Weaving a Theme of an Engineering Firm through the Projects of Thermal Design Courses

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Introduction

> "The Rhino Thermal Engineering Company has recently received a contract to provide a residential construction company with technical support for the mechanical aspects of their projects, including heating, ventilation, air conditioning, and plumbing. One of the first tasks …"

This statement serves as the introduction for each of the five projects assigned in two thermal design classes (ME 416 Computer Assisted Design of Thermal Systems at Michigan State University and ME 436 Design of Thermal Systems at the University of Portland), taught at two different institutions. Utilizing this theme approach provides a connection among the five projects that have very different learning objectives. This theme approach to these projects provides the students with additional motivation through role playing and also provides the opportunity to introduce them to the business of engineering firms. This use of a theme to connect the five projects in theses courses came about due to student input. During early offerings of the courses, students complained about the disconnect among the projects. Over the years several different themes have been used and a few more are still in the development stage.

This paper continues by presenting the five projects assigned in the courses. The different themes used are then discussed. Next, the details of the five projects associated with one of the themes (residential construction) are provided. Student feedback on this approach has been collected and the paper concludes with its presentation and a summary of the lessons learned through this experience.

Projects and Themes

The two thermal design courses (ME 416 at Michigan State University and ME 436 at the University of Portland) are taught at the senior level and have a heat transfer course as a co or prerequisite. The goals of the courses are stated below:

1. Development and practice of design skills as they apply to thermal systems.
2. Development of modeling skills.
3. Development and refining of computer skills

Consistent with theses goals is the strong project orientation of the courses. The five projects address the five major topics of the courses and all of have strong computer orientation that includes either the development of software or the use of existing software.

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The first project deals with the manipulation of thermal/physical information needed for a computer based thermal design and analysis. Specifically, the students are asked to develop an Excel spreadsheet that will calculate the thermodynamic and transport properties for a substance given a temperature and pressure. Constitutive equations are used to calculate the thermodynamic properties, which for simplicity leads to the substance being single phase. Transport properties are evaluated through the use of a curve fit that the students develop from property data, Excel's table look-up functions, and the basic relationships among the transport properties (i.e., the relationship between kinematic viscosity and dynamic viscosity).

For the second project the students are asked to write a MATLAB program that will simulate the operation of a turbomachine. The program requirements include the simple thermodynamic calculations for an ideal or adiabatic turbomachine and the calculation of an actual efficiency based on manufacturer's operating data for the turbomachine. Additionally, the students are provided with more advanced software that will enable them to explore design issues associated with the speed and diameter of the turbomachine and the selection of a turbomachine for a specified flow system.

Thermal environmental engineering design is the focus of the third project. Provided with in-house software, the students are asked to conduct a thermo-economic analysis for an occupied space that will lead to furnace, air conditioner, and insulation selection for the space thus illustrating the basics of Heating, Ventilating and Air-Conditioning (HVAC) design.

For the fourth project the students are asked to design the layout and set the operating conditions for a thermal power or propulsion system. They are asked to optimize the system with respect to an appropriate cost function. Again, in-house software is provided to assist the students in the analysis phase of the design process.

The fifth and final project is coupled to the fourth project as the students are asked to design a heat exchanger associated with the thermal system of the fourth project. In addition to the basics of heat exchanger design, this also provides the students with an opportunity to explore how equipment selection can impact system design and optimization. The authors have developed several Excel spreadsheet programs for different types of heat exchangers that are used by the students for this project.

Currently, five different themes have been used to connect these projects. In addition, projects and software associated with three other themes are under development. These themes and their associated projects are shown in Table 1. Each project is then framed with respect to a typical activity of an engineering firm consistent with the theme, e.g., consulting for a residential construction firm, consulting with a race car team, or consulting for a utility company. These activities for the themes are shown in Table 2. Identifying the themes in this way also provides the students with some background on engineering consulting.

Table 1 Themes and Projects for Thermal Design Courses

Theme	**Project #1 Property Evaluation**	**Project #2 Turbomachinery Modeling**	**Project #3 HVAC Design**	**Project #4 Thermal System Design**	**Project #5 Heat Exchanger Design**
Automobile	Liquid Ethylene Glycol	Pump	Automobile Air Conditioning System	Automobile Racing Engine	Racing Engine Intercooler
Steam Power Plant	Superheated Steam	Steam Turbine	Heating and Cooling of Power Plant Offices	College Steam Power Plant	Reheater for the College Steam Power Plant
Land Based Gas Turbine Power System	Oxygen Gas	Centrifugal Compressor	House Heating System	Gas Turbine Power Plant	Gas Turbine Intercooler
Residential Climate Control	Liquid Water	Fan	House Heating and Cooling System	Climate Control System	Air Cooling Coil
Distributed Power Generation	*Superheated Refrigerant*	*Centrifugal Gas Turbine*	*Office Building Cooling System*	*Micro-Turbine Cogeneration System*	*Evaporator*
Hypersonic Aircraft	*Hydrogen Gas*	*Axial Gas Turbine*	*Aircraft Climate Control*	*Combinational Jet Engine*	*Surface Cooling Heat Exchanger*
Computer Systems	*Subcooled Refrigerant*	*Fan*	*Computer Room Cooling*	*Computer Thermal Control*	*Compact Heat Exchanger*

Italicized entries are under development

Table 2 Themes and Engineering Firm Activities

Theme	**Engineering Firm Activity**
Automobile	Consulting for a car racing team
Steam Power Plant	Consulting for a Midwest university
Land Based Gas Turbine Power System	Consulting for a utility company
Residential Climate Control	Consulting for a residential construction company
Distributed Power Generation	*Consulting for a municipality*
Hypersonic Aircraft	*Consulting for NASA*
Computer Systems	*Consulting for a computer company*

Italicized entries are under development

To provide a better sense of how a theme is weaved through the five projects, we now provide the details of the projects for the residential construction theme.

Project 1: The project statement is given in Appendix A. Note that the students are provided with a rationale for the project, calculating pressure and heat losses in piping, which is consistent with the semester's theme of residential construction. Additionally, the students are provided with the constitutive equations for the thermodynamic properties and a temperature table for the five transport properties.

Project 2: For the residential construction theme, project 2 involves modeling and design of fans. The project statement is given in Appendix B. This project is framed within the context of the design of residential ventilation systems. This project is the most computer intensive of all of the projects as it requires the students to write a MATLAB program and use both a MATLAB pseudo-code and an Excel spreadsheet program. All relevant fan equations and operating conditions are provided to the students.

Project 3: The third project for the residential construction theme involves the selection of furnace, air conditioner, and insulation type and thickness. Its project statement is given in Appendix C. Using a fairly simple in-house DOS program (TEEHouse.exe), the students perform several thermoeconomic analyses in order to make design decisions.

Project 4: For the fourth project of the residential construction theme the students are asked to design the layout and specify the operating conditions for an air processing system that will provide heating and cooling to a residential building. The project statement is provided in Appendix D. Again a simple DOS program (AWARE.exe) is provided for the analysis component of the design. This project is coupled to the fifth project as operating data from the cooling coil design of project 5 is needed in the system design of project 4.

Project 5: The design of a cooling coil for the air processing system design of project 4 is assigned for project 5 and its description is given in Appendix E. The students are asked to size the heat exchanger and determine the optimum material and core geometry. Since project 4 and 5 are coupled, a single technical memo is required for both projects and they are worked on simultaneously. This forces the student teams of two to interact much like a design team would among the system designers and the equipment designers.

Student Feedback and Lessons Learned

To obtain feedback from the students, the survey shown in Figure 1 was administered. Student response was very positive to the use of a theme. Eighty-eight per cent (61 out of 69) felt that the common theme did make the course more interesting. Responses to question 1-3 are shown in Fig.2 and demonstrate the students' appreciation for the theme approach. As far as fields for other themes, the students were most attracted to automotive and aerospace and pretty neutral concerning the more standard steam and gas turbine power systems. They were very divided in terms of like and dislike for computer and nano-scale systems.

Figure 1 Student Survey

Survey on Common Theme Projects

I hope that you have noticed that the projects in this course have tied to a common theme involving the building construction industry. In order to understand how this common theme has affected your learning experience, please answer the following questions.

1. Was your motivation for the projects enhanced by having a common theme?

Very Much		Some		None
5	4	3	2	1

2. How much did you learned about the building construction industry due to the projects?

Very Much		Some		None
5	4	3	2	1

3. How was your learning during the projects affected by using a common theme?

Considerable		Some		Little
5	4	3	2	1

4. Did the common theme make the course more interesting?

Yes No

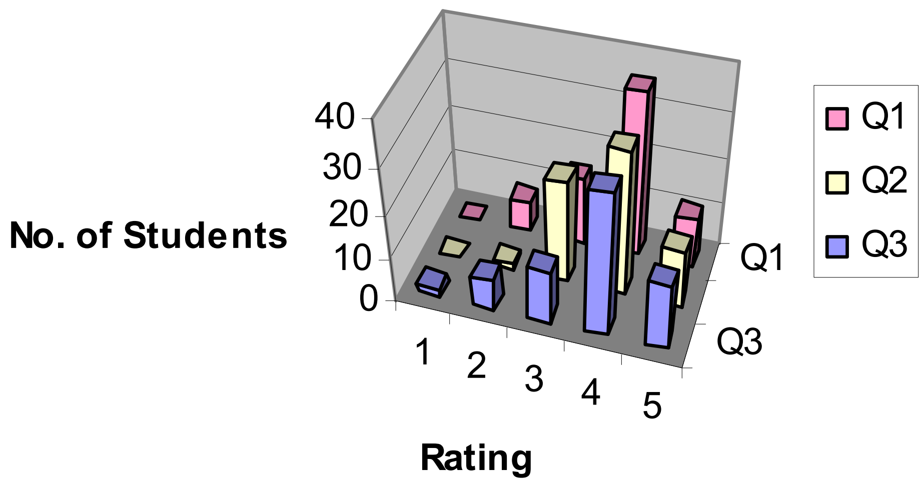
5. Using the scale below, indicate how you would feel about having the common theme for thermal design from these other engineering field.

Very Desirable		Neutral		Strongly Dislike
5	4	3	2	1

Computers	
Automotive	
Aerospace	
Steam Power Systems	
Gas Turbine Power Systems	
Single Building Power Systems	
Nano-scale Systems	

6. Please share any other comments about the use of a theme in the course.

Figure 2 Student Survey Results for Questions 1-3



Some of the more interesting or useful anecdotal comments included using a factory building powered by water, changing the theme from semester to semester (which in fact is done), showing the development of some of the software used in the projects, and having a greater "connection between the background of each project and the theme, like a continuing budget throughout the term".

A very successful approach has been used to connect the five projects of thermal design courses through the use of a theme. In addition to increasing students' interest and enhancing their learning, the themes allow the introduction of engineering activities and careers that might not be normally covered in a mechanical engineering curriculum. More details concerning these projects and the software used may be found at the following web sites:

www.egr.msu.edu/classes/ME416
www.egr.msu.edu/~somerton/TECAD
www.up.edu/classes/ME436

Author Biographies

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Appendix A Project 1 for Residential Construction Theme

Computerized Data Base for Liquid Water Properties

The Rhino Thermal Engineering Company has recently received a contract to provide a residential construction company with technical support for the mechanical aspects of their projects, including heating, ventilation, air conditioning, and plumbing. One of the first tasks will be to develop software that will calculate pressure and heat losses for the cold and hot water piping systems. In order to develop this software, a computerized data base for liquid water properties must be available. To address this need the student will develop computer software that can be utilized to access the thermophysical properties of liquid water. As a first approximation, it has been decided to treat water as an incompressible substance. The following properties should be available within a range of temperatures from 275 K to 600 K and a pressure range from the appropriate saturation pressure to 15 MPa.

Thermodynamic Properties

Saturation Pressure: P_{sat} (kPa)
Specific Volume: v (m^3/kg)
Density: ρ (kg/m^3)
Specific Heat: c_P (kJ/kg·K)
Internal Energy: $\hat{u}$ (kJ/kg)
Enthalpy: $\hat{h}$ (kJ/kg)
Entropy: $\hat{s}$ (kJ/kg·K)
Thermal Expansion Coefficient: β (K^{-1})

Transport Properties

Thermal Conductivity: k (W/m·K)
Thermal Diffusivity: α (m^2/s)
Dynamic Viscosity: μ (Nt·s/m^2)
Kinematic Viscosity: ν (m^2/s)
Prandtl Number: Pr (dimensionless)

The student's principal function will be to add the equations to the Excel workbook template **Property.xls**, which has been designed to assess the property evaluation and is shown below.

ME 416 CAD of Thermal Systems Fall 2003
Student: TECAD Rhino Thermophysical Properties of Liquid Water

		Case #1		
		Temperature (K)	Pressure (kPa)	
Property	Units	Student Values	Course Values	% Difference
Saturation Pressure	kPa			#DIV/0!
Density	kg/m^3			#DIV/0!
Specfic Volume	m^3/kg			#DIV/0!
Specific Heat	kJ/kg K			#DIV/0!
Internal Energy	kJ/kg			#DIV/0!
Enthalpy	kJ/kg			#DIV/0!
Entropy	kJ/kg K			#DIV/0!
Thermal Expansion	1/K			#DIV/0!
Thermal Conductivity	W/m K			#DIV/0!
Thermal Difusivity	m^2/s			#DIV/0!
Dynamic Viscosity	N s/m^2			#DIV/0!
Kinematic Viscosity	m^2/s			#DIV/0!
Prandtl Number	NONE			#DIV/0!

Lightly shaded cells will be user input. Values for dark shaded cells will be inputted during testing.

For thermodynamic properties constitutive equations should be used. Thermodynamic properties that require integration or differentiation should be developed using the symbolic manipulator associated with MATLAB. For at least one transport property a curve fit should be utilized. For at least one transport property a table look-up process should be used. A technical memo will be required which will include user instructions for the software. Among issues that the student should address in their technical memo are:

(i) Quantitative comparison with data provided (average error, etc.)
(ii) Quantitative comparison with other data available (e.g, thermo tables)
(iii) Symbolic development of enthalpy, entropy, and internal energy
(iv) Choice of base state for thermodynamic properties
(v) Choice of transport property for table look-up and curve fitting

A sample of the grading sheet is attached. The student must also provide a copy of their workbook on a 3 1/2 inch diskette with the technical memo. A format for the technical memo is available from the ME 416 web page.

Appendix B Project 2 for Residential Construction Theme

Computer Simulation of Fan Operation

The Rhino Thermal Engineering Company has recently received a contract to provide a large residential construction firm with software that will design the ventilation systems for the houses they build. One of the tasks involved in this contract is the development of a computer simulation for one of the devices in a ventilation system, the fan. To address this need the student team will develop a MATLAB program that can be utilized to perform the necessary fan calculations. The program should be able to predict the power required, isentropic efficiency, and exit conditions for centrifugal fans with either forward curved or backward curved blades. The software should model any one of three fan cases: an ideal fan, an adiabatic fan with an isentropic efficiency specified by the user, or an actual backward or forward curved bladed centrifugal fan represented by equations provided below.

It is probably best to begin program development by modeling an ideal fan. Then add the capability to handle an adiabatic fan with a specified isentropic efficiency. Next include the calculation for an actual fan using the equations provided. For this case the code should calculate the wheel diameter and fan speed at the maximum fan efficiency.

In all three of the cases the user will specify the inlet temperature, volume flow rate, outlet area, and required pressure boost. For all three cases the code shall calculate the exit temperature, the efficiency, the actual power, and, when appropriate, the fan speed and wheel diameter.

MATLAB functions for air thermodynamic property evaluation are available in the compressed file **idealgas.zip**, which can be downloaded from the ME 416 web page. The user instructions for these functions are attached.

Additionally, the student team is to use the MATLAB pseudo-code, **Rhino_Fan.p** and the Excel spreadsheet program **Fan_Duct.xls** to perform fan design studies. Both of these programs can be downloaded from the ME 416 web page. Using **Rhino_Fan.p** the team will develop a graph of efficiency versus specific speed for the two fans of interest, backward curved and forward curved. Using **Fan_Duct.xls,** the team will design a fan for each of the two flow systems given below:

<u>The President's Office:</u> A decision has been made to provide a dedicated ventilation system for the office of a university's president. The fan for this system is to be located in the basement of the administration building, while the president's office is located on the 15th floor of the building. Air is to be provided to the office at 0.5 m^3/s and 278 K. The galvanized iron ducting system is laid out as follows:

Conical Converging Bellmouth Entrance of rectangular geometry with a height (H) of 1 m, a width (W) of 0.78 m, a length (L) of 0.35 m, and an angle (θ) of 20°.

A horizontal duct section of length 20 m of height 0.9 m by width 0.7 m.

A 90° elbow

A horizontal duct section of length 20 m of height 0.9 m by width 0.7 m.

A 90° elbow

A vertical duct section of length 45 m of height 0.9 m by width 0.7 m, with a 45 m elevation change

A 90° elbow

A rectangular transition from a 0.9 m by 0.7 m cross-section to a 0.75 m by 0.6 m cross-section with a angle (θ) of 25°.

Automobile Climate Control: Consider the following climate control system made of plastic for a car that has a flow rate of air of 600 cfm at 85°F:

Conical Converging Bellmouth Entrance of rectangular geometry with a height (H) of 2.5 feet, a width (W) of 1.5 feet, a length (L) of 5 inches, and an angle (θ) of 80°.

A duct section of length 10 inches of height 1 foot by width 1 foot.

A compact heat exchanger of height 1 foot, width 1 foot, and depth 4 inches with the following core geometric characteristics: $\sigma = 0.534$, $\alpha = 587\ m^2/m^3$, $D_h = 0.00363$ m,

$f = 0.152Re^{-0.23}$

A duct section of length 15 inches of height 1 foot by width 1 foot.

A rectangular transition from a 1 ft by 1 ft cross-section to a 9 in by 8 in cross-section with a angle (θ) of 65°.

For each flow system the team will provide the type of fan, fan speed, and fan wheel diameter that is best for the situation described. For the fan selected the efficiency should also be provided.

A technical memo will be required which will include the user instructions for the fan software as well as the results the fan design analysis you conduct. The design team must also provide a copy of their program on diskette with the technical memo.

Appendix C Project 3 for Residential Construction Theme

House Heating and Cooling System

The Rhino Thermal Engineering Company has contracted to provide technical support on HVAC for the builder of a residential dwelling subdivision. Several of the principals of the company, Dr. Craig W. Somerton, Mr. Scott Strawn, Mr. Dan Lewis, Mr. Wayne Thelen, and Dr. Laura Genik, have developed a computer program that can be used to optimize the insulation, air conditioner, and furnace choices for the heating and cooling of a house. To complete the contract a design team of two or three students have been assigned. The team should consider two or three (corresponding to the number of students in the team) of the following residential dwellings for the optimization study,

1 story small house, 600-800 ft^2 (55-75 m^2) living space
1 story medium size house, 1000-2000 ft^2 (90-185 m^2) living space
2 story medium size house, 1000-2000 ft^2 (90-185 m^2) living space
1 story large house, 2500-5000 ft^2 (230-465 m^2) living space
2 story large house, 2500-5000 ft^2 (230-465 m^2) living space

located in one of the following cities:

1. New York City
2. Detroit
3. Chicago
4. Los Angeles
5. International Falls
6. Miami
7. Salt Lake City
8. Seattle
9. Phoenix
10. Portland

A team of two students could consider two different houses located in the same city as their two cases or the same house located in two different cities for their two cases.

The house temperature is to be maintained between 68°F (293 K) and 72°F (296 K) depending on whether heating or air conditioning is required. The team will design an optimum system with respect to the insulation thickness of the walls and roof of the house, choice of air conditioning system, and choice of furnace system.

The insulation board is available in 50 mm, 75 mm, 100 mm, and 125 mm thicknesses. To develop thicknesses greater than 125 mm, one or two additional layers of board are required. The insulation board comes in two types. Type A costs 5 cents per square meter of area for each millimeter of thickness and has a thermal conductivity of 0.04 W/m·K. Type B costs 6 cents per square meter of area for each millimeter of thickness and has a thermal conductivity of 0.03 W/m·K. Installation costs for the board are \$2.50 per square meter for the first layer and \$1.50 per square meter for each subsequent layer. Since it is modern construction, the house is considered to be tight with respect to air infiltration so that an air change per hour (ACH) is taken to be 0.5.

The capital cost of the furnace equipment is given by the following relationships.

80% efficiency furnace: Cost(in \$) = 450 + 4 x Load(in kW)
90% efficiency furnace: Cost(in \$) = 900 + 5 x Load(in kW)

Cost of natural gas is 3.1 cents per kilowatt-hour. The capital cost of the air conditioning equipment is given by the following relationships.

AC with COP of 2: Cost(in \$) = 600 x Load(in kW)
AC with COP of 3: Cost(in \$) = 800 x Load(in kW)

Cost of electricity is 6.3 cents per kilowatt-hour. The expected life of the building is 25 years and the interest rate for the utility company is 7%.

A computer program, TEEHouse.EXE (**T**hermal **E**nvironmental **E**ngineering **House**), has been provided to assist you in the calculations. It can be used to address the problem stated above.

In addition, the team should consider the robustness of the optimal design for the base conditions stated above as well as changes in the optimal solution's cost by addressing some of the following issues:

a. different ACH
b. different building life
c. different interest rate

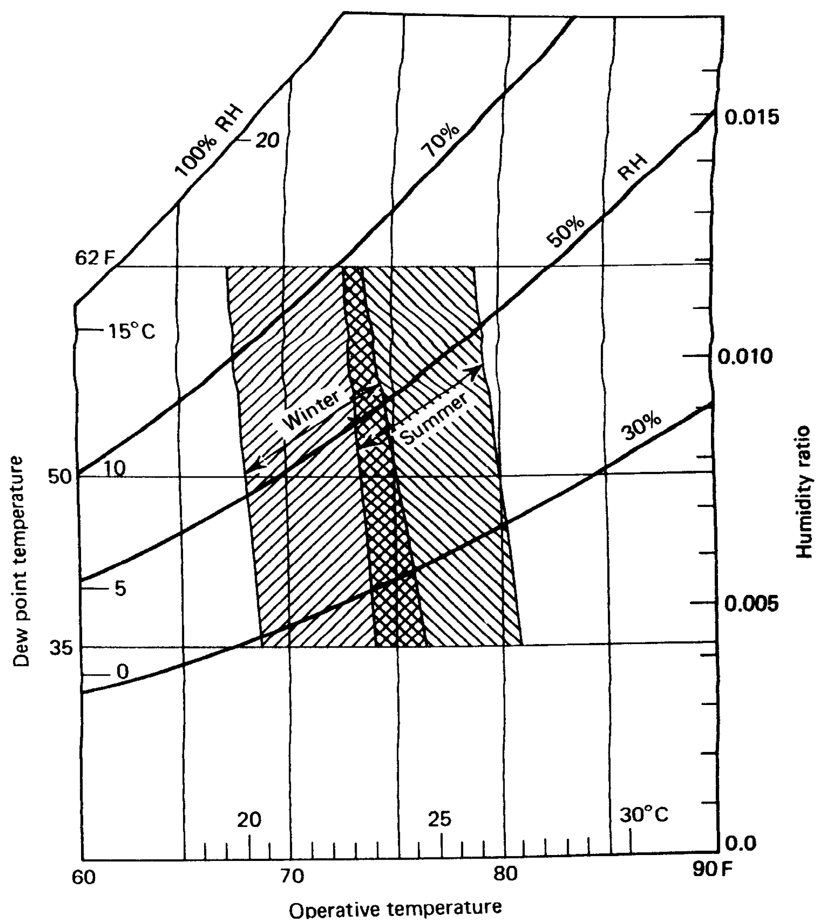
Additionally, the team should determine the natural gas cost that makes both furnaces optimal choices for the base case design, and the insulation cost that makes both insulations optimal choices. The results of the design study should be presented in technical memo format.

Appendix D Project 4 for Residential Construction Theme

Design of a Residential Air Conditioning System

The project team is to use the software package AWARE to design an air conditioning system for a residential building. Air is to be supplied to the living space within the comfort zone as shown in Figure 1.

Figure 1. Comfort Conditions for Residential Space



The ventilation, heating load, and cooling load requirements dictate a volume flow rate of 1000 cfm. The average outside temperature and relative humidity by month are shown in Table 1.

Table 1. Average Outside Air Conditions.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
T (°F)	13	16	42	58	68	79	89	89	75	58	45	20
ϕ (%)	20	30	35	45	50	75	80	80	70	40	35	30

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Using the software package AWARE, the project team may choose any combination of three different system components: heating coil, cooling coil, and evaporative spray cooler. By specifying these components in an appropriate order and with appropriate operating conditions, a system may be specified that produces air within the comfort zone (Fig. 1). The variation of the outside air condition would lead to different operating conditions and different devices, except that one multi-purpose system is desired. Identification of this general use system is a primary focus of the design. The project team should consider minimizing the coil heat transfer and water consumption in choosing the preferred design. Various components may be turned off in a specified system, for example an evaporative spray cooler may be turned off by stopping the water flow rate. Water for the evaporative cooler is available at 14°C. In the technical memorandum submitted by the project team, which also includes the results of Project #5, rationale for the selection of the preferred design must be provided as well as predicting operating results for each month that would include outlet air condition, heat transfer required, and water consumed.

Appendix E Project 5 for Residential Construction Theme

Heat Exchanger Design of a Cooling Coil

The project team is to select an appropriate heat exchanger for a water based cooling coil of the preferred residential air conditioning system (see Project #4 above) by using the program **Tube_Bank_HE.XLW**. This program will allow the user to evaluate different tube bank heat exchangers. It is proposed that system air will flow on the outside of the tube bank and that the cooling water will flow inside the tubes. The cooling water will enter the cooling coil at 14°C and must exit at a temperature no higher than 25°C.

In designing the cooling coil, the project team needs determine the frontal area that will minimize the cost of the heat exchanger. The following cases should be considered:

Heat exchanger made of copper or ASI 302 stainless steel
Outside tube diameters of 3/4 or 1 inch with wall thickness of 0.125 inches
Staggered tube arrays
Single Pass
Rectangular frontal area with a maximum dimension of 0.25 m^2 with a maximum dimension of 0.8 m
Tube separation distance (same in both directions) of 2 times the outside tube diameter

For cooling coil cost optimization an electric cost of \$0.06/kW·hr may be used. Material costs for the heat exchangers are as follows:

Material Costs:	copper:	\$ 2.00 per lb_m
	ASI 302 stainless steel:	\$ 1.75 per lb_m
Fabrication Costs:	equal to 1.5 times material costs	

An interest rate of 12% and period of 15 years are to be used for the economic analysis. Finally, the project team needs to consider the feedback of cooling coil performance with respect to climate control system performance. A single technical report will be required which will include the design study for both projects 4 and 5.