Implementation of Computational Tools in Energy-Related Mechanical Engineering Courses

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Abstract – This work focuses on the development of a computational tool to be implemented in an energy-related course such as Thermodynamics. Through the implementation of computational tools, it is expected that students and faculty will be afforded the time to focus primarily on the physics and conceptual material behind problems instead of on the mathematics of solving equations. The computational tool presented in this paper illustrates a Gas Turbine (Brayton) cycle and is intended for sophomore-level mechanical engineering students in Thermodynamics courses. The tool is developed in Microsoft Excel. Using this tool, undergraduate students will be able to immediately determine results due to variations in input design conditions and/or different system parameters, which can increase the quality and level of the material covered in the course. Feedback from students as well as class instructors indicates that the use of these tools will be invaluable for the students.

Keywords: computational tool, mechanical engineering, energy

INTRODUCTION

In the past, computer-based methods such as Computer Aided Design (CAD), Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) have advanced from the research stage to industrial-ready application. Nowadays, it is expected that recent engineering students have knowledge in CAD and sometimes in FEA. Most of the engineering schools offer undergraduate CAD courses, and some of them offer courses on FEA for more advanced students. Using such computational tools allows instructors to focus on application and inquiry rather than focusing only on theory [1]. However, in the authors’ opinion, there is a lack of computational tools for energy-related courses. Due to the lack of relevant software options and the high cost of the software that is available, the adoption of computational tools in energy-related undergraduate courses is impractical at the present time. In order to strengthen undergraduate energy-related instruction, new tools must be developed to incorporate the computational aspect into the energy curriculum. Some of the existing software that could be used to develop tools and to solve energy problems are Microsoft Excel and Mathcad. Mathcad and Excel are computational systems that have the potential to replace structured programming in undergraduate mechanical engineering courses, as structured programming has become less of a necessity in the mechanical engineering curriculum and industries [2].

In this study, Excel is used because students are usually familiar with it, indicating a shallow learning curve, and Excel is well-adapted for handling data files such as property data files for different substances. Excel also provides a more comprehensive and flexible tool for 2D plotting. At Mississippi State University, to date, only a few instructors have incorporated computational tools in their energy-related courses, and those tools have been used only in senior-level courses. However, the general student reception for the use of these tools has been positive. Luck and Mago [3] presented a study to investigate the use of Mathcad and Excel to enhance the study of psychrometric processes for buildings in an air conditioning course, and they determined that using these tools does improve student satisfaction with the course. Hodge and Taylor [4] implemented Mathcad in the energy systems design course to find that the use of Mathcad greatly strengthened the course. It allowed the course to focus more on relevant workplace applications and engineering design, rather than numerical analysis and structured programming. The use of Mathcad to solve piping problems, in particular, allows students to gain a more thorough

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understanding of the engineering aspects of the design projects instead of being fully-immersed in only the computational aspects of a problem [5]. Finally, Mathcad has been implemented into the alternate energy sources course to maximize course content within the single-semester time constraint [6]. However, as mentioned before, there is a need to implement this approach in additional energy-related courses starting at the sophomore level.

The primary motivation to develop these tools is to increase the conceptual understanding students have when solving the problems posed to them. Utilizing a computational tool, the number of calculations required to solve design-oriented problems can be greatly diminished. Additionally, the students themselves have expressed a desire to implement more computational tools into the early stages of engineering coursework. Students are required to purchase laptops as they enter the mechanical engineering curriculum at Mississippi State University, but few sophomore-level courses take advantage of the computational ability provided by this requirement. MSU mechanical engineering students have expressed a desire to maximize computer usage in order to substantiate their initial investment for the computer as well as to feel adequately prepared to enter the work-force.

COMPUTATIONAL TOOL DEVELOPMENT

The computational tool presented in this paper illustrates a Gas Turbine (Brayton) cycle and is intended for sophomore-level mechanical engineering students in Thermodynamics courses. Figure 1(a) shows an air-standard gas turbine cycle. In a Brayton cycle, the working fluid is considered to be air, which behaves as an ideal gas. The following assumptions are made for the modeling of the cycle:

a. The mass flow rate of air is constant through the entire cycle.
b. The combustion process is replaced by a heat transfer process from an external source.
c. The cycle is completed by transferring heat to the surroundings.
d. The working fluid, air, has constant specific heat, evaluated at 300K.

The Brayton cycle has four processes. First, the working fluid enters the compressor (State 1), and it is compressed to State 2 (Process 1-2). After that, heat from an external source is added to the working fluid to increase its temperature to State 3 (Process 2-3). The working fluid is expanded to State 4 (Process 3-4), and then heat is rejected from the working fluid to the surroundings (Process 4-1). Figure 1(b) illustrates the different processes in a temperature-entropy diagram. The advantage of this cycle is that it allows the user to examine the influence of different parameters on the overall cycle performance.

![Brayton Cycle Diagram](image)

Figure 1. a) Brayton Cycle and b) T-s diagram of the processes.

To analyze the cycle, the first Law of Thermodynamics is applied to each individual component [7].
Process 1-2: this is a compression process. The compressor efficiency is given by

\[ \eta_c = \frac{W_{c,s}}{W_{c,a}} \]  

(1)

where \( W_{c,s} \) and \( W_{c,a} \) represent the ideal and actual compressor power.

The compressor ideal power is an isentropic process \((s_1 = s_2)\) and it can be expressed as:

\[ W_{c,s} = \dot{m}_a (h_1 - h_{2,s}) = \dot{m}_a c_p (T_1 - T_{2,s}) \]  

(2)

where \( \dot{m}_a \) is the working fluid mass flow rate, \( h_1 \) and \( T_1 \) are the enthalpy and temperature of the air at the inlet of the compressor, respectively, and \( h_{2,s} \) and \( T_{2,s} \) are the enthalpy and temperature of the air leaving the compressor for the ideal case, respectively.

The temperature of the air exiting the compressor for the ideal case can be calculated as:

\[ T_{2,s} = T_1 \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} \]  

(3)

where \( k \) is the specific heat ratio, \( k = c_p / c_v \).

The actual compressor work can be calculated as

\[ W_{c,a} = \dot{m}_a (h_1 - h_2) = \dot{m}_a c_p (T_1 - T_2) \]  

(4)

where \( T_2 \) is the actual temperature of the air leaving the compressor.

Process 2-3: in this process, heat is added to the working fluid from an external source in the heat exchanger. It is assumed that this process occurs at constant pressure. The heat transfer rate added to the cycle can be expressed as:

\[ \dot{Q}_{in} = \dot{m}_a (h_3 - h_2) = \dot{m}_a c_p (T_3 - T_2) \]  

(5)

where \( h_3 \) and \( T_3 \) are the enthalpy and temperature of the air leaving the heat exchanger and entering the turbine, respectively.

Process 3-4: This is an expansion process. The turbine efficiency is given by

\[ \eta_t = \frac{W_{t,a}}{W_{t,s}} \]  

(6)

where \( W_{t,a} \) and \( W_{t,s} \) represent the actual and the ideal turbine power.

The turbine ideal power is an isentropic process \((s_3 = s_4)\), and it can be expressed as:

\[ W_{t,s} = \dot{m}_a (h_3 - h_{4,s}) = \dot{m}_a c_p (T_3 - T_{4,s}) \]  

(7)

where \( h_3 \) and \( T_3 \) are the enthalpy and temperature of the air at the inlet of the turbine, respectively, and \( h_{4,s} \) and \( T_{4,s} \) are the enthalpy and temperature of the air leaving the turbine for the ideal case, respectively.

The temperature of the air exiting the turbine for the ideal case can be calculated as:
\[ T_{4,s} = T_3 \left( \frac{P_A}{P_1} \right)^{\frac{1}{\kappa-1}} \]  

(8)

The actual turbine power can be calculated as

\[ W_{t,a} = m_a (h_3 - h_4) = m_a c_p (T_3 - T_4) \]  

(9)

where \( T_4 \) is the real temperature of the air leaving the turbine.

**Process 4-1:** in this process, heat is rejected from the working fluid to the surroundings. It is assumed that this process occurs at constant pressure. The rejected heat transfer rate can be expressed as:

\[ \dot{Q}_{out} = m_a (h_4 - h_1) = m_a c_p (T_4 - T_1) \]  

(10)

where \( h_4 \) and \( T_4 \) are the enthalpy and temperature of the air leaving the turbine and entering the heat exchanger.

**Net Power:** The net power of the cycle can be calculated as:

\[ W_{net} = W_{t,a} + W_{c,a} = m_a c_p [(T_3 - T_4) + (T_1 - T_2)] \]  

(11)

**Thermal Efficiency:** the thermal efficiency of the cycle can be expressed as:

\[ \eta = \frac{W_{net}}{\dot{Q}_{in}} = \frac{(T_3-T_4) + (T_1-T_2)}{(T_3-T_2)} \]  

(12)

**Back Work Ratio:** The back work ratio \((bwr)\) for the cycle is defined as the fraction of the turbine power that is used to operate the compressor. The \( bwr \) can be calculated as:

\[ bwr = \frac{W_{c,a}}{W_{t,a}} = \frac{T_2 - T_1}{T_3 - T_4} \]  

(13)

**COMPUTATIONAL TOOL DEVELOPED IN EXCEL**

The equations presented in the previous section were used to develop a computational tool in Excel. Figure 2 shows a screenshot of the main screen of the tool developed. In this tool, students need to input the information known for the cycle (Orange Section) such as: inlet temperature and pressure of the air entering the compressor, the temperature of air leaving the heat exchanger (maximum cycle temperature), the pressure ratio, defined as \( P_2/P_1 \), and the mass flow rate of the working fluid. In addition, if the students would like to evaluate a more realistic cycle they can input isentropic efficiencies for the compressor and the turbine. After the students enter all the required information, they can instantaneously obtain the temperature and pressure of the different states in the cycle (Blue Section) as well as the power and heat transfer rates for the different processes. In addition to numerical values, the tool illustrates the different processes in a temperature-entropy diagram. This is really important since students can quickly visualize how the processes are affected by just varying a simple parameter on the cycle.

If the students would like to perform a parametric analysis of the cycle, they can click the tab named “Parametric Study,” and will be able to study the effect of the varying different parameters such as the pressure ratio, the maximum cycle temperature, and the isentropic compressor and turbine efficiencies. A screenshot of this tab is presented in Figure 3. In this screen, the students need to input the minimum and maximum value of the variable to be analyzed and the tool displays a series of plots with valuable information.

To show the usability of the tool, a series of examples are presented.
Example 1: In an air standard Brayton cycle, the air enters at the compressor at 0.1 MPa and 298K. The pressure leaving the compressor is 10MPa, and the maximum temperature of the cycle 1200K. The compressor and turbine are assumed to be ideal. If the mass flow rate of air is 1 kg/s, determine:

a. The pressure and temperature at each point of the cycle.
b. The compressor and turbine power.
c. The heat rate added to the cycle.
d. The heat rate rejected by the cycle.
e. The cycle efficiency.
f. The back work.

The solution for this example is presented in Figure 4. This example illustrates how students can rapidly evaluate an ideal cycle and see how to represent the processes in the T-s diagram.
**Example 2:** Repeat Example 1, assuming the compressor and turbine efficiencies are 82% and 85%, respectively.

The solution for this example is presented in Figure 5. In this example, students can make the cycle more realistic by incorporating the effect of the compressor and turbine isentropic efficiencies on the overall cycle performance. By doing this, students can immediately see how the Process 1-2 and Process 3-4 are not isentropic anymore and how the overall efficiency of the cycle was reduced from 51.04% to 27.41%.

**Example 3:** Study the effect of changing several parameters on the cycle overall performance. Analyze the following cases:

a. Vary the pressure ratio from 5 to 20.

b. Vary the maximum cycle temperature from 1000K to 3000K.

c. Vary the compressor efficiency from 70% to 100%.

d. Vary the turbine efficiency from 70% to 100%.

The solution for this example is presented in Figure 6. In this example, students can evaluate the effect of varying parameters some parameters in the cycle while keeping the other parameters constant. This portion of the tools will allow students to quickly analyze and visualize the effect of varying the pressure ratio, the cycle maximum temperature, as well as the turbine and compressor isentropic efficiency on the overall cycle performance.
Figure 4. Screenshot of the tool with Example 1.
Figure 5. Screenshot of the tool with Example 2.
This paper discussed the development of a computational tool using Excel to complement instruction in a sophomore-level mechanical engineering energy-related course. The tool developed modeled a Brayton cycle and allows students, to quickly evaluate the performance of the cycle by determining parameters such as heat transfer rates, power inputs and outputs, and cycle efficiency as well as the temperature-entropy diagram. Additionally, the tool allows students to perform a parametric study to show variances in cycle efficiency, net power, heat transfer rates, and back work over a range of pressure ratios, compressor efficiencies, maximum cycle temperatures, or turbine efficiencies. The objective of this development is to enhance the undergraduate educational experience by allowing students to immediately see the effects of changes in input parameters as well as by reducing calculation intensity to allow a stronger focus on conceptual understanding. Now that this tool has been developed, the next step in this process is to implement the tool in a Thermodynamics course. The authors expect to begin implementation in the Spring 2014 semester.

REFERENCES


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