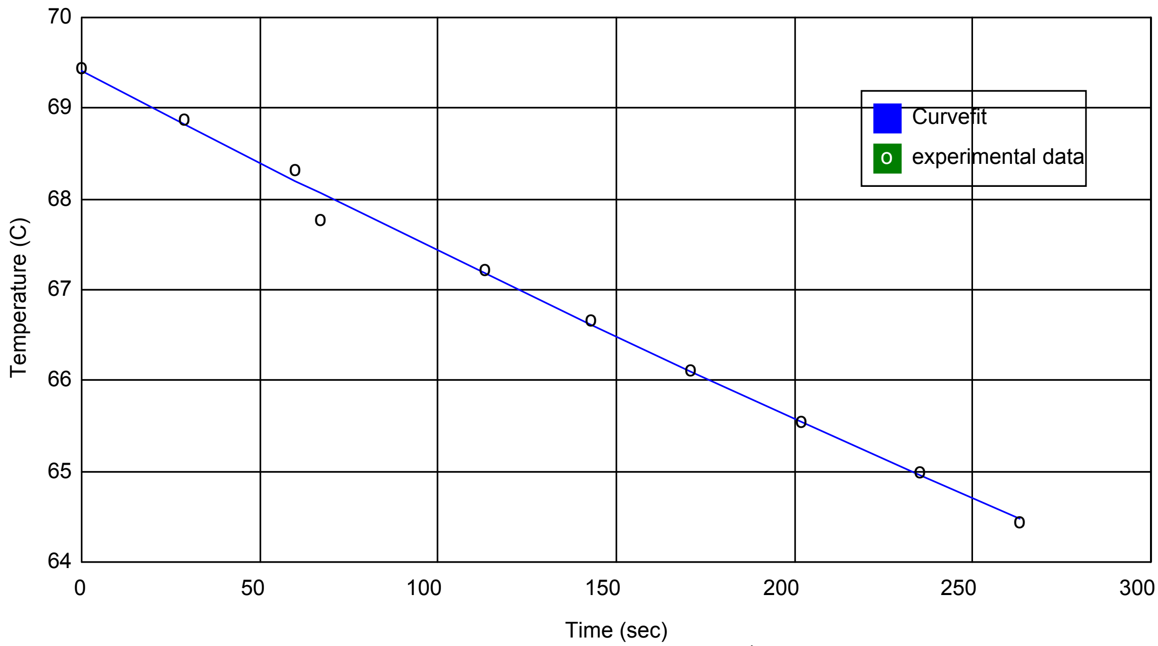

Figure 5 – the TK graph of temperature vs. time of the 1st plate at velocity of 968 ft/min

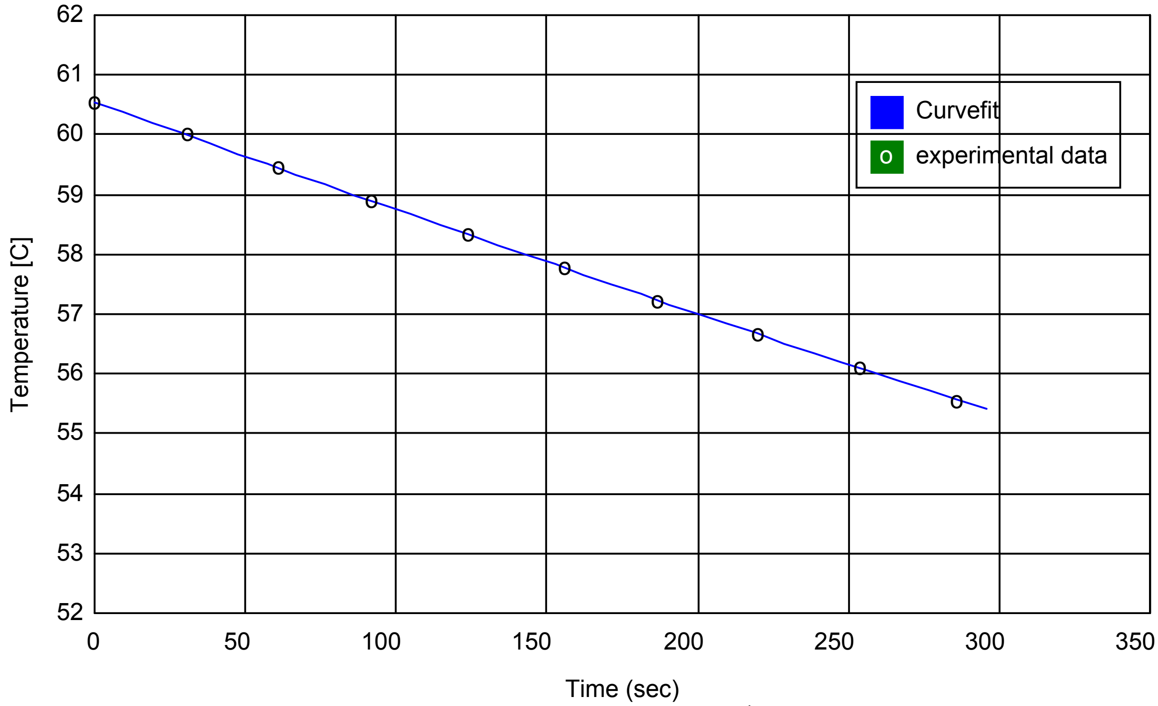

Figure 6 – The TK graph of temperature vs. time of the 1st plate at velocity of 1182 ft/min

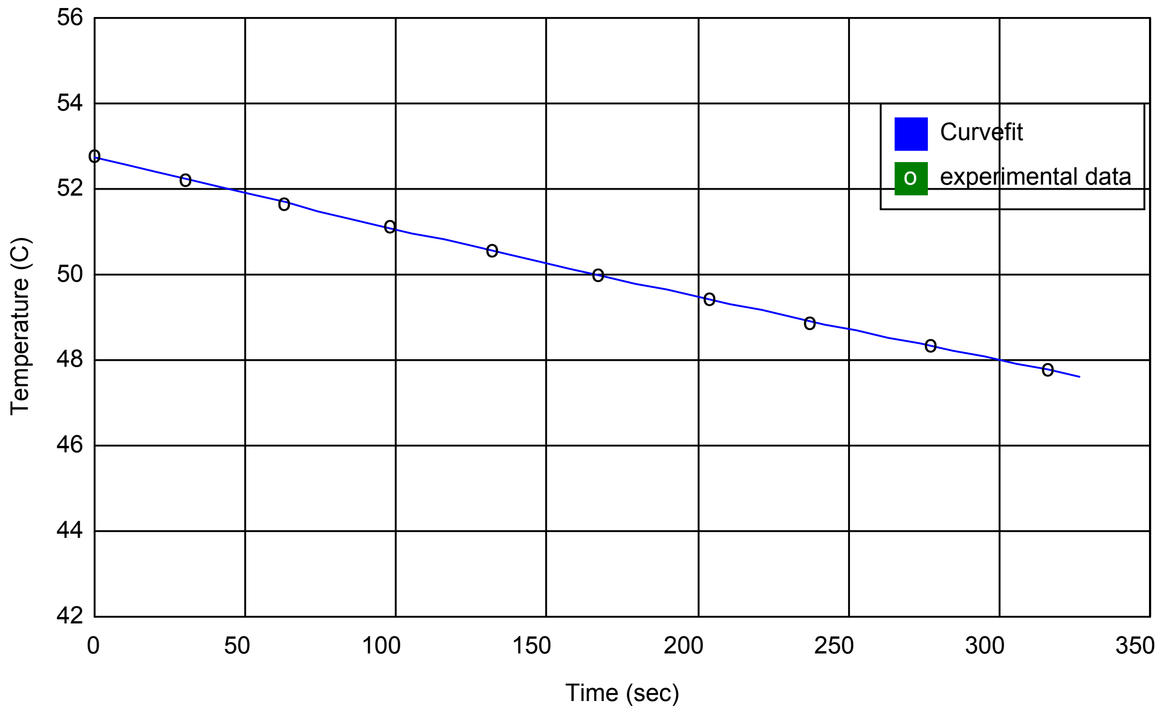

Figure 7 – The TK graph of temperature vs. time of the 1st plate at velocity of 1424 ft/min

Fourth plate

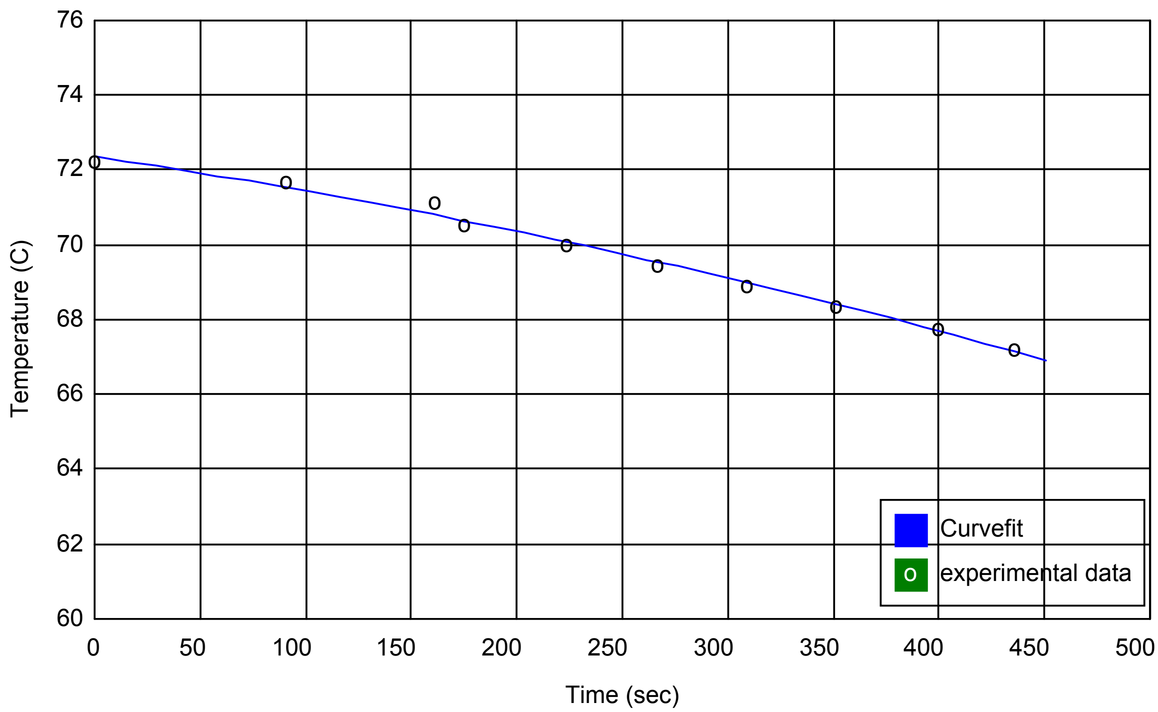

Figure 8 – The TK graph of temperature vs. time of the 4th plate at velocity of 738 ft/min

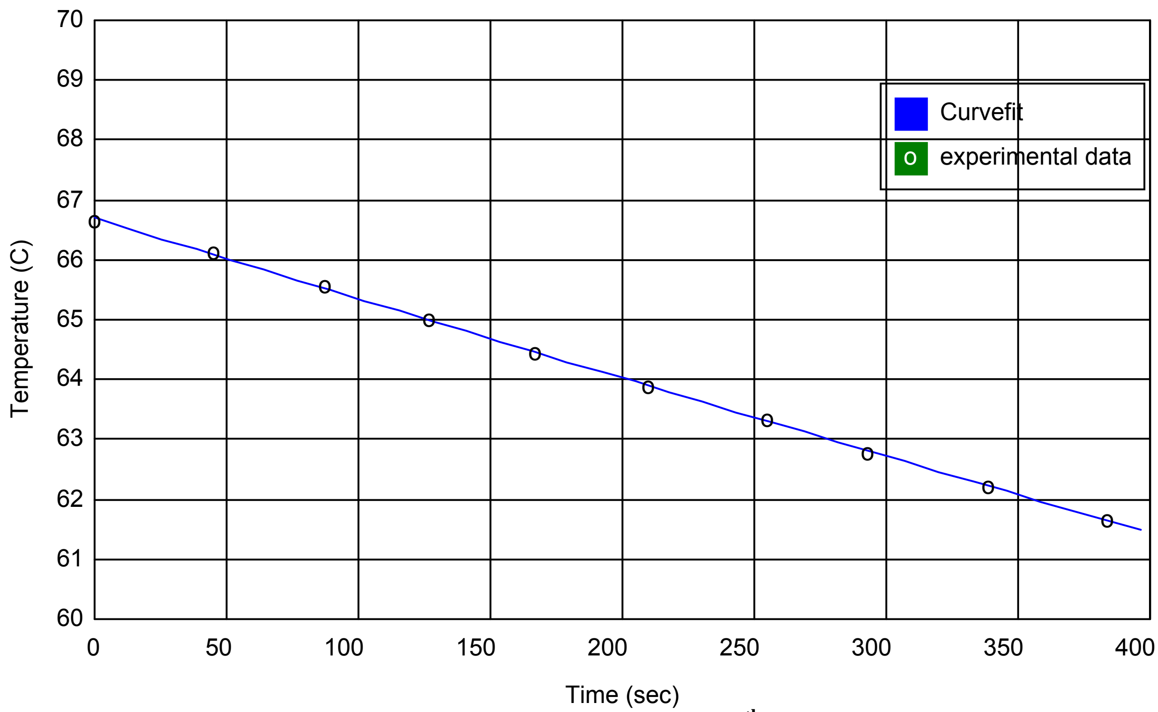

Figure 9 – The TK graph of temperature vs. time of the 4th plate at velocity of 912 ft/min

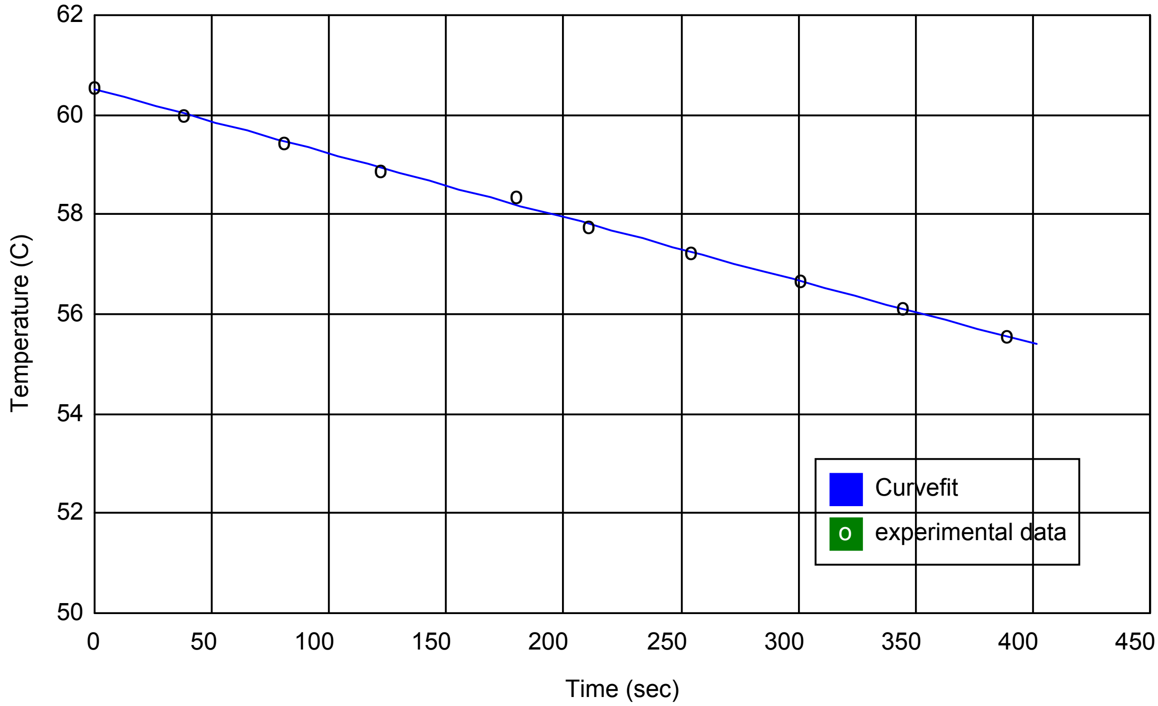

Figure 10 – The TK graph of temperature vs. time of the 4th plate at velocity of 1090 ft/min

Result Tables

Table 1 – Comparison of Experimental and Theoretical Heat Transfer Coefficients of the 1st Plate

Air velocity 968 ft/min			Air velocity 1182 ft/min			Air velocity 1424 ft/min		
h_{exp}	h_{theor}	% Error	h_{exp}	h_{theor}	% Error	h_{exp}	h_{theor}	% Error
40.7	12.6	223	45.0	14.0	221	53.7	15.3	251
40.4	12.6	221	45.1	14.0	222	53.7	15.3	251
40.0	12.6	217	45.3	14.0	224	53.7	15.3	251
39.9	12.6	217	45.5	14.0	225	53.6	15.3	250
39.4	12.6	213	45.7	14.0	226	53.6	15.3	250
39.0	12.6	210	45.8	14.0	227	53.5	15.3	250
38.6	12.6	206	46.0	14.0	229	53.3	15.3	248
38.1	12.6	202	46.2	14.0	230	53.1	15.3	247
37.6	12.6	198	46.4	14.0	231	52.9	15.3	246
37.1	12.6	194	46.6	14.0	233	52.6	15.3	244

Table 2 – Comparison of Experimental and Theoretical Heat Transfer Coefficients of 4^{th} Plate

Air velocity 738 ft/min			Air velocity 912 ft/min			Air velocity 1090 ft/min		
h_{exp}	h_{theor}	% Error	h_{exp}	h_{theor}	% Error	h_{exp}	h_{theor}	% Error
14.9	11.0	35.5	28.2	12.3	129	31.6	13.4	136
18.1	11.0	64.5	28.4	12.3	131	31.9	13.4	138
20.7	11.0	88.2	28.6	12.3	133	32.3	13.4	141
21.2	11.0	92.7	28.8	12.3	134	32.6	13.4	143
23.1	11.0	110.0	29.0	12.3	136	33.1	13.4	147
24.8	11.0	125.5	29.2	12.3	137	33.3	13.4	149
26.6	11.0	141.8	29.4	12.3	139	33.8	13.4	152
28.3	11.0	157.3	29.6	12.3	141	34.2	13.4	155
30.5	11.0	177.3	29.8	12.3	142	34.7	13.4	159
32.2	11.0	192.7	30.0	12.3	144	35.1	13.4	162

Discussion of the experiment results:

The results of the experiment are represented in Tables 1 & 2 and Figures 5-10. The experimental heat transfer coefficients at any air velocity are not a function of surface temperature; therefore, they should not be varied with change in temperature. However, these values did change over a small range. For example, the experimental heat transfer coefficient of the fourth plate at the air velocity of 912 ft/min changed from 28.16 to 30.04 W/m^2 C as the plate surface temperature varied from 66.69 to 61.64 C. The worst run in the experiment was the run with the air velocity of 738 ft/min over the fourth plate, which gave a huge variation in the heat transfer coefficients. In this run, the values of heat transfer coefficients went from 14. 93 to 32.17 W/m^2 C as the plate temperature decreased from 72.35 to 67.14 C.

Figures 5-10 indicate that the derivative of temperature with respect to time decreased as the temperature decrease, the experimental heat transfer coefficients should have the same behavior. However, except for the runs over the first plate at the air velocity of 968 and of 1424 ft/min, the experimental heat transfer coefficients increased as the temperature decreased.

Comparison of the experiment results with correlational calculation:

From Figures 6-10 and Tables 1 and 2, the students concluded that the experimental heat transfer coefficients do not agree with the theoretical values, which were calculated by using the Nusselt equations. The experimental values of heat transfer coefficient were higher than theoretical values. For instance, at the air velocity of 968 ft/min, the experimental heat transfer coefficient for the first plate is about 39 W/m^2 C while the theoretical value is 12.6 W/m^2C. The heat transfer coefficient over the 1^{st} plate had an average error of 229% from the theoretical heat transfer coefficient. The heat transfer coefficient for the 4^{th} plate had 134 % error.

Because of the transverse motion of eddies in turbulent flow, the heat transfer rate is greatly enhanced. As a result, turbulent flow is associated with much higher heat transfer coefficient. The high values for the experimental heat transfer coefficients observed in this experiment were due to the high turbulence generated by the fan. After comparing the heat transfer coefficient between the first and fourth plate, the students concluded that the heat transfer coefficient of the fourth plate is lower than that of the first plate. The main reason for that is the air velocity is lower in fourth plate than in the first plate. Consequently, the experimental heat transfer coefficient is smaller compared to that of the first plate.

Conclusions:

1. The experimental coefficients were much higher than the theoretical values. The reason for such high experimental coefficients is due to the fact that the fan generates turbulence on its own.
2. The experimental heat transfer coefficients, which were measured in the laboratory, were turbulent heat transfer coefficients.
3. Because the Reynolds numbers over the plate was below the critical Reynolds number ($5*10^5$), the flows of air were laminar. Therefore, the theoretical heat transfer coefficients were laminar heat transfer coefficients.

Recommendations:

1. Make duplicate runs at the same conditions to make sure that the data is consistent.
2. Use a different apparatus, such as a wind tunnel, to generate the airflow in order to avoid the error due to turbulence generated by the fan.

Experimental data

Table 3 – Experiment Data

1st Plate Air velocity 968 ft/min		1st Plate Air velocity 1182 ft/min		1st Plate Air velocity 1424 ft/min		4th Plate Air velocity 738 ft/min		4th Plate Air velocity 912 ft/min		4th Plate Air velocity 1090 ft/min	
Time	**Ts**	**Time**	**Ts**	**Time**	**Ts**	**Time**	**Ts**	**Time**	**Ts**	**Time**	**Ts**
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

NONMENCLATURE:

A_s - the surface area of the plate (m^2)
C_p - the aluminum specific heat (J/kg ^oC)
d – the length from the point of critical length to the end of the plate (m)
dT/dt - the derivative of the plate temperature with respect to time (T/^oC)
H – the height of the plate (m)

h_{exp} - the experimental forced heat transfer coefficient (W/m^2 ^{o}C)
h_{theor} – the theoretical heat transfer coefficient (W/m^2 ^{o}C)
k - the thermal conductivity of the air (W/m ^{o}C)
l - the length of the plate (m)
m - the aluminum plate mass (kg)
q_A - the accumulation duty (W)
q_{out} - the duty out of the plate (W)
T_s - the surface temperature of the plate ©
T_{sur} - the room air temperature ©
w – the width of the plate (m)

Dimensionless numbers:
Nu - the Nusselt number
Pr - the Prandtl number
Re - the Reynolds number

Greek Symbols:
δ - the Stefan-Boltzmann constant (W/m^2 K^4)
ε - the emissivity of the plate
μ - air viscosity (kg/m s)
ρ_{Al} - density of the aluminum plate (kg/m^3)
ρ_{Air} – density of air (kg/m^3)

References:

Cengel, Yunus. Heat Transfer: A Practical Approach, second edition, pg. 26 & 371 -374. McGraw-Hill, NY (2003).
McCabe, W. L., J.C.Smith, Unit Operations of Chemical Engineering, third edition, pg 309-344, McGraw-Hill, NY (1976).

TK solver programs

Table 4 – TK rule sheet for generating the regression equation for determining dT/dt

Status	Rule
Comment	; >>> Polynomial regression <<<
Satisfie	n = length('Y)
Satisfie	m = 'stat[1]
Satisfie	call matrix('Xs,'Y) ; generates matrix coefficients
Satisfie	call lineq2('a,'b,m+1) ; solves for regression coefficients
Satisfie	call standerr('Xs,'Y,'b;Syx,R2,SST) ; evaluates R2 and sums of squares
Satisfie	call statmaker(m,n,Syx,R2) ; puts results into interactive table
Satisfie	call curvemaker(m) ; generates the fitted polynomial
Satisfie	call residual(m,n;RSS) ; computes residuals
Satisfie	call anova(SST,RSS) ; generates ANOVA table (See Table Sheet)
Comment	; Note: Use interactive table 'works' for entering the experimental data
Comment	; and for specifying the order of the polynomial (STAT[1]).

Table 5 – TK Table showing the coefficients of the polynomial regression for the first plate at air velocity of 968 ft/min

Element	Time	Ts	residuals	SUMMARY	STATS
1	0	69.4	-6.870E-3	order	2
2	29	68.8	-1.775E-2	N	10
3	60	68.2	-1.011E-3	Syx	.028197287
4	67	68.1	+3.639E-2	adj R2	.999715181
5	113	67.2	+2.227E-2	p	3.30225E-6
6	143	66.6	-1.594E-2		
7	171	66.1	-2.960E-3	b0	69.4068702
8	202	65.5	-4.781E-2	b1	-.0205174
9	235	65	+2.837E-2	b2	6.99583E-6
10	263	64.5	+5.312E-3	b3	0

Table 6 – TK rule sheet for calculating experimental and theoretical heat transfer coefficients

Status	Rule
Comment	;PROGRAM FOR FORCED CONVECTION OVER A FLAT PLATE
Comment	;TO DETERMINE THE EXPERIMENT HEAT TRANSFER COEFFICIENT
Comment	;AT THE FIRST VELOCITY OF THE FAN
Satisfied	qa=-(qconv + qrad)
Satisfied	qa=M*Cp*(dTdt)
Satisfied	qconv=hexp*As*(Ts-Tsurr)
Satisfied	qrad=ε*δ*As*((Ts+273)^4 -(Tsurr+273)^4)
Satisfied	As=(w*.0254)*(l*0.0254)
Satisfied	M=ρ*Vol
Satisfied	Vol=(H*.0254)*(l*.0254)*(w*.0254)
Satisfied	dTdt=slope
Satisfied	As=(w*.0254)*(l*0.0254)
Satisfied	M=ρ*Vol
Satisfied	Vol=(H*.0254)*(l*.0254)*(w*.0254)
Comment	;CALCULATION THE SLOPE OF THE PLOT OF TEMP. VS. TIME
Satisfied	Ts = b1 - b2*Time + b3*Time^2
Satisfied	dTdt=-b2+2*b3*Time
Comment	;USING THE NUSSELT EQUATION
Comment	;TO CALCULATE THE THEORY HEAT TRANSFER COEFFIECIENT AT 1424FT/MIN
Satisfied	Tfilm=(Ts+Tsurr)/2
Satisfied	Vel=v*.00508; converts velocity in ft/min to m/s
Satisfied	Re=(Vel*(l*0.0254)*ρAir)/μAir
Comment	;Eq 7-19, p.373 Laminar flow heat transfer corrleation for a flat plate
Satisfied	NuLaminar=2*(0.332)*Re^(1/2)*Pr^(1/3)
Satisfied	NuLaminar=(hLaminar*l*.0254)/kAir
Comment	;Eq. 7-24 p. 374 Turbulent flow heat transfer correlation for a flat plate
Satisfied	NuTurb=(0.037*Re^(0.8)-871)*Pr^(1/3)
Satisfied	NuTurb=(hTurb*l*.0254)/kAir
Satisfied	IF Re>500000 THEN h=hTurb ELSE h=hLaminar

Table 7 – TK variable sheet for calculating experimental and theoretical heat transfer coefficients

Status	Input	Name	Output	Unit	Comment
					FORCED CONVECTION OVER THE FIRST PLATE
					AT AIR VELOCITY OF 968 FT/MIN
					*** POLYNOMIAL REGRESSION***
	69.417835	b1			The coefficient in the polynomial equation
	.020636267	b2			The coefficient in the polynomial equation
	7.17698E-6	b3			The coefficient in the polynomial equation
L	113	Time			The change in time corresponding to the change in temperature
					***DATA FOR CALCULATING THE EXPERIMENTAL
					AND THEORY HEAT TRANSFER COEFFICIENT***
L		qa	-246.31955	W	The accumulation duty
L		qconv	242.255649	W	The convection duty
L		qrad	4.06389974	W	The radiation duty
	903	Cp		J/kg C	The aluminum specific heat (Table A-3, p.858)
L		dTdt	-.01901427	C/s	The derivative of the temperature with respect to time
L		hexp	39.3505502	W/m^2 C	The experimental heat transfer coefficient
		As	.13935456	m^2	The plate surface exposed to the air
L		Ts	67.1775797	C	The average temperature of the plate surface
	23	Tsurr		C	The air temperature
	.09	ε			The emissivity of the aluminum plate (Table A-18, p.878)
	5.67E-8	δ		W/m^2 K^4	The Stefan-Boltzmann constant
	12	w		in	The width of the plate
	18	l		in	The length of the plate
	2702	ρ		kg/m^3	The aluminum plate density (Table A-3, p.858)
		Vol	.005309409	m^3	The volume of the aluminum plate
	1.5	H		in	The height of the plate
		Tfilm	45.0887898	C	The film temperature
		Vel	4.91744	m/s	The average velocity of air in m/s
	968	v		ft/min	The average velocity of air in ft/min
		Re	128455.085		The Reynolds number
	1.109	ρAir		kg/m^3	The density of air at film temperature (Table A-15,p.856)
	.00001941	μAir		kg/m s	The air viscosity at film temperature (Table A-15,p.856)
		NuLamina	213.702653		The laminar Nusselt number
	.7241	Pr			The Prantdl number at film temperature (Table A-15,p.856)
		hLaminar	12.6155612	W/m^2 C	The laminar heat transfer coefficient
	.02699	kAir		W/m C	The air thermal conductivity at film temperature (Table A-15)
		NuTurb	-376.19308		The turbulent Nusselt number
		hTurb	-22.207898	W/m^2 C	The turbulent heat transfer coefficient