# Development of Authentic Engineering Problems for Problem-centered Learning

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## Abstract

In 2013, Seattle University was awarded a National Science Foundation (NSF) grant to develop an instructional framework that promotes self-directed learning and enhances problem-solving skills in undergraduate engineering students without sacrificing knowledge of fundamental engineering principles. The framework was designed for implementation in an undergraduate heat transfer course. The instructional framework used an Inverted Classroom (IC) to free class time. Material traditionally covered in a lecture format was made available through an online learning management system and moved outside of class time. During class time, student teams worked on authentic engineering problems (AEP) that addressed different heat transfer topics. These AEPs were conceptualized and designed by industrial partners, who are practicing engineers in aerospace, medical device, HVAC, and process industries. AEPs were developed in consultation with thermal systems faculty and address specific topics in the heat transfer curriculum. Industrial partners delivered the problems directly to the students. After two weeks of working on these problems student teams presented their results to the entire class. Their presentations and results were assessed by the industrial partner who developed the problem and a thermal systems faculty member who does not teach heat transfer. This paper describes the five AEPs, and how the AEPs were used in the course.


## Introduction

One of the major tasks outlined by the Committee on Engineering Education of National Academy of Engineering (NAE) in educating the engineers of 2020 was a "better alignment of engineering curricula and the nature of academic experience with the challenges and opportunities graduates will face in the workplace."[1] The need for this task stems from the fact that most modern and traditional instructional frameworks do not provide students with the skills or experience that they will need to solve open-ended, real world engineering problems on the job. In 2013, Seattle University was awarded a National Science Foundation grant to implement and study a new framework that addressed this issue.[2] This study was done over a two-year period in an undergraduate heat transfer course.

In 2014, heat transfer was taught in a traditional classroom setting to establish a control for the new instructional framework. Using a standard textbook,[3] the heat transfer course provided students theoretical knowledge of conduction, convection, and radiation and practical skills necessary to design and analyze heat transfer systems. At Seattle University, the heat transfer course is taught in the junior year over a 10-week quarter with three 65-minute classes and a 90-minute laboratory session per week.

In 2015, heat transfer was taught in an Inverted Classroom (IC). IC promotes students' self-directed learning in fundamental heat transfer principles using online videos, quizzes, and interactive problems outside of class time. Class time was used, in part, for mini-lectures, demonstrations, questions/answer sessions to correct student misconceptions, and exams to ensure attainment of engineering fundamentals. However, the majority of class time was freed for students to work on authentic engineering problems (AEP). These problems are key to the instructional framework. The problems were developed by industrial partners and based on engineering problems taken from the partners' respective industries. The problems were developed to challenge students with solving ill-structured, real-world problems related to heat transfer.

Developing the authentic engineering problems (AEP) was an important part of the proposed instructional framework. This paper describes the content of each authentic engineering problem and its related heat transfer principles, and discusses how the authentic problems were used in the class.

## Authentic Engineering Problems (AEPs)

An authentic engineering problem (AEP) is a real-world open-ended problem that provides motivation and context for students' self-directed learning in specific topics, and provides students with experience and challenges similar to what they will face in industry. The AEPs used in this study were developed by industrial partners in consultation with the instructor for the heat transfer course. Prior to teaching the course, the instructor solicited industrial partners for problems from their industry that were related to specific topics in heat transfer. In one case, for example, the instructor asked an industrial partner if they could identify an AEP related to heat exchangers. The industrial partner then developed the AEP based on real-world problems from their industry. Industrial partners were encouraged to develop problems that were realistic, even if that meant that solving the problem would require exploring topics outside of heat transfer. The goal was to free the industrial partners to develop realistic problems without being constrained by educational parameters. Once the AEPs were developed, they were reviewed by the course instructor to ensure that the scope of the project was reasonable for the course. Each industrial partner presented their AEP to students using their own words, without modifications from faculty members, in order to preserve the authenticity. After the industrial partner's presentation of the problem, students worked in three-person teams to solve the AEP. During a two-week period, the instructor facilitated a discussion among students and guided them to determine the knowledge they must gain and information they must gather to solve each AEP. At the end of the two-week period, each student team gave a four-minute presentation on their solution of the AEP to the industrial partner and a faculty member. The industrial partner then provided feedback to the students. To ensure that that AEPs can be reused from year to year, the AEP presentations were video-taped. This is important in case industrial partners are unable to present in class in the following years.

Five AEP's were developed during the course of this project. The industrial partners who provided these five problems were from aerospace, HVAC (Heat, Air Ventilation, and Cooling), medical device, and process industries. Table 1 lists the key heat transfer topics related to each AEP and the industrial partner who provided that AEP.

Table 1. Heat Transfer Topics Related to Each AEP

| **AEP Number** | **AEP 1** | **AEP 2** | **AEP 3** | **AEP 4** | **AEP 5** |
|---|---|---|---|---|---|
| **Industrial Partner** | Aerospace | HVAC | Medical Device | Process | HVAC |
| **Key Heat Transfer Topics** | a. Three Modes of Heat Transfer<br><br>b. Conservation of Energy | a. Heat Diffusion Equation<br><br>b. Thermal Circuit | a. Lump Capacitance Method (LCM)<br><br>b. Transient Conduction with Spatial Effects | a. Internal Pipe Flow Convection<br><br>b. Heat Exchangers | a. Radiation<br><br>b. View Factor |

The description of each AEP, as designed by the industrial partners, are presented in the following sections with minimal modifications to format and figure and table numbers to preserve each problem's authenticity. Note that the level of difficulty and assumptions given in each AEP are vastly different due to the varying needs and expectations of the different industrial partners. This parallels what a practicing engineer might encounter in the real-world and it adds to the authenticity of each AEP.

***AEP 1: Airplane Fuel Tank Heat Transfer***

Commercial airplanes store fuel inside the wings in the "main tanks" (shown in pink in Figure 1). In addition to supplying fuel for the engines to burn, the main tanks are commonly used to cool the airplane hydraulic fluid, via heat exchangers located inside the tanks. The main fuel tanks are cooled in-flight by the atmospheric air flow over them.

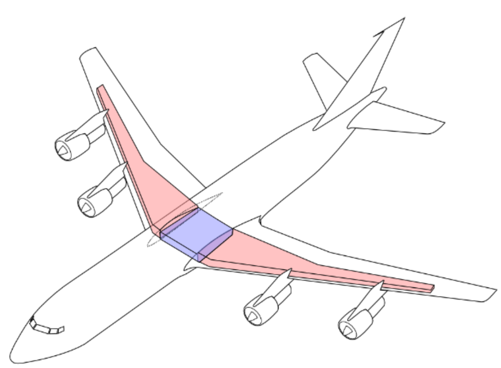

Figure 1. Typical Airplane Fuel Tanks[4]

Other methods can be used to cool the airplane hydraulic fluid, like ram air heat exchangers, but they increase the airplane drag, so to optimize performance, the amount of heat put into the main tanks should be maximized.

The question is how much hydraulic heat, in Btu/min, can be put into the fuel tanks without going over the fuel tank temperature limit?

The conditions of concern are:

- In-flight cruise, at 35,000 ft, Mach 0.8, static air temperature -5°F
- Ground operation, at sea level, no wind, static air temperature 120°F

Assumptions:

1. The sun is directly overhead on a clear day.
2. The sky temperature is -50°F, and the ground surface temperature is 120°F.
3. The fuel tanks can be approximated as rectangular with dimensions of (10’ X 60’ X 2’ deep).
4. The 4 vertical surfaces of the fuel tank are thermal insulated (adiabatic).
5. The upper and lower wing skins are made of either carbon fiber reinforced plastic (CFRP) or aluminum, about 0.4-inch thick.
6. The fuel tank temperature limit is 140°F.
7. The tanks are full of Jet A fuel (kerosene).
8. The airplane wings are level.
9. For the purpose of thermal analysis, the fuel temperature can be assumed to be at one bulk temperature (no temperature gradient in the fuel).

Calculate the steady-state radiation, convection and conduction to determine the maximum allowable hydraulic heat load.

Which modes of heat transfer are dominant for the different conditions shown in Table 2?

Table 2. Results Needed for APE 1

| **Condition** | **Maximum Hydraulic Heat Load (Btu/min)** |
|---|---|
| CFRP wings, in-flight | **?** |
| CFRP wings, on the ground | **?** |
| Aluminum wings, in-flight | **?** |
| Aluminum wings, on-the ground | **?** |

*AEP 2: Two-Dimensional Heat Transfer*

The Seattle University Facilities Group is planning to remodel the classrooms in the campus Administration Building, which was originally constructed in 1940. The classroom walls are constructed of 10-inch thick concrete, 0.5-inch gypsum wall board,[a] and a building component referred to as "tile furring." A wall section from the original 1940 drawings is shown in Figure 2.

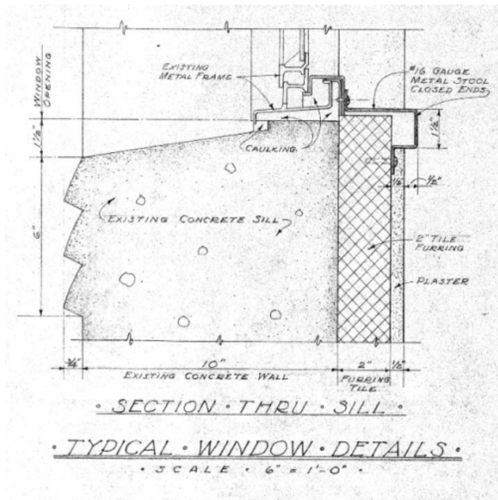


Figure 2. Typical Administration Building Wall Section[5]

The tile furring referred to above was traditionally made from burned fire clay and installed in buildings of this era for the purpose of moisture protection. It is no longer used because modern painted wallboard (such as that to be installed in the classroom) serves that purpose. Figure 3 is a three-dimensional depiction of a typical brick wall using tile furring.

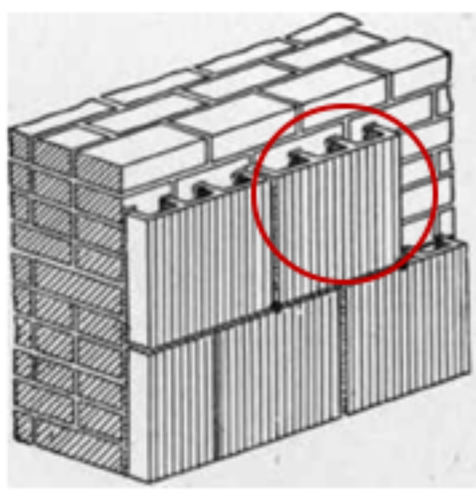

Figure 3. Tile Furring Attached to a Brick Wall[5]

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[a] The 1940 sketch indicates plastered walls. It is assumed that they were replaced with modern ½-inch gypsum wall board.

It has occurred to campus planners that opportunities exist to improve the thermal performance of these walls and reduce the campus carbon footprint. They have asked the ME Department to determine the reduction in wall heat loss that would result if the air gaps in the tile furring were filled with expanded perlite insulation.

Assuming 240 square feet of wall per typical classroom, tile furring “web” 0.5 inches thick, and air gap dimensions of 2.0 inches by 3.0 inches:

1. What instantaneous reduction in heat loss (Btu/hr) will result?
2. Assuming heating combustion efficiency is 80%, is the estimated annual energy savings per classroom (therms of natural gas) that would result from this change?

Assessment Criteria:

1. Are two-dimensional heat transfer methods required?
2. If required, which is the most appropriate method?
   a. A Finite Difference Method
   b. Parallel path method
   c. Isothermal planes method
   d. Modified zone method
3. Energy savings indicated in “Therms” of natural gas.
4. If simplified methods used, they should be appropriate to the thermal complexity
5. Simplified “single-measure” method for annual energy savings calculation.

Necessary Assumptions:

1. 240 square feet of wall per typical classroom
2. Tile furring “web” is 0.5 inches thick, and air gap dimensions are 2.0 inches by 3.0 inches
3. Outdoor winter design temperature
4. Indoor winter design temperature
5. Appropriate material conductivities
6. ASHRAE air film factors used to account for convection and integrated into the U-factor wall calculation
7. Radiation accounted for in the ASHRAE air film factors
8. Heating system combustion efficiency is 80%

References needed:
2013 ASHRAE Handbook of Fundamentals:

Chapter 19 – Energy Estimating and Modeling Methods
Chapter 25 – Heat, Air, and Moisture Control in Building Assemblies – Fundamentals
Chapter 26 – Heat, Air, and Moisture Control in Building Assemblies – Material Properties
Chapter 27 – Heat, Air, and Moisture Control in Building Assemblies – Examples

***AEP 3: Transient Thermal Heat Transfer Module***

Purpose/Goal: To teach students of heat transfer different types of transient heat transfer solutions using real world problems.

Learning objectives: 1. The lumped capacitance method and how to apply it. 2. The higher order solutions and why they are more accurate and when to use them instead of the LCM.

Scope: In this module, students will solve a real word problem that is presented by an engineer. The problem, due to its complexity, must be solved with higher order transient equations. This problem will be broken into two parts. First lumped capacitance method will be applied to a simplified model of the problem and compared with data from that model. Then the same LCM will be applied to a more complex model of the problem. Data from testing on the complex model will be compared to the solution. Students will see how the LCM does not predict the thermal behavior. Finally, the higher order solution will be applied and compared to the data.

Background: Cancerous tumors in many organs can be treated inside the body if they cannot be safely removed. Treatment in-situ can be done with drugs as well as with heat. Many different types of medical devices are used to heat cancerous tissue from the inside out. Typically, these devices fall into a category called Radio Frequency Ablation (RFA). RFA uses high frequency electrical energy, in the radio frequency range, to heat tissue using a process called Joule heating. RF is used because it is above the frequency that the nerve fibers can respond to so it won't cause the heart to stop or muscles to twitch. Joule heating, named after the man that discovered it, is the process of heating something by passing electrical current through it. Figure 4 shows a picture of a device and its effect on tissue.

Problem: In this study, an RFA device is designed with two electrodes (bipolar). Each 13 mm long, in tandem, with a 3mm gap between. It is 1 mm in diameter. The device is inserted into a tumor that is 2 cm in diameter. The device is energized by a generator that is outputting 10W. The probe has 0.5% loss by heating along its length. Energy is applied for 2 minutes and then the device is removed.

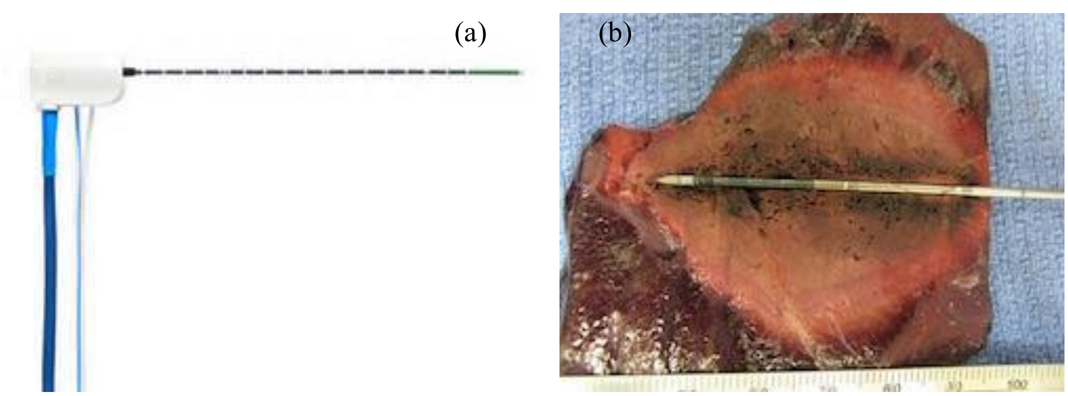


Figure 4. Picture of (a) a RFA device and (b) its effect on tissue. Note the discoloration of the tissue in an egg shape around the applicator.

What is the temperature of the tissue at the edge of the tumor?

Simplification of the problem: Let's model the tumor with a thin copper disk that is approximately 2 cm in diameter. A heater is placed at the center of the disk to supply the heat. Using this physical model, and a transient solution, does the data match the solution you derived?

Higher order solutions: Now let's model this tumor with a disk of beef that is 2 cm in diameter. Again, a heater is placed at the center to supply the heat. Using this model, does the simplified solution predict the temperatures achieved? What type of solution must be applied to match the data?

Here are some important assumptions to consider:
Assume the heating emanates from the surface of the device's electrodes. However, this is a simplification of the problem. The RF electrical current doesn't heat the surface of the electrodes, it is governed by Ohm's law. Where does the heat really emanate from in the RF case? How does this change the problem? If tissue dies when heated to $60^{o}C$ will there be any viable tumor tissue left after the RFA is applied?

***AEP 4: CHP Heat Exchangers***

Combined heat and power system (CHP as shown in Figure 5), also called cogeneration (cogen), is the simultaneous production of electricity and heat from a single fuel source. The Gresham, OR, Wastewater Treatment Plant (WWTP) utilizes CHP to provide electricity for plant operations and heat for the plant hot water loop. The plant hot water loop provides heat to two approximately 900,000 gallon anaerobic digesters (used to produce digester gas while reducing the amount of solids which need to be sent to a landfill), several plant buildings, and process heat exchangers. The plant hot water loop is shown in Figure 6. The heat producing equipment in this system includes two digester gas (which is produced in the anaerobic digesters) powered, CAT engine-generators that produce 400 kW of electric power each as well as 1,830 MBH (1,830,000 Btu/hr) of usable heat, and a boiler capable of operating on digester gas and natural gas which produces 4,000 MBH.

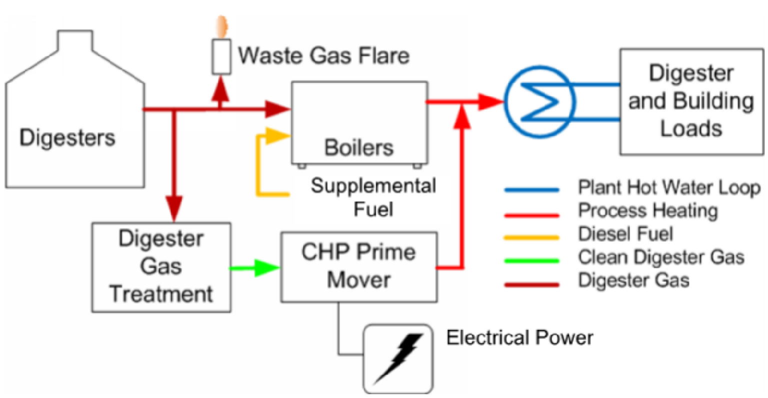


Figure 5. Typical Combined Heat and Power (CHP) System

Each engine has a jacket water system, which removes the heat generated during operation. The jacket water system picks up additional heat from the engine exhaust in the Cogen Exhaust Heat Recovery Units No. 1 and No. 2 also as shown in Figure 6. The exhaust gas is cooled down to nearly $300^{o}F$ while heating up the jacket water. The jacket water is cooled by the plant hot water loop in the Cogen Hot Water Heat Exchangers No. 1 and No. 2. The jacket water must be cooled down to 220°F for proper engine operation. If the plant hot water loop does not require heat, the Cogen Waste Heat Exchangers No. 1 and No. 2 must dump the heat to the plant water loop. The plant water is then sent to the drain.

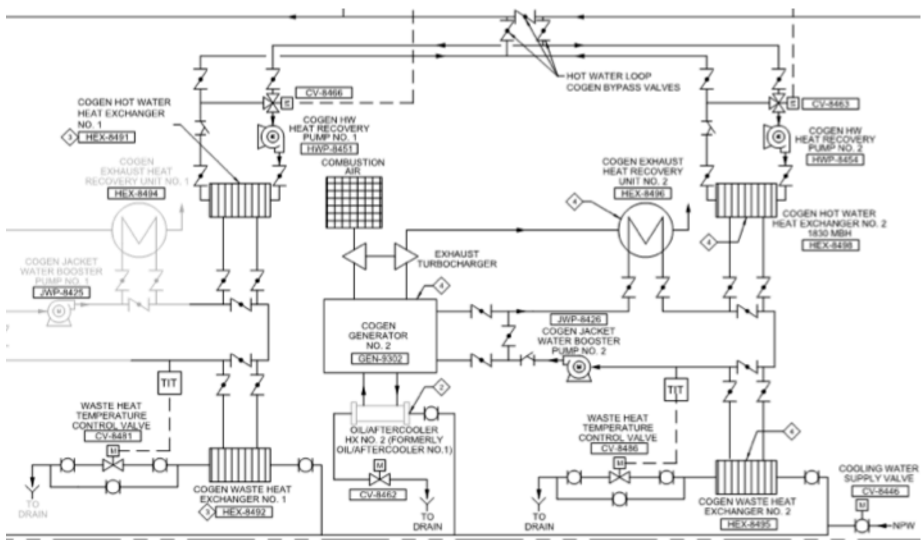


Figure 6. Part of the Gresham CHP System[6]

The major parameters for this design are given below for each type of heat exchanger.

*Cogen Exhaust Heat Recovery Units No. 1 and No. 2*

Hot Side: Internal Combustion Exhaust
Inlet Temperature: 862°F
Outlet Temperature: >300°F
Flow Rate: 1114 SCFM (standard cubic feet per minute)

Cold Side: Engine Jacket Water (50% $H_2O$, 50% Ethylene Glycol)
Inlet Temperature: 230°F
Outlet Temperature: 236°F
Flow Rate: 260 gpm

Capacity Required: >700 MBH

Other considerations:

- Combustion exhaust can be corrosive, especially when burning anaerobic digester gas, the materials of construction should be capable of withstanding this corrosion.
- The plant would like to minimize the amount of heat wasted through the waste heat exchanger. The Cogen exhaust heat recovery unit should be capable of bypassing some or all of the exhaust flow.
- Space is a major concern; the heat exchanger should be as compact as possible.

*Cogen Hot Water Heat Exchanger No.1 and No.2*

Hot Side: Engine Jacket Water
Inlet Temperature: 236°F
Outlet Temperature: 220°F
Flow Rate: 260 gpm

Cold Side: Hot Water Loop (50% $H_2O$, 50% Ethylene Glycol)
Inlet Temperature: 150°F
Outlet Temperature: 177°F
Flow Rate: 250 gpm

Capacity Required: 1770 MBH

*Cogen Waste Heat Exchanger No. 1 and No. 2*

Hot Side: Engine Jacket Water
Inlet Temperature: 236°F
Outlet Temperature: 218°F
Flow Rate: 260 gpm

Cold Side: Engine Jacket Water (50% $H_2O$, 50% Ethylene Glycol)
Inlet Temperature: 65-75°F
Outlet Temperature: <100°F
Flow Rate: 150 gpm

Capacity Required: 2000 MBH

Given the above sizing criteria, determine the appropriate heat exchanger type and size for each application. Explain your answer.

### *AEP 5: The Impact of Radiation Heat Transfer upon Human Comfort*

A student sitting in a glassed-in northeast corner of the Lemieux Library café (as shown in Figure 7), remarks to a fellow engineering student that he is cold and wished the campus facilities group would heat the room to a proper temperature. The other student borrows a few instruments from the Heat Transfer Laboratory nearby and determines that the outdoor temperature is 20°F, the indoor temperature is 70°F and the indoor relative humidity is 30% RH.

The students initially check the ASHRAE Comfort Chart (Figure 8) using their indoor temperature and humidity and note that this measured temperature/humidity combination predicts conditions at the lower end of the comfort region for an average person dressed for winter.

Figure 7. A glassed-in northeast corner of the Lemieux Library café

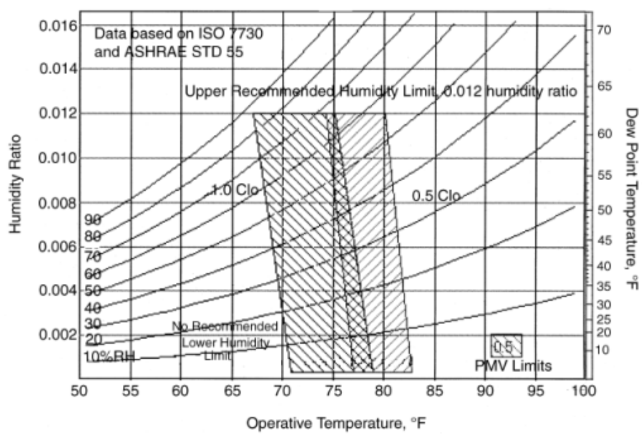


Figure 8. The ASHRAE Comfort Chart[7]

In the course of this review, one of the students notes that the scale of the comfort chart abscissa is given as *operative* temperature, rather than air temperature. Since operative temperature is a function of both local air temperature and mean radiant temperature, they realize that this is a radiation heat transfer calculation, and they need help from a Heat Transfer student to properly assess the comfort of the people in the space. They have determined that <u>you</u> are that student.

For the space described and depicted in Figure 7; use the information, data collected, and ASHRAE Comfort Chart to:

1. Determine the mean radiant temperature.
2. Determine the operative temperature.
3. Predict whether the student should be expected to be comfortable in the space where he was sitting.
4. Specify an alternative temperature/humidity setting that will result in a thermally acceptable environment for sedentary individuals.

Run your assessment for both single pane and double pane windows and report on the difference that window construction will make upon your conclusion.

Assessment Criteria:

1. Human comfort is generally understood to exist in a conditioned space having thermal coordinates (humidity and operative temperature, $t_o$) which fall within the graphical region circumscribed on the ASHRAE Comfort Chart
2. The Operative Temperature, $t_o$, is influenced by the mean radiant temperature experienced by the person in their environment; and to a lesser extent by convection due to the local air velocity.

   $$t_{op} = A t_a + (1 - A)\bar{t}_r \quad , \qquad (1)$$

   where

   $\bar{t}_r$ = mean radiant temperature, °F

   $t_a$ = local air temperature, °F

   A = 0.5 for air velocities < 40 fpm.
3. The mean radiant temperature, can be determined by the following:

   $$\bar{T}_r^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \ldots + T_N^4 F_{p-N} \quad , \qquad (2)$$

   where

   $\bar{T}_r$ = mean radiant temperature, °R

   $T_N$ = surface temperature of surface *N*, °R

   $F_{p-N}$ = angle factor between a person and surface *N.*
4. Angle factors are available in equation or graphic form in both publications cited in the Reference section. They must be determined from the area and local geometry of all the enclosing “panels” that are “seen” by the person whose comfort is being assessed. Angle Factor Charts and equations are shown in Figure 9. The equations apply to a small *horizontal* plane, whereas the charts (not shown) reflect the view of a rotated person represented by plane projections.
5. A site visit will be required to measure the window areas and a, b, and c view factor dimensions.[b]

Necessary Assumptions:

1. The indoor glass surface temperature must be calculated or measured. (It’s best if it’s a cold day.)
2. The indoor surface temperatures of ***non-exterior*** walls, floors and ceilings may be assumed to be the indoor air temperature.
3. The indoor surface temperatures of ***exterior*** walls, floors and ceilings must be calculated or estimated based upon the thermal conditions.
4. The air velocity may reasonably be assumed to be 40 feet per minute or less.

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[b] If outdoor temperature conditions are sufficiently low, we may consider having the students take measurements of all indoor and outdoor conditions, including indoor glass surface temperatures.

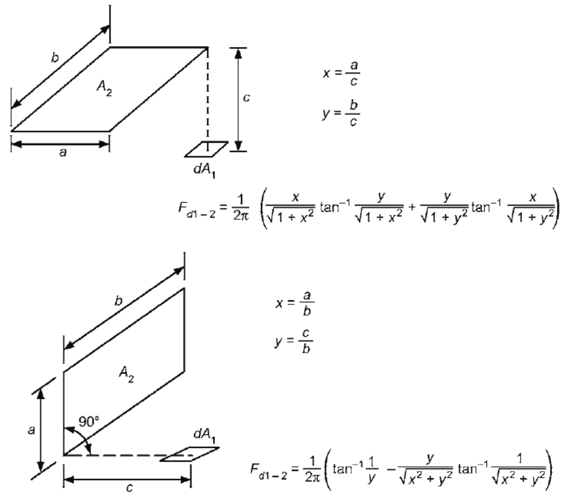


Figure 9. ASHRAE Angle Factors[8]

**Conclusion**

The AEPs provided open-ended problem that gave students experiences and challenges reflective of industry problems. At the end each AEP working period, student teams presented their solutions to the AEP. In general, the industrial partners were impressed with the students' performance in solving open-ended AEPs. Combining knowledge obtained from IC, students were able to make appropriate assumptions and formulate solutions closer to what practicing engineers would do. The instructor also observed that students' presentation skills improved throughout the quarter. The majority of teams could communicate their solutions effectively within four minutes. Detailed assessment results will be included in upcoming journal papers.

There are several issues that will be addressed in future offering of the course. Students felt rushed during a couple of AEPs. The allotted times were not long enough for AEPs 1 and 3, but were too long for AEPs 4 and 5. Instead of setting aside allotting two weeks for each AEP, the instructor should allow flexibility in the course schedule to adjust the time length based on problem difficulty.

In conclusion, leaving it up to industrial partners to develop the AEPs without concern for the continuity of the curriculum, the careful scaffolding of typical PBL problems, or the limitations of a course's scope can be disconcerting. The instructor loses some control of the course. The advantage is that the problems are more likely to provide students with challenges and experiences that they will face in industry. And students are more likely to feel and be prepared for life after graduation.

**Acknowledgements**

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