AC 2007-467: DESIGN OF THERMAL SYSTEMS: A LOST COURSE

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Abstract

In a typical mechanical engineering curriculum, Design of Thermal System course is the culminating course for thermal fluid stem where synthesis of junior and senior level classes is presented with respect to real-world engineering systems such as a coal-fired power plant. The course covers design process, equipment selection, economic consideration, mathematical modeling, and numerical simulations of energy systems. Even though the course is generally a required course for many engineering programs, the author found that many curricula have either stopped offering the course or included some aspects of the course in some junior level courses. At Lamar University the faculty member who used to teach the class was recently retired and the author took up the challenges of teaching the course for the first time in the Fall 2006 semester. This paper discusses the relevancy and necessity of the course for undergraduate students based on the experience of the author in developing the course materials as well as implementing and conducting the course. The discussion covers course content, materials, resources, and students' opinion and responses on the content and usefulness of the course as it is presented to them.

Introduction

In a typical mechanical engineering curriculum, there are two concentration stems, energy and design, that the students can specialize in. In each stem, there are one or more design courses that culminate in synthesizing junior level engineering science courses to develop and instill design skills in students. Design of Thermal Systems is such a course in the energy stem at Lamar University. MEEN 4313 Thermal Systems Design is the senior level core course that deals with different aspects of designing and simulating thermal and energy systems. The course is designed in order to demonstrate how knowledge from junior level classes such as thermodynamics, heat transfer, fluid mechanics, engineering economics, and numerical analysis can be used to design and simulate energy systems. This is also the course to assess the thermal system design capabilities of students with regards to Accreditation Board for Engineering and Technology (ABET) outcomes.

The faculty member who used to teach the class was recently retired and the author took up the challenges of teaching the course for the first time in the Fall 2006 semester. This paper describes the author's own experiences in the implementation and delivery of the course in details.

Course Description

MEEN 4313 Design of Thermal Systems course is a required course for mechanical engineering seniors and is offered every fall semester. The prerequisites for the course are the completion of undergraduate fluid mechanics, thermodynamics, heat transfer and numerical analysis courses. The class is a 3-credit hour class with 3 hours of lecture time each week. The typical semester lasts for about 15 weeks so the total instruction time is 45 hours. The main objectives of the course according to the previous instructor are

- To utilize the students' knowledge of thermodynamics, heat transfer and fluid mechanics in the design of integrated thermal systems
- To utilize accurate and efficient computational methods for the solution of thermal system models

One of the first difficulties encountered by the author was to find a suitable textbook for the course as the previous text, Design of Thermal Systems by Stoecker[1], was out of print. In searching for the textbook, the author found that there were only a few books suitable for the class but almost all those books were already out of print. The list of books considered for the class is given below:

- *Design of Thermal Systems* by W. F. Stoecker[1]
- *Analysis and Design of Energy Systems* by B. K. Hodge and R. P. Taylor[2]
- *Design of Fluid Thermal Systems* by W. S. Janna[3]
- *Elements of Thermal-Fluid System Design* by L. C. Burmeister[4]
- *Design and Optimization of Thermal Systems* by Y. Jaluria[5]
- *Design Analysis of Thermal Systems* by R. F. Boehm[6]
- *Design and Simulation of Thermal Systems* by N. V. Suryanarayana, O. Arici and N. Suryanarayana[7]
- *Thermal Design and Optimization* by A. Bejan, G. Tsatsaronis, and M. Moran[8]

The main criteria for choosing the textbook are topical contents, problem sets, worked examples, and design projects. Comparing these textbooks is difficult as many core topics are similar but each text has its own unique content suitable for students' learning. For example, the texts by Stoecker[1] and Jaluria[5] emphasize optimization methods but the book by Suryanarayana et al.[7] does not cover any optimization method. The book by Hodge and Taylor[2] includes a chapter on uncertainty analysis whereas the book by Burmeister[4] has a chapter on reliability. The text by Bejan et al.[8] was not considered for the course, as the author would not cover exergy analysis that was emphasized in that book. In addition, all except the book by Janna[3] are out of print according to publishers but Prentice Hall can print their books if one requests from them. It is surprising to the author that the book by Suryanarayana et al.[7] is out of print even though the book is first published in 2002.

The previous faculty member who taught this course placed strong emphasis on optimization and as a result, his text was the one by Stoecker[1]. However, the author would like to provide more coverage on the topics of component selection, modeling, and simulation methods with only a brief introduction to optimization and its application in thermal systems. The author also would like to emphasize the practical aspects of component selection, cost estimation, and economic analysis. As a result, the author has chosen the text by Boehm[6] for the course which covers most of the topics that the author intends to discuss in class. Another advantage in choosing the book by Boehm is that it contains many suggested design projects. However, the book is not without its disadvantages. First, the solution manual is not available according to the publisher since it was published about twenty years ago. In addition, some of the component data and cost estimates have changed significantly and computer based simulations have made huge progress since the book was published. These topical shortcomings were overcome by using supplementary materials from other textbooks and resources described later in the paper. Once the text is selected, the author conducted more research on the similar courses at other universities and found that this particular course, Design of Thermal Systems, has been generally phased out in many universities. In other universities, selected topics on the design of thermal system have been relegated to other engineering science courses.

Review of recent literature on the course reveal some papers dealing with design of thermal systems. Sexton[9] discussed the use of computer simulation in teaching energy system design, providing the solution of an optimization project using MathCAD. Lee and Ceylan[10] described how they used the problem-based learning method in their thermal systems design class. The paper by Somerton and Genik[11] discussed the use of an engineering firm theme in their thermal design courses, and described how students responded to the approach. Wedekin and Kobus[12] described in their paper the use of a design project in the Fluid and Thermal System Design course to expose students to the complete design process. All these papers emphasized on how students could attain higher learning skills such as application, synthesis, and evaluation by using computer simulations and conducting labs and experiments. The most recent paper on the thermal system design class is by Mueller[13]. He described the development of course, an elective course, with detailed discussions on the contents, texts, materials covered, and the response from students. This paper discusses the author's own experiences in teaching the course for the first time. Observation of students' learning and feedback and responses from the students about the course serve as the main motivation for writing the present paper.

Course Content

The course content follows the book closely for the first 6 chapters: design analysis process, selection of fluid flow equipment, heat exchanger design options, fitting data and solving equations, economic consideration, and preliminary cost estimation. Chapter 7 dealing with availability analysis was not covered at all. System flowsheeting of chapter 8 was covered in detail together with the information flow diagram method taken from the texts by Stoecker[1] and Jaluria[5]. The text does not cover the topic of simulation directly and as a result, materials on system simulation from other texts were used. A brief introduction to optimization techniques (Chapter 9) is discussed in only two class sessions. More detailed discussions of course contents are discussed below.

Since the course is a design course in thermal systems, the first topic is about the design process. The first chapter of the text provides enough materials to discuss the types of design, and design processes typically followed in thermal systems. The class discussion on the topic centered on different types of design solutions: non-functional, functional, satisfactory and optimal, and major differences between these solutions. Additional materials from Jaluria book[5] were used to emphasize the important issues and differences between mechanical design and thermal system design. The most useful exercise to show the differences between these design solutions is to ask students to solve the problems of chapter 1. For example, a pipe flow problem with a pressure drop constraint is given, and the students are asked to identify functional, non-functional, satisfactory, and optimal design solutions (pipe diameter) to provide a specified flow rate. Most of the students when asked to provide a multitude of solutions rather than a single solution (or a number) seemed lost and did not know how to come up with these different solutions at all. Close guidance from the instructor is required for students to understand and tackle these problems but these are the types of open-ended realistic problems that provide better learning experience to the students.

The next portion of the course deals with component selection for thermal systems including selection of pumps, fans, turbines, and heat exchangers. The text provides different types of fluid machinery and how to select them in Chapter 2. For example, a data table on each type of pump and their relevant operating parameters are given, and an example problem is used to demonstrate use of these tables to select an appropriate type of pump. In addition to fluid machinery, the text provides useful information regarding storage vessels, valves and piping. The instructor provides additional materials in the form of choosing a specific pump model using manufacturer's catalog and the appendix section of the text by Fox and McDonald[14]. In addition, web-based selection of a pump from Goulds Pump[15] was demonstrated in class to provide additional exposure of real world engineering practice. In terms of fans and compressors, materials on industrial fans and their selection from Greenheck Fan[16] and Chicago Blower[17] companies were used as supplements. From these materials students learned several important parameters, such as environmental conditions (pressure, temperature, altitude) and sound levels, necessary to consider in identifying and selecting industrial fans.

Chapter 3 of the text deals with an overview of different types of heat exchangers, heat exchanger analysis and selection, and thermal insulation. The additional materials used for the topic of heat exchangers include identification and selection of heat exchangers based on engineering guides provided by Young Radiator[18] and FlatPlate Heat Exchanger[19] companies. Young Radiator[18] provides a procedure for selecting a specific shell-and-tube heat exchanger based on pressure drop constraints. FlatPlate Heat Exchanger[19] has a program on their web site to select a flat plate type heat exchanger for a given application. It is important to point out to the students that the selection procedure given by the manufacture in their engineering guide is actually the same as that taught in a heat transfer course (LMTD or NTU method) but a much more streamlined version to facilitate the selection process. In addition to exposure on the methods used in industry, these engineering guides provide students with other critical issues encountered in selecting a heat exchanger, such as types of fluid, nature of fluids, pressure and temperature ranges, materials, sizes and dimensions, etc.

The next part of the course involves mathematical concepts essential to modeling and simulation: curve fitting, regression, solution of linear and non-linear equations. Since most of these materials have been covered in numerical analysis course, the instructor provides only a brief review of most relevant topics and their applications in modeling and simulation of thermal systems. Examples of curve fitting include developing equations for properties of fluid such as viscosity and enthalpy as a function of temperature that are used in simulation software packages such as NASA CEA code[20] and Reaction Design CHEMKIN[21]. For solutions of linear and non-linear equations involving multiple variables, only successive substitution and Newton-Raphson methods were discussed in details.

The next part of the course is engineering economics and cost estimation. Chapter 5 of the text covers basic concepts of engineering economics and how to evaluate the economics of the project. Every mechanical engineering senior is required to take engineering economics class in their sophomore year so only a brief review of the material is dealt in class. Chapter 6 of the book is one of the major reasons for choosing the text as it covers cost estimation of various components based on the factor method. The factor method is based on the cost function that can be scaled with the size of the equipment that also takes into account the effect of inflation. The text book includes a comprehensive table for estimating costs of many different types of equipment and component relevant to thermal and energy systems. It is a unique and simple method to estimate the cost of the whole system and thus, the book by Hodge and Taylor[2] also include the method and the data tables.

The materials covered so far in the course are essential to the design of thermal systems. The next part of the course deals with mathematical modeling and simulations of these systems. As mentioned before, the text only includes the system flowsheeting which is the block diagram representation of a thermal system such as a power plant. The flowsheeting represents mass and energy flows between different components of the system. In order to implement the modeling and simulation, developing the set of equations from the system flowsheeting is essential. The same method is referred to as information flow diagram in Stoecker and Jaluria books, and materials from both books are used to supplement the materials in the text. The students are required to use the knowledge from heat transfer, thermodynamics and fluid mechanics to develop equations and choose appropriate input and output variables for each block diagram representing heat exchangers, pumps, etc. This is the most difficult part of the course according to students as there are multiple ways to devise system flowsheets and thereby obtain different sets of modeling equations. Typically these system of equations are non-linear so either successive substitution or Newton-Raphson method is used to solve them. The text lacks any examples of solutions of these equations so the materials from Stoecker's book[1] were used extensively for the simulation part. In addition, simulations of practical energy systems such as solar water heating from the book by Suryanarayan et al.[7] were used as examples. The last part of the course covers an introduction to different optimization method as they are applied to thermal systems.

Course Evaluation

The course evaluation consists of homework assignments, quizzes, exams and a group design project. Homework assignments are given once the coverage of a chapter is complete, and count 10% of the final grade. Quizzes are given after completion of two chapters, and count 20% of the total grade. Two exams, midterm and final, counts 20% each towards the final grade and the group project is worth 30% of the final grade.

Course Resources

Many of the resources used by the instructor are taken directly from the equipment manufacturers, engineering handbooks, and Standards to provide students with real-world engineering practice. For fluid machinery, the main resources come from manufacturers such as Gould pump and Chicago Blower companies as follows:

- Fans fundamentals: Fan Selection, Application-based Fan Selection, Performance Theory by GreenHeck Fan
- Pump Selection Guide by Goulds Pumps
- Valve Selection Guide by DeZurik[22]
- Centrifugal Pumps from Chemical Engineer Resource Page[23]
- Centrifugal Pump Intro by Joe Evans[24]

- Single Stage Pressure Blowers, and Industrial Centrifugal Fans by Chicago Blower
- Hydraulic Data for Pump Application, and Liquid Data and Materials Compatibility Guide by Blackmer[25] (for compressors and positive displacement pumps)

The instructor made use of the followings equipment selection programs for electing pumps, fans, etc.

- System Syzer® Calculator by Bells and Gossett[26]
- CAPS by Greenheck Fan
- ESP Plus by Bell & Gossett (now Goulds Pump)

For heat exchangers, the following resources are used:

- Fixed Tube Bundle Heat Exchangers by Young Radiator
- Plate Heat Exchangers by FlatPlate
- Shell and Tube Heat Exchanger Design by TFD
- Selection and Design of Cooling Towers by Shriram Towertech[27]
- Engineering Brochure by Cooling Tower Systems (CTS)[28]

For heat exchanger selection programs, the instructor used

- FlatPlate Selection software by FlatPlate
- ACE Shell & Tube Heat exchanger Selection by Armstrong[29]

The instructor discusses only some of these resources in class due to time constraint. However, all the resources mentioned above were made available to the students by hosting the documents or providing a link to the resource on the course web site. In addition to these resources, the materials from the following course web sites were used: Computer Assisted Design of Thermal Systems at Michigan State University[30], and Thermal Systems Design at Northern Illinois Univesity[31]. Students were tested in quizzes and exams on their ability to understand and apply these resources. For example, the students were asked to select a pump based on given flow rate and head or to select a heat exchanger for a particular heat transfer application.

Outcome and Assessment

The course is used to assess achievement of the following departmental outcomes:

(a) the ability to design an ability to apply knowledge of mathematics, science and engineering
(c) an ability to design a system, component or process to meet desired needs
(e) an understanding of professional and ethical responsibility
(h) a recognition of the need for, and an ability to engage in life-long learning
(m) an ability to use statistics and linear algebra
(n) an ability to work professionally in both thermal and mechanical systems areas including the design and realization of such systems
(o) an ability to work effectively as team members in mechanical engineering projects

Even though there are seven outcomes given above, outcomes (c) and (n) are the major outcomes required to achieve with regards to the course. From the description of course content, it is clear that outcomes (a), (c) (m) (n) and (o) are assessed by using homework assignments, quizzes, exams and group design project. The use of group projects in engineering provides cooperative learning environment for students to gain teamwork skills. Each student group is assigned a project from the book that requires the design of a thermal system such as steam-powered car, solar water heating system, thermal insulation of a room, etc. The group is required to submit an engineering report containing detailed descriptions of the design process, design evaluations and analysis, component selection, and cost estimation. The group is also required to present the project in front of the class followed by Q&A session from the class. To achieve outcomes (e) and (h), the instructor asked an alumnus who is working in a chemical plant to give a seminar on industrial experience. In addition, discussions of engineering standards such as Hydraulic Institute Standards, and use of engineering handbooks are utilized where appropriate to provide students exposure to professional conduct and necessity of lifelong learning.

Lessons Learned

There were 15 seniors taking the class in the fall semester. At the end of the course, students were asked to provide feedback on the course materials and their usefulness for their professional career as an entry-level engineer. Most of the feedback is very positive, and 90% of the students regarded the course as extremely useful for their career. In addition, 86% of the students regarded the course as stimulating their interests in the subject matter and almost 90% agreed they learned a great deal from this class.

Teaching this class is a rewarding experience for the instructor, providing students with the course materials and enhancing their knowledge and experience in the area of design of thermal systems. Wedekind and Kobus[12] mentioned the need for an integration of all the design steps into a cohesive learning experience and stated that *Fluid and Thermal System Design* course is the course where the students obtain the entire taxonomy of the design process. According to Mueller[13], the new elective course, *Design and Optimization of Thermal-Fluid Systems*, was developed in order to improve the performance of students in the areas of engineering economics and energy conversions. Based on the author's experience, the students need more exposure to overall thermal system design and implementation as they cannot see the big picture and apply the engineering principles learned in junior-level classes such as heat transfer and thermodynamics. Thermal System Design class is the only course where the students are required to apply, synthesize, and evaluate their skills and knowledge from previous courses into a complete system design. Thus, every Mechanical engineering curricula should require the Thermal System Design course for senior graduating students.

Some useful suggestions for instructors who will be teaching this class in the author's opinion are

- Extensive use of open-ended problems and projects to emphasize that there are many solutions to these problems and projects
- Use of engineering and product selection guides from equipment manufacturers to provide relevant industrial experience and exposure
- Relate the engineering materials and procedure from manufacturers to traditional materials in the text

- Require inclusion of costs analysis and component specifications in design problems and projects
- Provide numerical simulations and optimization using a mathematical software package such as MathCAD or matlab

Conclusions

This paper discussed the experiences of an instructor who has taught the Design of Thermal Systems course for the first time. The paper provides detailed descriptions of the class, selection of the text, course contents and evaluation, course resources, and outcome evaluation. It is the author's opinion that Design of Thermal Systems is an extremely useful to students and should be a required course for any Mechanical Engineering curriculum.

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