Solar Flux and Absorptivity Measurements: A Design Experiment in Undergraduate Heat Transfer

W. Roy Penney, Kendal J. Brown, Joel D. Vincent and Edgar C. Clausen

Ralph E. Martin Department of Chemical Engineering
University of Arkansas

Introduction

A number of methods have been developed for enhancing student learning including multimedia developments[1,2], active, problem-based learning[3], collaborative learning[4,5], and participation in cooperative education[6]. Several papers have specifically addressed methods for improving or supplementing the teaching of heat transfer including the use of spreadsheets to solve two-dimensional heat transfer problems[7], the use of a transport approach in teaching turbulent thermal convection[8], the use of computers to evaluate view factors in thermal radiation[9], implementation of a computational method for teaching free convection[10], and the use of an integrated experimental/analytical/numerical approach that brings the excitement of discovery to the classroom[11]. Supplemental heat transfer experiments for use in the laboratory or classroom have also been presented, including rather novel experiments such as the drying of a towel[12] and the cooking of French fry-shaped potatoes[13]. Suggestions for the integration of heat transfer course material into the laboratory and classroom were described by Penney and Clausen[14-19], who presented a number of simple hands on heat transfer experiments that can be constructed from materials present in most engineering departments. This cross-course integration of course material has been shown to be a very effective learning tool that causes students to think beyond the content of each individual course[20], and will be the subject of this paper.

As part of the requirements for CHEG 3143, Heat Transport, junior level chemical engineering students at the University of Arkansas were required to execute design project assignments which illustrate a concept from the course. One of these experiments required a student group of two students to:

- measure the solar flux at various angles of incidence on a black (painted) aluminum plate and compare the result with data from the National Weather Service, and
- using the solar flux, measure the absorptivity of unpainted aluminum

The group was required to write a fully documented TK (Tool Kit) computer program to perform the design calculations, and to write a formal report that fully details the experimental work.

The purpose of this paper is to describe the required apparatus and procedures for this relatively simple experiment, and to present results from calculations used in obtaining the solar fluxes as a function of the angle of incidence and the absorptivity. Exercises such as this are effective in urging the students to apply the principles of heat transfer to actual physical systems, and thus to better visualize physical applications of classroom principles.

Conceptual Heat Transfer Background

All matter emits a characteristic amount of electromagnetic radiation. When this radiation is absorbed by another object, the thermal state of the object is changed and radiation heat transfer takes place. The radiation heat transfer between two objects is proportional to the difference in their temperatures raised to the fourth power, given by the Stefan-Boltzmann law[21]:

$$Q = \varepsilon\sigma A\left(T_1^4 - T_a^4\right) \quad (1)$$

When an object is exposed to a radiation flux such as solar radiation, only a certain amount of the incident radiation is absorbed by the surface of the object, α:

$$Q_{absorbed} = \alpha Q_{incident} \quad (2)$$

In this experiment, Equation (2) was used to calculate the incident solar flux by experimentally measuring the rate of heat transfer absorbed by the surface and the known solar absorptivity for a black surface. A black (painted) aluminum plate was used as the surface, and a thermocouple was attached to the surface to measure temperature with time. To begin the experiment, the plate was first cooled to below ambient temperature, and then placed inside a glass picture frame backed with insulation. The frame was oriented toward the sun at a selected angle of incidence, and the temperature was measured as a function of time. To determine the solar flux, a transient model was first developed to describe the heat transfer to the plate. The solar flux was changed by iteration until the theoretical temperature profile closely fit the experimental data. The experiment was repeated for several angles of incidence.

The experimental solar flux was used to calculate the solar absorptivity of the unpainted side of a milled aluminum plate. The temperature profile of the unpainted plate, as it was exposed to the sun, was determined in the same fashion as described above. The transient model was again used, but the absorptivity was now determined by iteration while using the experimental solar flux.

The remainder of this paper describes the experiment as developed by one of the teams engaged in this classroom/laboratory activity. The data that are presented could vary based on the actual context of the experiment, but the structure of the experiment serves as an example of a complete, well executed instructional activity.

Experimental Equipment and Supplies List

The following supplies and equipment were used to perform the experiment. Of course, the size of the plate and corresponding picture frame are not critical to the experiment, and the size given below reflects what was available to the students.

- 26cm x 34cm picture frame with a glass plate, but no backing
- Dow Styrofoam® insulation, 2 in thick
- Packing tape
- 26cm x 34cm aluminum plate, 1/8 in thick
- Non-reflective black spray paint
- Stopwatch
- Thermocouple and reader
- Watertight bag of ice

Experimental Procedure

A schematic drawing of the experimental apparatus is presented in Figure 1, and photographs of the experimental apparatus for both parts of the experiment are presented in Figures 2 and 3.

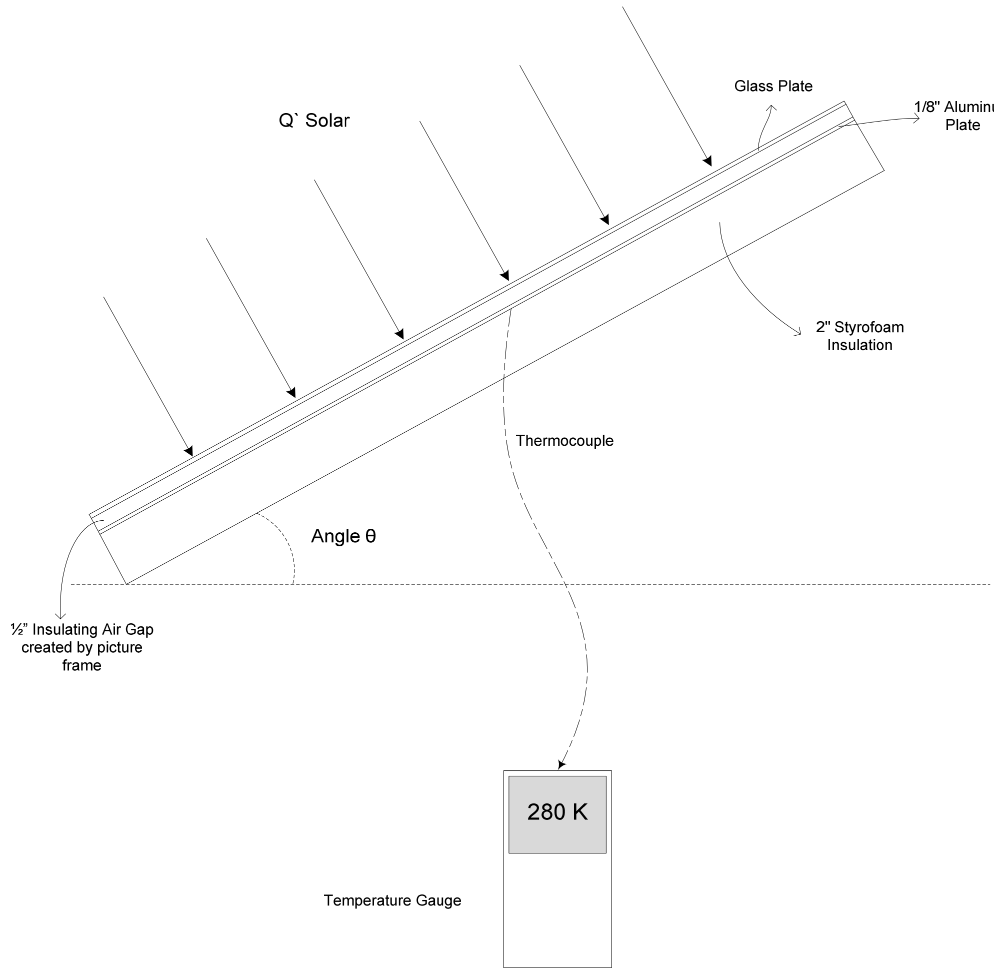

Figure 1. Schematic of Experimental Apparatus

Setup/Testing

The experimental procedure for determining the solar flux as a function of the angle of incidence is as follows:

1. Securely attach the picture frame to the insulation using the packing tape in a manner that allows the aluminum plate to rest inside the picture frame with its back directly against the insulation.
2. Spray paint one side of the aluminum plate with the non-reflective paint, making sure that the entire plate is covered evenly.
3. Once the paint has dried, tape the thermocouple to the center of the unpainted side of the plate

4. Place the bag of ice on top of the black side of the plate until the temperature of the plate falls below 65°F.
5. Dry the plate and place it inside the picture frame, with the painted side facing out.
6. Place the glass plate in the picture frame above the aluminum plate.
7. Orient the entire apparatus normal to the sunlight by arranging it so that a rod placed normal to the surface of the plate does not cast a shadow.
8. Beginning at 65°F, record the amount of time required for the plate to increase each 1°F, until the plate reaches 85°F.
9. Remove the plate from the frame and, once again, place under ice.
10. Repeat the experiment for other angles of incidence.

To determine the solar absorptivity of the unpainted side of the plate, repeat the experiment with the unpainted side of the plate facing the sun, and with the thermocouple attached to the painted side.

Figure 2. Experimental Setup with Black Side of Plate Facing Forward

Figure 3. Experimental Setup Showing Unpainted Side with Thermocouple

Safety Concerns

1. Wear safety glasses at all times during experimentation.
2. Use caution when handling the aluminum plate and cover glass. Both are sharp and may puncture or cut skin.

Experimental Results

Time-temperature data for the black plate at different angles of incidence from the sun are shown in Table 1, and time-temperature data for the unpainted aluminum plate, placed normal to the sun, are shown in Table 2. As expected, the time for the black plate to heat to a final temperature of 85°F increased with the angle of incidence. In addition, the black plate heated much faster than the aluminum (unpainted) plate, when both plated were oriented normal to the sun.

Table 1. Experimental Time/Temperature Data for the Black Plate at Different Angles of Incidence, θ

Temperature, °F	**Time, sec**		
	θ = 0°	**θ = 45°**	**θ = 60°**
65	0	0	0
66	6.5	4.9	6.0
67	11.3	10.3	11.9
68	15.8	14.9	18.3
69	19.3	19.5	24.6
70	21.8	24.9	31.0
71	24.0	30.0	37.3
72	27.9	35.4	44.2
73	31.5	40.4	50.5
74	36.0	45.9	56.9
75	40.3	51.8	63.7
76	44.2	57.2	70.1
77	48.8	63.2	77.4
78	53.8	68.7	84.3
79	57.6	74.6	91.0
80	62.7	80.5	99.2
81	67.0	86.9	106.0
82	71.5	92.8	113.3
83	76.6	98.8	120.7
84	81.1	105.6	128.4
85	86.1	111.6	135.3

Table 2. Experimental Time/Temperature Data for the Aluminum Plate, Placed Normal to the Sun (θ = 0°)

Temperature, °F	**Time, sec**
61	0
62	11.6
63	24.8
64	37.6
65	51.8
66	64.0
67	78.5
68	93.0
69	106.3
70	121.3
71	136.3
72	151.3

73	166.8
74	182.3
75	198.3
76	212.3
77	226.4
78	240.0
79	256.5
80	271.4
81	284.6

Simulation and Data Reduction

Based on information they had received during course instruction, the students were required to develop a model mathematical model of the experimental process. To calculate the solar flux incident to the aluminum plate, a heat balance is first performed over the plate:

$$Q_{in} - Q_{out} + Q_{gen} = Q_{acc} \tag{3}$$

With no heat generation by the plate, Equation (3) reduces to:

$$Q_{in} - Q_{out} = Q_{acc} \tag{4}$$

The heat accumulated in the system is given by the equation:

$$Q_{acc1} = \rho_{al} A \Delta x_p Cp_{al} \left(\frac{dT_1}{dt}\right) \tag{5}$$

and the heat entering the plate is given by:

$$Q_{in1} = A \tau_g \alpha \, Q_{solar} \tag{6}$$

The heat leaving the plate is given by the equation:

$$Q_{out1} = \varepsilon \sigma A \left(T_1{}^4 - T_{sky}{}^4\right) - \frac{kA(T_2 - T_1)}{\Delta x/2} \tag{7}$$

Substituting Equations (5), (6), and (7) into Equation (4) and isolating $\frac{dT_1}{dt}$ yields:

$$\left(\frac{dT_1}{dt}\right) = \frac{\alpha \, Q_{solar}}{\rho_{al} Cp_{al} \Delta x_p} - \frac{\varepsilon \sigma \left(T_1{}^4 - T_{sky}{}^4\right)}{\rho_{al} Cp_{al} \Delta x_p} + \frac{2k(T_2 - T_1)}{\rho_{al} Cp_{al} \Delta x \Delta x_p} \tag{8}$$

To accurately model the system, a nodal analysis must also be written over the insulation. With no heat generated, Equation (4) should be used in the case of the first node, which is modeled as a half node. Thus, the heat accumulated in the first insulation node is given by the equation:

$$Q_{acc2} = \rho_{insul} A \Delta x Cp_{insul} \left(\frac{dT_2}{dt}\right) \tag{9}$$

and the heat entering the first insulation node is given by:

$$Q_{in2} = \frac{kA(T_1 - T_2)}{\Delta x/2} \tag{10}$$

The heat leaving the first insulation node is given by the equation:

$$Q_{out2} = -\frac{kA(T_3 - T_2)}{\Delta x} \tag{11}$$

Substituting Equations (9), (10), and (11) into Equation (4) and isolating $\frac{dT_2}{dt}$ yields:

$$\left(\frac{dT_2}{dt}\right) = \frac{k(2T_1 + T_3 - 3T_2)}{\rho_{insul} Cp_{insul} \Delta x^2} \tag{12}$$

Next, the interior nodes must be considered. The heat accumulated in the ith node (for i = 3-19) is given by the equation:

$$Q_{acci} = \rho_{insul} A \Delta x Cp_{insul} \left(\frac{dT_i}{dt}\right) \tag{13}$$

The heat entering the ith node is given by the equation:

$$Q_{ini} = \frac{kA(T_{i-1} - T_i)}{\Delta x} \tag{14}$$

and the heat leaving the ith node is given by:

$$Q_{out2} = -\frac{kA(T_{i-1} - T_i)}{\Delta x} \tag{15}$$

Substituting Equations (13), (14), and (15) into Equation (4) and isolating $\frac{dT_i}{dt}$ yields:

$$\left(\frac{dT_i}{dt}\right) = \frac{k(2T_{i+1} + T_{i-1} - 2T_i)}{\rho_{insul} Cp_{insul} \Delta x^2} \tag{16}$$

Finally a heat balance must be performed over the last node, which is treated as though no heat is leaving the insulation. Convection leaving from the back side could be considered but, for the time span of this experiment, these effects are assumed to be negligible. Thus, Equation (3) simplifies to:

$$Q_{in} = Q_{acc} \tag{17}$$

The heat accumulated in the last node is given by the equation:

$$Q_{acc20} = \rho_{insul} A \Delta x Cp_{insul} \left(\frac{dT_{20}}{dt}\right) \tag{18}$$

and the heat entering the last node is given by:

$$Q_{in20} = \frac{kA(T_{19} - T_{20})}{\Delta x / 2} \tag{19}$$

Substituting Equations (18) and (19) into Equation (17) and isolating $\frac{dT_{20}}{dt}$ yields:

$$\left(\frac{dT_{20}}{dt}\right) = \frac{2k(T_{19} - T_{20})}{\rho_{insul} Cp_{insul} \Delta x^2} \tag{20}$$

Equation (7) is solved using the ODE STIFFR program in TK Solver®. Q_{solar} is found by adjusting its value until $\frac{dT}{dt}$ matches the recorded experimental data. A copy of a TK Solver® program is appended. In the case of the sun's rays being normal to the plate, a measured Q_{solar}

is known. Therefore, the results of the calculated Q_{solar} can be compared with the actual Q_{solar} using the equation:

$$\%error = \frac{Calculated - Actual}{Actual} * 100 \quad (21)$$

For the cases where the solar fluxes are incident at 45° and 60°, the following equation is used to determine the actual solar flux.

$$Q_{solar\theta} = Q_{solar}\cos(\theta) \quad (22)$$

The above procedure was also used to analyze the data for solar flux incident at angles of 45° and 60°. The calculated solar flux for the sun's rays normal to the plate is then used to calculate the solar absorptivity (α) of aluminum. The absorptivity is found by varying α until $\frac{dT}{dt}$ matches the recorded experimental data. This calculated absorptivity can then be compared with the actual absorptivity of aluminum from the literature using Equation (21).

Results and Discussion

Figure 4 shows a plot of temperature (K) as a function of time (s) for the black (painted) surface placed normal to the sun (θ = 0°). Both the experimental data from Table 1 and the predicted temperatures from the model development and the solar flux which causes the model to best fit the experimental data (750 W/m^2) are presented. Similar plots were obtained for the black surface placed at angles of 45° and 60°, and for the unpainted aluminum surface placed normal to the sun. This good correlation between experimental data and the model correlation indicates that the assumptions made about convection leaving the plate were valid.

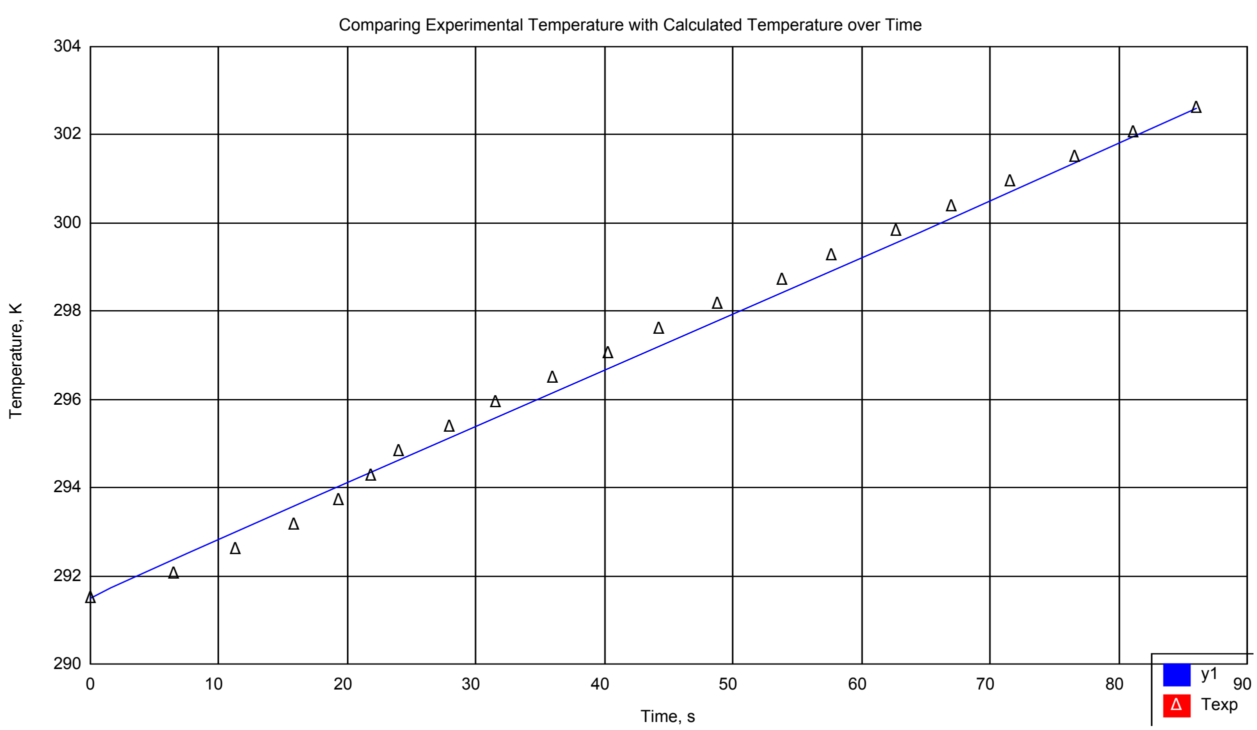

Figure 4. Experimental Temperature Measurements (Δ) and Predicted Temperatures (--) with Time for Black (Painted) Surface Placed Normal to the Sun ($\theta = 0°$)

Table 2a shows a comparison of the experimentally determined solar fluxes and the solar fluxes measured by the National Weather Service in Westville, OK[22]. The National Weather Service in Westville, OK is located 23 miles west of Fayetteville, AR (where the experiment was performed), and is at a similar elevation. The National Weather Service data were recorded at 11:00 am on April 7, 2008, essentially the same time that the experimental data were taken. The experimental solar fluxes matched the fluxes generated by the National Weather Service with a maximum error of 4%, quite good for an experiment of this type. Table 2b shows a comparison of the experimentally determined solar absorptivity of the unpainted milled aluminum plate and the absorptivity from the EPA[23]. As is noted, the experimental absorptivity of 0.13 falls within the accepted range of 0.10-0.15 for milled aluminum, as found by the EPA.

Table 2a. Comparison of Experimental Solar Fluxes with Fluxes Generated by the National Weather Service (NWS) in Westville, OK at Different Angles of Incidence

Angle of Incidence	Solar Flux, W/m^2		% Error
	Experimental	NWS	
0°	750	750	0
45°	525	530	1
60°	390	375	4

Table 2b. Comparison of Milled Aluminum Solar Absorptivities, Determined Experimentally and from the Literature

Absorptivity	
Experimental	from literature[22]
0.13	0.10-0.15

[22] http://www.epa.gov/ttn/chief/old/ap42/ch07/s01/draft/d7s01_table7_1_6.pdf

Conclusions/Observations

Despite problems in accurately measuring the angle of incidence and in obtaining solar flux information for the exact site of the experimental measurements, the experimental solar fluxes agreed very well with the fluxes obtained by the National Weather Service in Westville, OK. The solar fluxes were found to decrease with increasing angle of incidence, from 750-390 W/m^2, as the angle of incidence was increased from 0° to 60°. In measuring the solar absorptivity of milled aluminum, the experimental value of 0.13 was well within the range presented by the EPA.

Educationally, the students were presented with an application of heat transfer correlations and techniques presented in class, and they obtained reasonable estimates of the solar fluxes as a function of the angle of incidence and the solar absorptivity of milled aluminum.

Nomenclature

A	area for heat transfer, m^2
C_{pinsul}	specific heat of insulation, J/kg·K
C_{pal}	specific heat of aluminum, J/kg·K
i	node number, 1-20 (as subscript)
k	thermal conductivity, W/m·K
N	number of nodes
Q_{acc}	heat accumulation, W
Q_{gen}	heat generation, W
Q_{in}	heat transferred in, W
Q_{out}	heat transferred out, W
Q_{solar}	solar flux, W/m^2
$Q_{solar\theta}$	actual solar flux, W/m^2
T	temperature, 252 K
T_{sky}	effective sky temperature, K
t	time, s
α	solar absorptivity
Δx	node thickness, m
Δx_p	thickness of plate, m
ε	emissivity of black paint, 0.98
θ	angle of incidence, °
σ	Stefan Boltzmann constant, 5.67×10^{-8} $W/m^2 \cdot K$
ρ	density of insulation, 24 kg/m^3
ρ_{al}	density of aluminum, 2702 kg/m^3
τ_s	solar transmissivity (of glass), 0.88

References

1. Ellis, T., 2004, "Animating to Build Higher Cognitive Understanding: A Model for Studying Multimedia Effectiveness in Education," *Journal of Engineering Education*, Vol. 93, No. 1, pp. 59-64.
2. Wise, M., Groom, F.M., 1996, "The Effects of Enriching Classroom Learning with the Systematic Employment of Multimedia" *Education*, Vol. 117, No. 1, pp. 61-69.
3. Grimson, J., 2002, "Re-engineering the Curriculum for the 21st Century," *European Journal of Engineering Education*, Vol. 27, No. 1, pp. 31-37.
4. Bjorklund, S.A., Parente, J.M., Sathianathan, D., 2004, "Effects of Faculty Interaction and Feedback on Gains in Student Skills," *Journal of Engineering Education*, Vol. 93, No. 2, pp. 153-160.
5. Colbeck, C.L., Campbell, S.E., Bjorklund, S.A., 2000, "Grouping in the Dark: What College Students Learn from Group Projects," *Journal of Engineering Education*, Vol. 71, No. 1, pp. 60-83.
6. Blair, B.F., Millea, M., Hammer, J., 2004, "The Impact of Cooperative Education on Academic Performance and Compensation of Engineering Majors," *Journal of Engineering Education*, Vol. 93, No. 4, pp. 333-338.
7. Besser, R.S., 2002, "Spreadsheet Solutions to Two-Dimensional Heat Transfer Problems." *Chemical Engineering Education*, Vol. 36, No. 2, pp. 160-165.
8. Churchill, S.W., 2002, "A New Approach to Teaching Turbulent Thermal Convection," *Chemical Engineering Education*, Vol. 36, No. 4, pp. 264-270.
9. Henda, R., 2004, "Computer Evaluation of Exchange Factors in Thermal Radiation," *Chemical Engineering Education*, Vol. 38, No. 2, pp. 126-131.

10. Goldstein, A.S., 2004, “A Computational Model for Teaching Free Convection,” *Chemical Engineering Education*, Vol. 38, No. 4, pp. 272-278.
11. Olinger, D.J., Hermanson, J.C., 2002, “Integrated Thermal-Fluid Experiments in WPI’s Discovery Classroom,” *Journal of Engineering Education*, Vol. 91, No. 2, pp. 239-243.
12. Nollert, M.U., 2002, “An Easy Heat and Mass Transfer Experiment for Transport Phenomena,” *Chemical Engineering Education*, Vol. 36, No. 1, pp. 56-59.
13. Smart, J.L., 2003, “Optimum Cooking of French Fry-Shaped Potatoes: A Classroom Study of Heat and Mass Transfer,” *Chemical Engineering Education*, Vol. 37, No. 2, pp. 142-147, 153.
14. Clausen, E.C., Penney, W.R., Marrs, D.C., Park, M.V., Scalia, A.M., N.S. Weston, N.S., 2005, “Laboratory/Demonstration Experiments in Heat Transfer: Thermal Conductivity and Emissivity Measurement,” *Proceedings of the 2005 American Society of Engineering Education-Gulf Southwest Annual Conference*.
15. Clausen, E.C., Penney, W.R., Dorman, J.R., Fluornoy, D.E., Keogh, A.K., Leach, L.N., 2005, “Laboratory/Demonstration Experiments in Heat Transfer: Laminar and Turbulent Forced Convection Inside Tubes,” *Proceedings of the 2005 American Society of Engineering Education-Gulf Southwest Annual Conference*.
16. Clausen, E.C., Penney, W.R., Colville, C.E., Dunn, A.N., El Qatto, N.M., Hall, C.D., Schulte, W.B., von der Mehden, C.A., 2005, “Laboratory/Demonstration Experiments in Heat Transfer: Free Convection,” *Proceedings of the 2005 American Society of Engineering Education-Midwest Section Annual Conference*.
17. Clausen, E.C., Penney, W.R., Dunn, A.N., Gray, J.M., Hollingsworth, J.C., Hsu, P.T., McLelland, B.K., Sweeney, P.M., Tran, T.D., von der Mehden, C.A., Wang, J.Y., 2005, “Laboratory/Demonstration Experiments in Heat Transfer: Forced Convection,” *Proceedings of the 2005 American Society of Engineering Education-Midwest Section Annual Conference*.
18. Clausen, E.C., Penney, W.R., 2006, “Laboratory Demonstrations/Experiments in Free and Forced Convection Heat Transfer,” *Proceedings of the 2006 American Society for Engineering Education Annual Conference and Exposition*.
19. Penney, W.R., Lee, R.M., Magie, M.E. and Clausen, E.C., 2007, “Design Projects in Undergraduate Heat Transfer: Six Examples from the Fall 2007 Course at the University of Arkansas,” *Proceedings of the 2007 American Society of Engineering Education Midwest Section Annual Conference*.
20. Birol, G., Birol, Í., Çinar, A., 2001, “Student-Performance Enhancement by Cross-Course Project Assignments: A Case Study in Bioengineering and Process Modeling,” *Chemical Engineering Education*, Vol. 35, No. 2, pp. 128-133.
21. Çengel, Y.A., 2007, *Heat Transfer: A Practical Approach*, 3rd edition, McGraw-Hill Book Company, New York.
22. National Weather Service Forecast Office, Tulsa, OK, personal communication.
23. http://www.epa.gov/ttn/chief/old/ap42/ch07/s01/draft/d7s01_table7_1_6.pdf, accessed June 24, 2008.

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.

KENDAL J. BROWN, JOEL D. VINCENT
Mr. Brown and Mr. Vincent are junior level chemical engineering students at the University of Arkansas. They participated with their classmates (in groups of two) in performing design exercises as part of the requirements for CHEG 3143, Heat Transport.

EDGAR C. CLAUSEN
Dr. Clausen currently serves as Professor, Associate Department Head and the Ray C. Adam Endowed Chair in 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.

TK Solver Example Solution (black (painted) surface, placed normal to sun)

Status	Statement
Comme	;THIS PROGRAM CALCULATES THE TRANSIENT TEMPERAURE DISTRIBUTION IN A
Comme	; ALUMINUM PLATE AND THE INSULATION IT IS SITTING ON AS IT RECIEVES SOLAR
Comme	;RADIATION NORMAL TO ITS SURFACE
Activ	W=.26 ;;;WIDTH OF ALUMINUM PLATE, m
Activ	L=.34 ;;;LENGTH OF ALUMINUM PLATE, m
Activ	A=L*W ;;;AREA OF ALUMINUM PLATE, m^2
Activ	thick=2*.0254 ;;;THICKNESS OF INSULATION, m
Activ	k=.023 ;;;THERMAL CONDUCTIVITY OF INSULATION, W/m*K
Activ	N=20 ;;;NUMBER OF NODES
Activ	Δx=thick/(N-1) ;;;NODE THICKNESS, m
Activ	Cp=1600 ;;;SPECIFIC HEAT OF INSULATION, J/kg*K
Activ	ρ=24 ;;;DENSITY OF INSULATION, kg/m^3
Activ	ρal=2702 ;;;DENSITY OF ALUMINUM, kg/m^3
Activ	Cpal=903 ;;;SPECIFIC HEAT OF ALUMINUM, J/kg*K
Activ	α=.97 ;;;ABSORPTIVITY OF BLACK PAINT
Activ	ε=.98 ;;;EMISSIVITY OF BLACK PAINT
Activ	σ=5.67*10^-8 ;;;STEFAN-BOLTZMAN CONSTANT, W/m^2*K^4
Activ	τs=.88 ;;;SOLAR TRANSMISSIVITY OF GLASS
Activ	Qsolar=750 ;;;SOLAR FLUX, W/m^2
Activ	Tsky=252 ;;;EFFECTIVE SKY TEMPERATURE, K
Activ	c=(σ*ε)/(ρal*Cpal*Δx) ;;;EXPRESSION FOR RADIATION LEAVING PLATE
Activ	b = α*τs/(ρal*Cpal*Δx) ;;;EXPRESSION FOR RADIATION ENTERING PLATE
Activ	a = (k)/(ρal*Δx^2*Cpal) ;;;EXPRESSION FOR CONDUCTION INTO INSULATION
Activ	a1 = (k)/(ρ*Δx^2*Cp) ;;;EXPRESSION FOR CONDUCTION THROUGH INSULATION
Comme	;;;TEMPERATURES FOR PLATE VERSUS TIME
Activ	Y`[1] = (b*Qsolar)+(2*a*(Y[2]-Y[1]))+(c*(Y[1]^4-Tsky^4))
Comme	;TEMPERATURES FOR INSULATION NODES
Activ	Y`[2]=a1*(2*Y[1]+Y[3]-3*Y[2])
Activ	FOR i = 3 to 19
Activ	Y`[i] = a1*(Y[i-1]+Y[i+1]-2*Y[i])
Activ	NEXT
Comme	;LAST ELEMENT IN THE INSULATION. IT IS ASSUMED TO HAVE NO HEAT LEAVING.
Activ	Y`[20] = a1*(2*Y[19]-2*Y[20])

Element	Time, s	Tplate	Tin1, K	Tin2, K	Tin3, K	Tin4, K	Tin5, K	Tin6, K	Tin7, K	Tin8, K	Tin9, K	Tin10,	Tin11,	Tin12,	Tin13,	Tin14,	Tin15,	Tin16,	Tin17,	Tin18,	Tin19,
1	0	291.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
2	.0743	291.5	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
3	.18574	291.5	296.3	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
4	.35291	291.5	296.2	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
5	.60366	291.6	296	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
6	.97979	291.6	295.8	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
7	1.544	291.7	295.4	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
8	2.3645	291.8	295.1	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
9	3.2498	291.9	294.7	296.3	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
10	4.1981	292.1	294.4	296.2	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
11	5.2179	292.2	294.2	296	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
12	6.3199	292.3	294	295.9	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
13	7.5176	292.5	293.9	295.8	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
14	8.8274	292.7	293.8	295.6	296.3	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
15	10.27	292.9	293.8	295.5	296.2	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
16	11.873	293.1	293.8	295.4	296.2	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
17	13.668	293.3	293.8	295.3	296.1	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
18	15.701	293.6	293.9	295.2	296	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
19	18.028	293.9	294	295.1	295.9	296.3	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
20	20.723	294.2	294.2	295.1	295.8	296.3	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
21	23.883	294.6	294.4	295.1	295.8	296.2	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
22	27.627	295.1	294.8	295.1	295.7	296.1	296.4	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
23	32.019	295.6	295.1	295.2	295.7	296.1	296.3	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
24	36.959	296.3	295.6	295.4	295.7	296	296.3	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
25	42.552	297	296.1	295.6	295.7	296	296.2	296.4	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
26	48.922	297.8	296.8	296	295.8	296	296.2	296.3	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
27	56.205	298.7	297.5	296.4	296	296	296.2	296.3	296.4	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
28	64.554	299.8	298.4	297	296.3	296.2	296.2	296.3	296.4	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
29	74.147	301	299.5	297.7	296.7	296.4	296.3	296.3	296.4	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
30	85.149	302.5	300.7	298.5	297.3	296.7	296.4	296.3	296.4	296.4	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5
31	86.1	302.6	300.8	298.6	297.3	296.7	296.4	296.4	296.4	296.4	296.4	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5	296.5

St	Input	Name	Output	Un	Comment
		%error	0		PERCENT ERROR
	750	Qsolar			CALCULATED SOLAR FLUX, W/m^2
	750	Qsolaract			ACTUAL SOLAR FLUX, W/m^2

Status	Rule
Satis	Call BLANKM('qinHD, 'qinP,'qoutP,'qoutHD,'Tp)
Satis	call ODE_STIFFR('EQ,0,86.1,'Y,'x) ; 3rd argument is the total time of integration
Comme	; you can switch to ODE_STIFFBS from ODE_STIFFR.
Comme	;Determine percent error between experimental value and actual value
Satis	%error=((Qsolar-Qsolaractual)/Qsolaractual)*100