The Use of a Semester Long Theme Problem in a Senior Level Thermal Engineering Course

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Abstract

Formerly, a senior level capstone course in thermal engineering (ME 411 Applied Thermal Science) was a required part of the curriculum in mechanical engineering at Michigan State University. The intent of the course was to culminate several aspects of thermodynamics and heat transfer together in a single course with an emphasis on the design component of the topics. Among the topics covered were power system analysis, refrigeration systems, psychrometrics, combustion, heat exchangers, and numerical heat conduction. Though this list of topics may seem to be a hodgepodge, it is somewhat reflective of the eclectic nature of engineering. Through the use of a theme problem for the course, three computer mini-design projects were conducted. The use of the theme problem provided continuity to the course and demonstrated the engineering relationships of these eclectic topics.

The theme problem chosen was the analysis of a land based gas turbine power system. The three mini-design projects assigned focused on power system analysis, heat exchanger design, and numerical heat conduction. For the first project, students were provided with computer software that allows the thermodynamic simulation of a user specified gas turbine system. Students were asked to consider improvements in thermal efficiency through the optimization of operating conditions and through the use of intercooling and compressor staging processes. An Excel spreadsheet program for the sizing of a plate-frame heat exchanger was used for the second project. The students considered several design alternatives in balancing the heat transfer process with the pressure drop. The third project focused on the problem of turbine blade cooling. The problem was modeled as two-dimensional heat conduction with internal heat generation (actually a heat sink representing the internal cooling). The differential equation was written in finite difference form, and the finite difference grid was laid out over an Excel spreadsheet. The node equations were then entered on the spreadsheet, and the calculate function was used to resolve the circular references that occurred. The students then explored various design aspects of the blade cooling.

In engineering education there is a tendency to partition the educational process; to separate thermodynamics from heat transfer from fluid mechanics, and to isolate mechanical systems from thermal engineering. Engineering in industry does not consist of these isolated disciplines but rather requires a holistic approach. It would appear to be of value to teach a course that cuts across different disciplines and the use of a theme problem in this type of course can provide a common thread in the educational process.

Introduction

To bring a certain amount of cohesion to the engineering education process, a semester long theme problem was introduced into ME 411 Applied Thermal Science at Michigan State University. The course by its nature is a combination of applied thermodynamics and heat transfer. For the semester, the students analyzed a land-based gas turbine power plant. The three mini-design projects assigned each had this common thread. The first followed a broad thermodynamic approach to thermal system design, the second emphasized heat exchanger design within the gas turbine system, and the third and final project introduced computational heat transfer applications in the use of turbine blade cooling design. Also, these 3 mini-design projects followed an inverse relationship for the computer burden on the student. The first project utilized a PC/DOS based program where the students were required to generate input files and interpret output files. The second project required the use a MS-Excel spreadsheet that was already set-up with the appropriate equations to analyze the heat exchanger. The final project allowed students to explore other options of canned software or to design their own numerical solution method. For the third project the recommended method was to use an MS-Excel spreadsheet and that will be discussed in detail here.

Design project 1:
Intercooling and Compressor Staging Gas Turbine Power Systems

Prior to the introduction of the mini-project to the class, lectures were given on the analysis of gas turbine systems. These lectures began with the ideal Brayton cycle and then moved on to the consideration of regeneration and intercooling with staged compression. Several examples were worked in class utilizing a cycle analysis method that was introduced earlier in the course when the Rankine cycle was taught. It was emphasized that although the students would be using a computer program to perform the calculations for the mini-design project, a thorough understanding of gas turbine system analysis must include an understanding of the calculation process that can only be achieved through hand calculations. With the basics of gas turbine system operation and analysis covered the mini-design project statement was presented. Note that a hand calculation is required in the technical memo.

To introduce the students to the software package a computer-projection system connected to a lap top computer was used in the classroom. An example involving a simple, jet-propulsion system was then solved using the software. This consisted of creating the input file, running the program, and viewing the results. The students were urged to re-run the example before moving on to the mini-project. The following statement was provided to the class.

Project Assignment: A technical memo will be handed in with all requested graphs and figures. The technical memo should have an introduction that briefly recapitulates the assignment and illustrates an understanding of gas turbine power systems. The next section should be results and discussion that includes the solution to the problem statement as well as relevant work, equations and conclusions. The output files from GASTURB should be placed in the appendix. The appendix will also include a hand calculation of a gas turbine cycle with two stages of compression and one intercooler. The undergraduate students may work in groups of two. Graduate students must work individually.

Design Assignment: The student is to investigate the use of intercoolers and compressor staging. In particular, the student should make design based recommendations on the use and operation of intercoolers and compressor staging. Air enters the gas turbine system at 300 K and 100 kPa. The combustion chamber operates at 900 kPa and produces a hot gas stream at 1400 K. It may be useful for the student to consider the following sub-problems.

(i). Using the computer program GASTURB, determine the intercooler operating pressure for two stages of compression that will minimize the work of the compressors. You may assume ideal compressor operation, no pressure loss in the intercooler, and an intercooler exit temperature of 300 K. This should be done for a number of final exit pressures to demonstrate that the optimum pressure for the intercooler will be given by

$$P_{IC} = \sqrt{P_{in} \cdot P_{out}} .$$

Comments: The student should develop an input file for GASTURB that consists of three devices: compressor #1, intercooler, compressor #2. The inlet temperature and pressure are 300 K and 100 kPa. The intercooler exit temperature is 300 K. With the exit pressure of compressor #2 set at some value (say 900 kPa), the intercooler pressure (specified as the exit pressure of compressor #1) should be varied from the system inlet pressure to the exit pressure of compressor #2. The work required should then be plotted against the intercooler pressure and the optimum intercooler pressure at which the work is minimized can be determined. Optimum intercooler pressures should be determined for several values of the exit pressure for compressor #2. By performing a log-log graph of the optimum intercooler pressure versus the product of the inlet pressure and the exit pressure of compressor #2 the square root form given above can be verified.

(ii). Next consider three stages of compression and two intercoolers. For the same inlet conditions and a final exit pressure of 900 kPa, determine the optimum pressures for each intercooler.
Comments: The approach is similar to part (i). Intercooler #1 pressure should be fixed and intercooler #2 pressure varied. Then reset intercooler #1 pressure and again vary intercooler #2 pressure. These calculations will yield graphs of the compressor work versus intercooler #2 pressure at various values of intercooler #1 pressure. The two intercooler pressures that minimize the work can then be determined.

(iii). Show that intercooling is not feasible if regeneration is not used.
Comments: The student should consider a two-stage compression with intercooling gas turbine system without regeneration. Using the operating conditions specified above, the student should vary the intercooler pressure and calculate the thermal efficiency of the system. A graph of thermal efficiency versus intercooler pressure should demonstrate the required point. Next, regeneration should be added and again a graph of thermal efficiency versus intercooler pressure should be generated. The regenerator may be assumed to have an efficiency of 1.0.

Extra Credit Problems

(iv). Show how the optimum intercooler pressure for a two-stage compression process is affected by the efficiency of the compressors and the percent intercooling.

(v). Develop a mathematical relationship to predict the optimum intercooling pressures for a three-stage compression process.

(vi). If the output power of the two stage compression gas turbine system with regeneration is 10 MW, determine the maximum capital cost for the staging components (a second compressor and the intercooler) for feasibility. You may take the cost of electricity to be $0.025/kW□hr, an interest rate of 20%, and a equipment lifetime of 30 years.

Limitations

The program has very limited artificial intelligence (currently not fool proof) so that it is possible that the program may terminate through a run time error or give unrealistic results for unrealistic systems. Most of the limitations are associated with the modeling of the regenerator. The program can handle only one regenerator (though it would be specified as two devices during the input mode, corresponding to its two sides).

Selected Results of Design Project 1

A sample of the results of the mini-design project are given below. In Figure 1 a typical graph of compressor work versus intercooler pressure is shown. The intercooler pressure that minimizes the compressor work is easily identified.

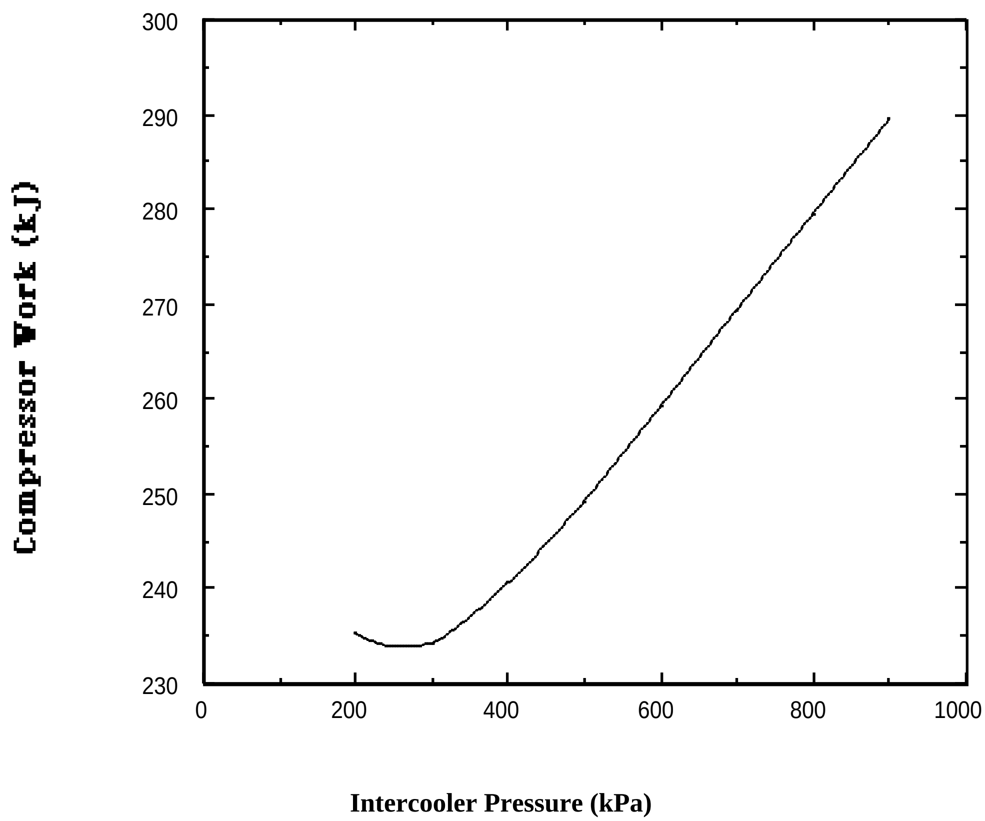

Figure 1. Minimizing Compressor Work with Intercooler Pressure

For the third part of the mini-project, an optimization of the cycle thermal efficiency with respect to intercooler pressure is to be performed. Figure 2 shows the results of this analysis for systems with and without regeneration. It is very clear that regeneration makes a great improvement in the efficiency of the system but also that intercooling is not needed when regeneration does not occur.

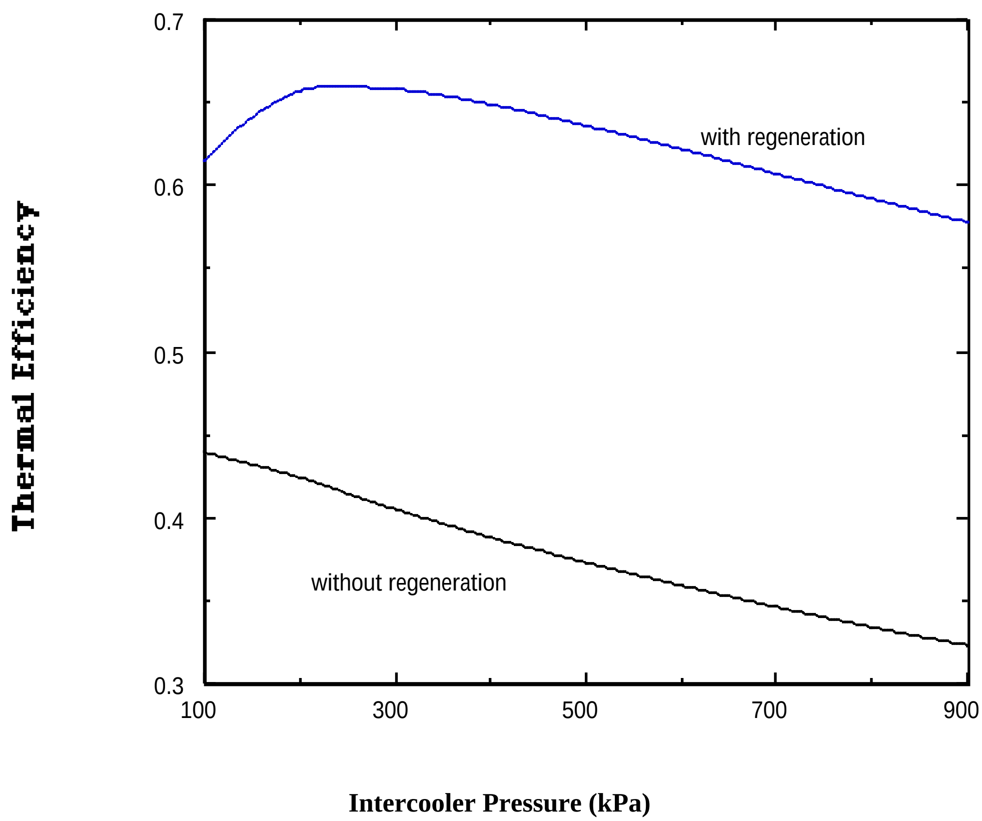

Figure 2. Optimization with and without Regeneration

Discussion and Recommendations for Design Project 1

Most of the difficulties encountered by the students could be attributed to a lack of computer experience. It would appear that few had ever run a canned computer program. There was confusion concerning the development of the batch input files and the appending nature of the output file was also a problem as the students often would not scroll down to the most recent output. Though the authors have used the computer projection system in a regular classroom several times for other classes, it appears that a better approach would be to use the projection system in a computer lab, so that the students could run the program at the same time that the instructor was demonstrating it.

With the GASTURB program other mini-design projects could be developed focusing on reheating or regeneration. If equipment cost information was available, an optimization as to the number of compressor stages with intercooling or the number of reheat stages could be conducted. The software package is available for educational purposes from the Thermal Engineering Computer Aided Design (TECAD) homepage in the Department of Mechanical Engineering at Michigan State University. The URL address is

http://www.egr.msu.edu/~somerton/TECAD.

Though many faculty members in the thermal/fluids stem of mechanical engineering may feel uncomfortable with incorporating design into their courses, such integration can be accomplished utilizing several of the thermal systems computer packages available. Approaching the second thermodynamics course in this fashion could serve to significantly re-invigorate this part of the mechanical engineering curriculum.

Design project 2
Design of Plate-Frame Intercooler and Regenerator Heat Exchangers for a Gas Turbine Power System

Prior to this design assignment the students were presented with a heat exchanger methodology for solving both sizing and rating type problems with the effectiveness-NTU method. Considerable time was spent explaining the use and application of a plate frame heat exchanger as well as other type heat exchangers.

A formatted spreadsheet was utilized for this design assignment. The use of the speardsheet was demonstrated in class with a projection system and laptop computer. The students were required to vary certain parameters to obtain the design of heat exchanger.

<u>Design Assignment</u>: The design team is to investigate the required sizes and operating conditions for plate-frame heat exchangers in a gas turbine power system. In particular, the design team should make design recommendations based on the use and operation of the heat exchangers. The gas turbine power system will supply a net power of 10 MW and operate under the optimal conditions from a prior investigation. For this power system 1 intercooler and 10 regenerators in parallel will be designed.

Part I: Intercooler Design

(i). Using the Excel spreadsheet Plate_hx, determine the appropriate mass flowrate of the cooling fluid and the number of plates for a square heat exchanger with dimensions .2 m x .2 m. The hot side flow rate is dictated by the net power requirement, recall that the net work for the gas turbine cycle at the optimal conditions was 462.3 kJ. The operating temperatures for the hot fluid are 409.9 K and 300 K. Assume that the cold fluid is available at 270 K and can only increase 30 degrees.
Comments: A straight forward sizing problem for a heat exchanger to obtain the appropriate temperatures.

(ii). Using the Excel spreadsheet Plate_hx, determine the outlet temperatures for the heat exchanger of .2 x 1.2. The cold side gas should flow at 1.3 times greater then in part (i) and the number of plates should be set to 0.75 the number in part (i). The inlet temperatures for both fluids are the same as part (i).
Comments: A straight forward rating problem to obtain the outlet temperatures.

Part II: The Regenerator

(iii). For various operating conditions (see Table 1) for the regenerator determine the minimum size of the plate-frame heat exchanger required.
Comments: For effectiveness of 0.95, 0.9, 0.85, and 0.8 minimize the number of plates to be utilized for a range of square heat exchangers. Produce a graph of number of plates as a function of the length or width of the heat exchanger for each effectiveness of the heat exchanger.

(iv). For various operating conditions for the regenerator, determine the minimum pumping power required.
Comments: For effectiveness of 0.95, 0.9, 0.85, and 0.8 minimize the pumping power to be utilized for a range of square heat exchangers. Produce a graph of required power as a function of the length or width of the heat exchanger for each effectiveness of the heat exchanger.

Extra Credit Problems

(v). If the output power of the two stage compression gas turbine system with regeneration is 10 MW, determine the minimum cost for the heat exchangers manufacture and operation. You may take the cost of electricity to be $0.025/kW□hr, an interest rate of 20%, and a equipment lifetime of 30 years.

Material Costs:	304 stainless $0.40 per lb_m
Fabrication Costs:	estimated as 1.5 times material costs

(vi) Show how the minimum pumping power varies with the overall volume of the heat exchanger.

Table 1. Temperatures for Various Regenerator Effectiveness

ε	$T_{in,c}$	$T_{out,c}$	$T_{in,h}$	$T_{out,h}$
.95	409.9	792.4	811.7	430.8
.9	409.9	773.1	811.7	451.7
.85	409.9	753.7	811.7	472.5
.8	409.9	734.2	811.7	493.2

Suggestions for Discussion

The following are suggestions for discussion for the design memo for Project 2. Do not let this limit your thoughts and insights to the investigation, but let it be a starting point. Keep in mind that you are designing 2 components of a larger system.

Part I: For intercooler design, consider what the differences are between the sizing problem and the rating problem. Intrinsically, what are the main differences between the designs and does this effect the operation of the Gas Turbine power system?

Part II: For the regenerator design, various effectiveness were/are investigated. What is the implication of the various effectiveness as they relate to the minimum number of plates and the minimum pressure drop for the heat exchangers? With the same effectiveness, what is the difference in each design? Under what criteria would one design be preferred over the other?

Selected Results of Design Project 2

Samples from the results of the mini-design project are given below. The mass flow rate of hot air that needs to be cooled within the intercooler will be the power required, 10 MW, divided by the net work of the gas turbine system at the optimal conditions or

$$\dot{m}_H = \frac{10{,}000}{462.3} = 21.6 \text{ kg/s}$$

With the required temperatures entered into the spreadsheet, the cold fluid mass flow rate (water chosen as the cooling fluid) is varied until the required hot flow rate of 21.6 kg/s is attained. The following results are then obtained:

Number of Plates	42

Cold Fluid		
Fluid Code:	5	
	Water	
Properties:		**Units:**
M dot	19.20	Kg/s

Figure 3. Mass Flow Rate and Sizing Results for the Intercooler Analysis

Next the intercooler specified in (ii) is analyzed with the rating spreadsheet to obtain:

Cold Fluid				**Hot Fluid**		
Fluid Code:	5			Fluid Code:	1	
	Water				**Air**	
Properties:		**Units:**	Tout,hot guess:	**Properties:**		**Units:**
M dot	25.00	Kg/s	281.39	**M dot**	21.60	Kg /s
T in	270.00	K	Tavg,hotguess	**T in**	409.90	K
T out	296.83	K	345.645	**T out**	281.39	K
T ave	135.00	K	% Diff.:	**T ave**	345.65	K
Cp	4190.815	J/(Kg.K)	0.000	**Cp**	1012.699	J/(Kg.K)
Dyn.Visc.	0.00128964	N s/m^2		**Dyn.Visc.**	2.07E-05	N s/m^2
T. Cond	0.584	W/(m K)	Tout,cold guess:	**T. Cond**	0.030	W/(m K)
Density	999.901	Kg/m^3	296.83	**Density**	1.002	Kg/m^3
Prandtl	9.251	none	Tavg,cold guess	**Prandtl**	0.699	none
Fouling Res.	0.000035	(W/m^2K)^-1	283.415	**Fouling Res.**	0.000035	(W/m^2K)^-1
			% Diff.:			
			0.000			

Figure 4. Rating Results for the Intercooler Analysis

For the regenerator design the graph below shows there is no minimum in the number of plates. However, as the width or length increases, the number of plates required does plateau out.

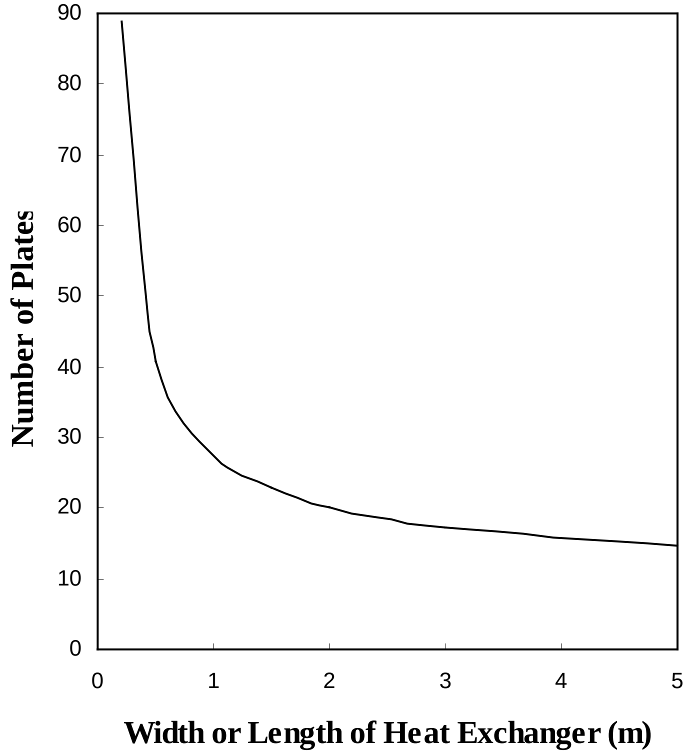

Figure 5. Sizing Results for the Regenerator Analysis

As the graph below shows there is no minimum in the power requirement. However, as the width or length increases, the power required does plateau out. Also the extremely high values for the power might suggest the appropriateness of using a plate frame heat exchanger for gases.

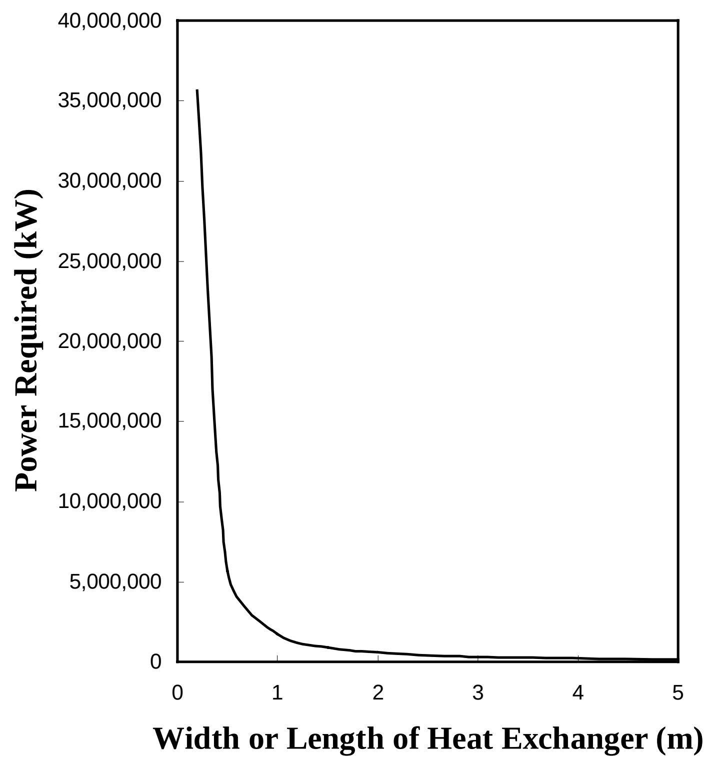

Figure 6. Power Results for the Regenerator Analysis

The extra credit problems look at the economics of heat exchanger design and use the data generated for the regenerator part.

Design project 3
Turbine Blade Cooling in a Gas Turbine Power System

Prior to this assignment the students were given examples of various numerical methods. The emphasis, however, was placed on a finite difference approach. Definitions of first and second order correct were given along with estimates of the error associated with the application of each. Discritization of several differential equations were utilized. The majority of the design teams used the spreadsheet solution method utilizing the intrinsic circular reference solve function in MS-Excel. Certain design groups used the commercially available FIDAP to solve the numerical problem that implements a finite element method.

Design Assignment: One of the greatest concerns in the operation of turbines is the thermal stresses caused by the high temperature gases flowing over the turbine blades. One manner in which to compensate for this is to cool the turbine blades during operation so as to maintain the average temperature below a critical temperature. The design team is to model a turbine blade as a two-dimensional rectangular fin with convective boundary conditions and use a heat sink term to model the cooling of the blades. Using a numerical method the design team will solve the 2-D energy equation for this configuration. It is suggested that the design team implement the numerical method on a spreadsheet or in a computer program. The minimum number of nodes is 9. The dimensions of the rectangular fin are 0.45 m by 0.08 m. It is recommend that a direct matrix inversion method be used. The memo should include the nodal equations as well as the matrix formulation.

$$0 = k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] + \dot{q}'''$$

$$-k\frac{\partial T}{\partial x}\bigg|_{x=l,y} = h\left(T_{x=l,y} - T_\infty\right)$$

$$-k\frac{\partial T}{\partial x}\bigg|_{x=0,y} = 0$$

$$-k\frac{\partial T}{\partial x}\bigg|_{x,y=0} = 0$$

$$-k\frac{\partial T}{\partial x}\bigg|_{x,y=a} = h\left(T_{x,y=a} - T_\infty\right)$$

(i) Determine the normal operation conditions of the turbine blade without cooling. That is determine the average temperature of the blade if the convection coefficient is 450 W/m^2·K and the incoming gases are at 1800 K. Select an appropriate material. Comments: The design team should set the heat sink term to zero and solve for the nodal temperature distribution with in the blade and then take the average of the distribution.

(ii) Now assume that the incoming gases have reached the adiabatic flame temperature of 2800 K. The predetermined average temperature for the blade must still be maintained and the convection coefficient will be 900 W/m^2·K during peak operation and 450 W/m^2·K during average operation. The amount of cooling necessary must be determined. Investigate this for two different materials, one metal and one non-metal. Also investigate the same conditions at a lower adiabatic flame temperature of 2300 K. Comments: The volumetric cooling term is to be determined for two convection coefficients and two different materials to maintain the average temperature of the blade at 1000 K when the incoming gases are at 2300 K and 2800 K**.**

Extra Credit:

(iii) Increase the grid size and investigate any improvement in accuracy. Generate a graph of T average vs. number of grid points.

(iv) Increase the accuracy of the boundary conditions to second order correct.

Selected Results of Design Project 3

The solution procedure for this problem required discritizing of the two dimensional steady state energy equation. The given differential equation can be written in finite difference form with second order correct procedures as follows for node (2,2):

$$T_{22}\left(\frac{-2}{\Delta x^2}-\frac{-2}{\Delta y^2}\right)+T_{32}\left(\frac{1}{\Delta x^2}\right)+T_{12}\left(\frac{1}{\Delta x^2}\right)+T_{23}\left(\frac{1}{\Delta y^2}\right)+T_{21}\left(\frac{1}{\Delta y^2}\right)=-\frac{\dot{q}'''}{k}$$

These terms are re-arranged to solve for node (2,2) then the solutions may be found by using the goal seek or solver mechanism available in Excel. Figure 7 indicates the solution to Part II of the design project statement where the temperature distribution has been found for the turbine blade based on the combustion gases being at the lower adiabatic flame temperature. The criteria for the solver mechanism is that the average temperature is below 1000 K. Figure 8 displays the temperature results with a surface graph.

Finite Difference Model for Turbine Blade Cooling						
h (W/m^2 K)	**Tamb (K)**	**k (W/m K)**	**q(W/m^3)**	**delx**	**dely**	
900	2300	14.9	-1.22E+07	0.225	0.02	
	3	1221	1231	1556		
	2	732	748	1232		
	1	569	587	1128		
		1	2	3		
		Tavg (K):	**1000**			

Figure 7. Numerical Temperature Results

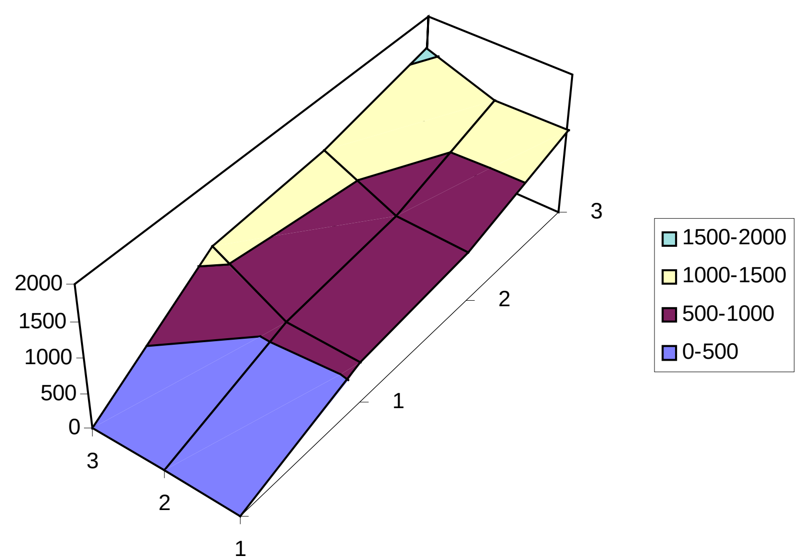

Figure 8. Display of Temperature Results

Further solutions such as the extra credit problems, looked at changes in solutions based on the order of the finite differencing as well as investigate other numerical methods. As previously stated some students chose to use available finite element codes as for the solutions and the comparisons were done between the two methods.

Conclusions and recommendations

A more appropriate section may be ‘lessons learned’; however, as engineers we prefer to ‘conclude and recommend’. The theme problem not only supplied the students with continuity in their projects but the lectures always returned to this concentration as well. The ability to refer to a real life project that the students felt they were involved with over the entire semester brought some real world experience to the classroom; allowing the students to go beyond the everyday solution of ‘homework’ problems to something they could see from several design angles. The ability of the students to incorporate several different types of computer programs for the various solution methods also expands their learning experiences. It is still surprising how many students resist using a computer.

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