Computational Tools to Enhance the Study of Gas Power Cycles in Mechanical Engineering Courses

Alta A. Knizley and Pedro J. Mago
Department of Mechanical Engineering, Mississippi State University

Abstract

Previously, a computational tool illustrating a gas-turbine Brayton cycle was developed for use in thermodynamics courses at Mississippi State University. The purpose of this paper is to extend this analysis and to develop a similar tool for other gas power cycles. Two other commonly examined gas power cycles include the Otto and Diesel cycles. Computational tools, developed in Microsoft Excel, to enhance student visualization of the overall cycle effects due to parameter variations are developed for each of the afore-mentioned cycle types, providing students with a comprehensive set of gas power cycle analysis tools. Utilization of these tools in the classroom serves to enhance student understanding through direct visualization, and it can increase the efficiency of classroom instruction by allowing more time to address conceptual understanding over repeated algebraic calculations.

Keywords

Computational Tool, Thermodynamic Cycles, Gas Power Cycles

Introduction

Previously, Knizley and Mago presented a computational tool for use in Thermodynamics courses to examine a gas-turbine Brayton Cycle[1]. This tool allowed students to better understand Brayton cycle operation through visualization of the effects that single parameter changes introduce to the overall properties and processes of the Brayton cycle. Based upon the favorable response to this single-cycle tool, the authors currently seek to develop a set of similar analysis tools for additional gas power cycles, the Otto and Diesel Cycles, to increase the exposure of mechanical engineering students to software utilization and to the deeper conceptual understanding that accompanies such tools. The Brayton cycle analysis tool was developed using Microsoft Excel, chosen because it is a capable software program that is also readily available to mechanical engineering students. These three cycles present a thorough representation of gas power cycles in a Thermodynamics course.

While many computational tools are readily available for analytical techniques (MatLAB, MathCAD, Excel), structural analysis and design (FEA, CAD software), and fluid flow (CFD) components of mechanical engineering, few cost-effective computational tools exist for undergraduate thermal/energy-related courses. Many of the computational tools that are available in energy-related areas are for graduate or split-level courses, as opposed to a purely undergraduate mechanical engineering course such as Thermodynamics[2,3]. Since approximately 75% of a survey sample of mechanical engineering programs require undergraduates to utilize computational systems[4], it may be beneficial to such programs to offer more resources for computational tool development in energy-related courses. In this paper, computational tools are developed using Microsoft Excel, since that program is readily available to most students.

Having a strong set of computational tools available for an undergraduate curriculum can allow instructors to focus more on problem-based learning instead of traditional lecture format in the classroom. The computational tools developed here give students the freedom to instantly explore how variations to one parameter affect others, without becoming overwhelmed by analytical calculations. This allows the instructor more freedom to present problem-based, in-class, and group-oriented assignments when the analytical calculation time is reduced through the use of these tools. Furthermore, this allows for a more student-centered approach to energy-related curriculum, which has been shown to be a favorable trend in engineering education[5,6].

Model of Otto and Diesel Cycles

The computational tool presented in this paper illustrates the modeling equations and processes for the Otto and Diesel gas power cycles[7] and is intended for sophomore-level mechanical engineering students in Thermodynamics courses. In both cycles, the working fluid is considered to be air, which behaves as an ideal gas. The Otto cycle is an ideal cycle representing a spark-ignited internal-combustion (IC) engine with the following processes: isentropic compression of air (Process 1-2), constant-volume heat addition (Process 2-3), isentropic expansion of air (Process 3-4), and constant volume heat rejection (Process 4-1). The pressure volume diagram for these processes in the Otto Cycle are shown in Fig. 1.

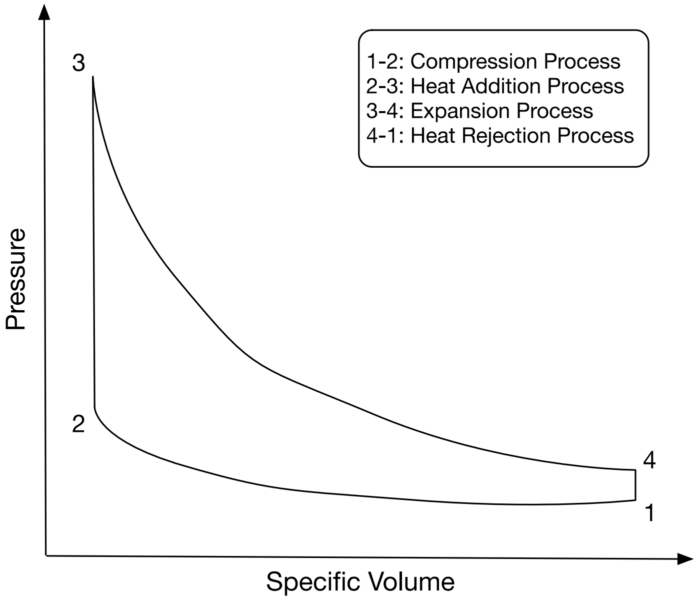


Figure 1. P-V Diagram for Otto Cycle

For the Otto cycle, thermal efficiency is defined as

$$\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - (CR)^{1-k} \qquad (1)$$

where T_1 and T_2 are the temperatures at the beginning and end of the isentropic compression process, respectively, representing bottom dead center intake temperature and top dead center temperature after compression. k is the ratio of specific heats and CR is the compression ratio, which is defined as

$$CR = \frac{v_1}{v_2} = \frac{v_4}{v_3} \tag{2}$$

where v represents the specific volume at each state.

For the proposed computational model, the working fluid, air, is assumed to have constant specific heats evaluated at 300 K, and the mass of air is considered constant throughout the cycle. The inputs to the model include air properties of specific heat (c_v), gas constant (R), specific heat ratio (k), intake pressure (P_1), intake temperature (T_1), temperature after heat addition (T_3) (maximum combustion temperature), compression ratio (CR), and mass of air. Using the ideal gas law, compression ratio relationships, and ideal gas process relationship, pressure (P), temperature (T), and specific volume (v) properties at all states (1,2,3,4) may be determined:

$$P \cdot v = R \cdot T \tag{3}$$

where P is pressure, v is specific volume, R is gas constant, and T is temperature, all at the same state, in the ideal gas equation of state.

A polytropic relationship can be used to model ideal gases undergoing isentropic processes such as from State 1 to 2 (compression process) and from State 3 to 4 (expansion process):

$$P \cdot v^k = constant \tag{4}$$

Using Eqs. (2) and (4) the relationship between the temperatures in the cycle can be expressed as:

$$\frac{T_2}{T_1} = (CR)^{k-1} = \frac{T_3}{T_4} \tag{5}$$

Using the First Law of Thermodynamics for a closed system:

$$\Delta U = Q - W \tag{6}$$

and the assumption that air is an ideal gas with constant specific heats, work and heat can be calculated for each process:

$$\Delta U = m \cdot c_v \cdot \Delta T \tag{7}$$

$$Q_{1-2} = 0 \tag{8}$$

$$W_{1-2} = m \cdot c_v \cdot (T_1 - T_2) \tag{9}$$

$$Q_{2-3} = m \cdot c_v \cdot (T_3 - T_2) \tag{10}$$

$$W_{3-4} = m \cdot c_v \cdot (T_3 - T_4) \tag{11}$$

$$Q_{4-1} = m \cdot c_v \cdot (T_1 - T_4) \tag{12}$$

Finally, the net work for the cycle, thermal efficiency of the cycle, and mean effective pressure (*mep*) are also evaluated. Net work and *mep* are calculated using:

$$W_{net} = W_{1-2} + W_{3-4} = Q_{2-3} + Q_{4-1} \tag{13}$$

$$mep = \frac{W_{net}}{v_1 - v_2} \tag{14}$$

The Diesel cycle represents an ideal compression-ignition IC Engine using the following processes: isentropic compression of air, constant-pressure heat addition, isentropic expansion of air, and constant-volume heat rejection. Similar equations are used to model the Diesel cycle, however it should be noted that Process 2 to 3 in the Diesel cycle varies significantly from that of the Otto cycle, as the constant pressure heat addition in the Diesel cycle also includes simple compressible work. Figure 2 shows the process diagram for the Diesel cycle.

For the Diesel cycle, the CR is still defined as:

$$CR = \frac{v_1}{v_2} \tag{15}$$

However, v_2 and v_3 are no longer equivalent, so an expansion ratio can be defined as:

$$ER = \frac{v_4}{v_3} \tag{16}$$

Properties at all states may be found using ideal gas relationships (Eqn. (3) and Eqn. (5)) and process information. Eqn. (8) – (9) and (11) – (12) for the Otto Cycle are also used to model the Diesel cycle, but, for Process 2 to 3, work and heat are calculated as:

$$Q_{2-3} = \Delta U_{2-3} + W_{2-3} = m \cdot c_p \cdot (T_3 - T_2) \tag{17}$$

$$W_{2-3} = P \cdot m \cdot (v_3 - v_2) \tag{18}$$

where $c_p = R + c_v$ and P is the pressure for States 2 and 3.

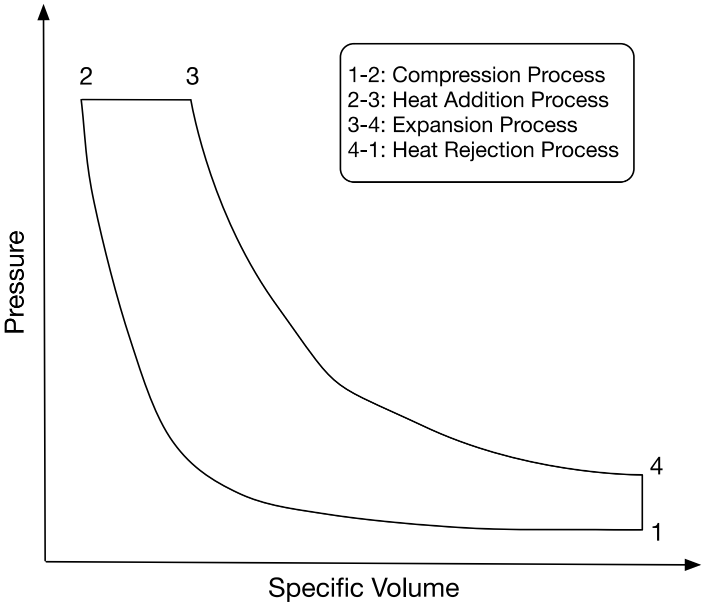


Figure 2. Process Diagram for Diesel Cycle

For both models described above, the relevant equations have been input directly into the Excel spreadsheets. No knowledge of Excel Visual Basic for Applications (macro) programming is required for the student to understand the operation of these computational tools. This allows for students to clearly identify and understand the mathematics describing the thermodynamic system and to adapt the tool for specific cases if required. Output tables and plots are automatically generated, utilizing built-in Excel formulas and plotting techniques, provided the necessary input parameters are appropriately assigned in the "Data Input" tables.

Utilizing the Computational Tool

Once the equations are compiled into an Excel spreadsheet, the input data can be adjusted to display output data of pressure, temperature, and specific volume for each state, work and heat transfers in each process, and net work, thermal efficiency, and mep for the overall Otto cycle. Figures 3 shows the computational tool developed for Otto cycle while Figure 4 illustrates the computational tool for Diesel Cycle. The following examples, adapted from Borgnakke and Sonntag[7], illustrate how this computational tool could be used in a classroom environment.

Example 1:

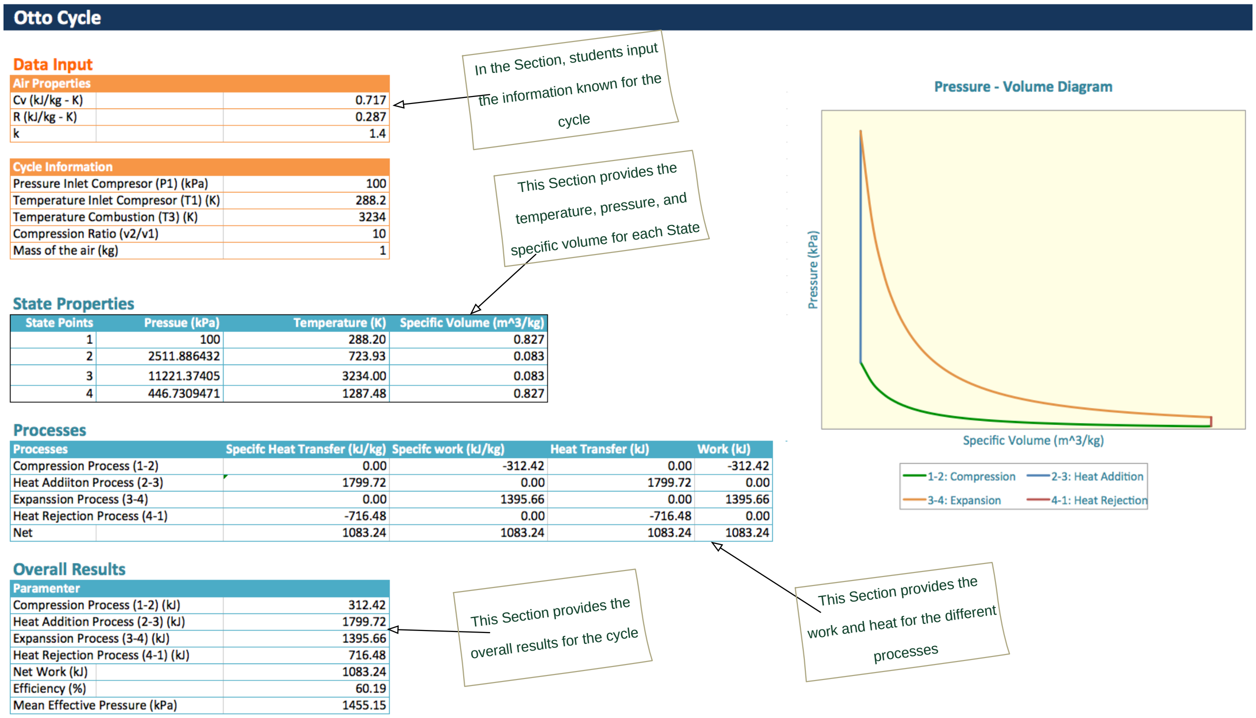
The compression ratio in an air-standard Otto cycle is 10. At the beginning of the compression stroke, the pressure is 0.1 MPa and the temperature is 15°C. For an intake temperature of 288.15 K and a combustion temperature of 3234 K, determine the pressure and temperature at each state in the cycle, the thermal efficiency of the cycle, and the mep for the cycle.

The results are presented in Figure 3. The pressure and temperature at each state are: $P_1 = 100$ *kPa,* $P_2 = 2511.9$ *kPa,* $P_3 = 11.2$ *MPa,* $P_4 = 446.8$ *kPa,* $T_1 = 288.15$ *K,* $T_2 = 723.8$ *K,* $T_3 = 3234$ *K,* $T_4 = 1287.5$ *K. The efficiency is 60% and the mep is 1455.5 kPa.*

Example 2:

Repeat example one using a new compression ratio of 12.

The results are presented in Figure 5. The pressure and temperature at each state are: $P_1 = 100$ *kPa,* $P_2 = 3242.3$ *kPa,* $P_3 = 13.5$ *MPa,* $P_4 = 415.3$ *kPa,* $T_1 = 288.15$ *K,* $T_2 = 779$ *K,* $T_3 = 3234$ *K,* $T_4 = 1197$ *K. The efficiency is 63% and the mep is 1463 kPa.*



Otto Cycle

Data Input

Air Properties		
Cv (kJ/kg - K)		0.717
R (kJ/kg - K)		0.287
k		1.4

Cycle Information	
Pressure Inlet Compresor (P1) (kPa)	100
Temperature Inlet Compresor (T1) (K)	288.2
Temperature Combustion (T3) (K)	3234
Compression Ratio (v2/v1)	10
Mass of the air (kg)	1

In the Section, students input the information known for the cycle

This Section provides the temperature, pressure, and specific volume for each State

State Properties

State Points	Pressue (kPa)	Temperature (K)	Specific Volume (m^3/kg)
1	100	288.20	0.827
2	2511.886432	723.93	0.083
3	11221.37405	3234.00	0.083
4	446.7309471	1287.48	0.827

Processes

Processes	Specifc Heat Transfer (kJ/kg)	Specifc work (kJ/kg)	Heat Transfer (kJ)	Work (kJ)
Compression Process (1-2)	0.00	-312.42	0.00	-312.42
Heat Addiiton Process (2-3)	1799.72	0.00	1799.72	0.00
Expanssion Process (3-4)	0.00	1395.66	0.00	1395.66
Heat Rejection Process (4-1)	-716.48	0.00	-716.48	0.00
Net	1083.24	1083.24	1083.24	1083.24

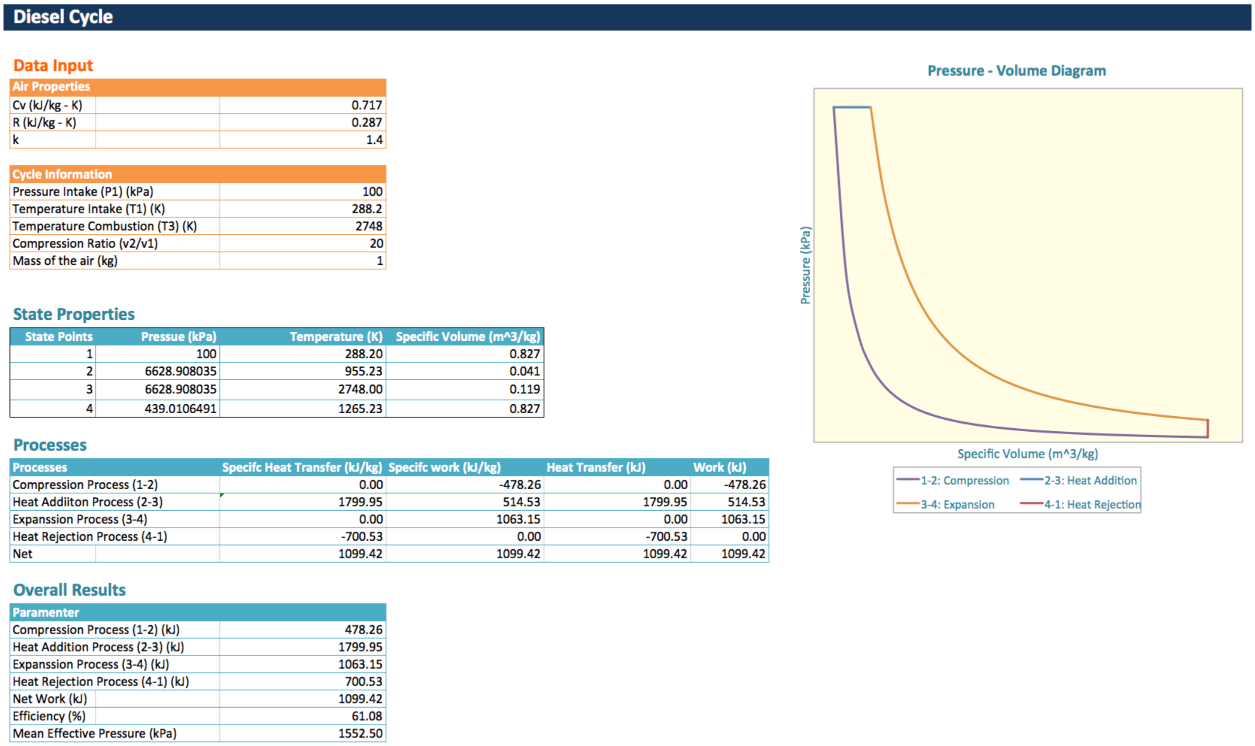
Overall Results

Paramenter	
Compression Process (1-2) (kJ)	312.42
Heat Addition Process (2-3) (kJ)	1799.72
Expanssion Process (3-4) (kJ)	1395.66
Heat Rejection Process (4-1) (kJ)	716.48
Net Work (kJ)	1083.24
Efficiency (%)	60.19
Mean Effective Pressure (kPa)	1455.15

This Section provides the overall results for the cycle

This Section provides the work and heat for the different processes

Figure 3. Display with input parameters T_1 = 288.2 K and CR =10



Diesel Cycle

Data Input

Air Properties	
Cv (kJ/kg - K)	0.717
R (kJ/kg - K)	0.287
k	1.4

Cycle Information	
Pressure Intake (P1) (kPa)	100
Temperature Intake (T1) (K)	288.2
Temperature Combustion (T3) (K)	2748
Compression Ratio (v2/v1)	20
Mass of the air (kg)	1

State Properties

State Points	Pressue (kPa)	Temperature (K)	Specific Volume (m^3/kg)
1	100	288.20	0.827
2	6628.908035	955.23	0.041
3	6628.908035	2748.00	0.119
4	439.0106491	1265.23	0.827

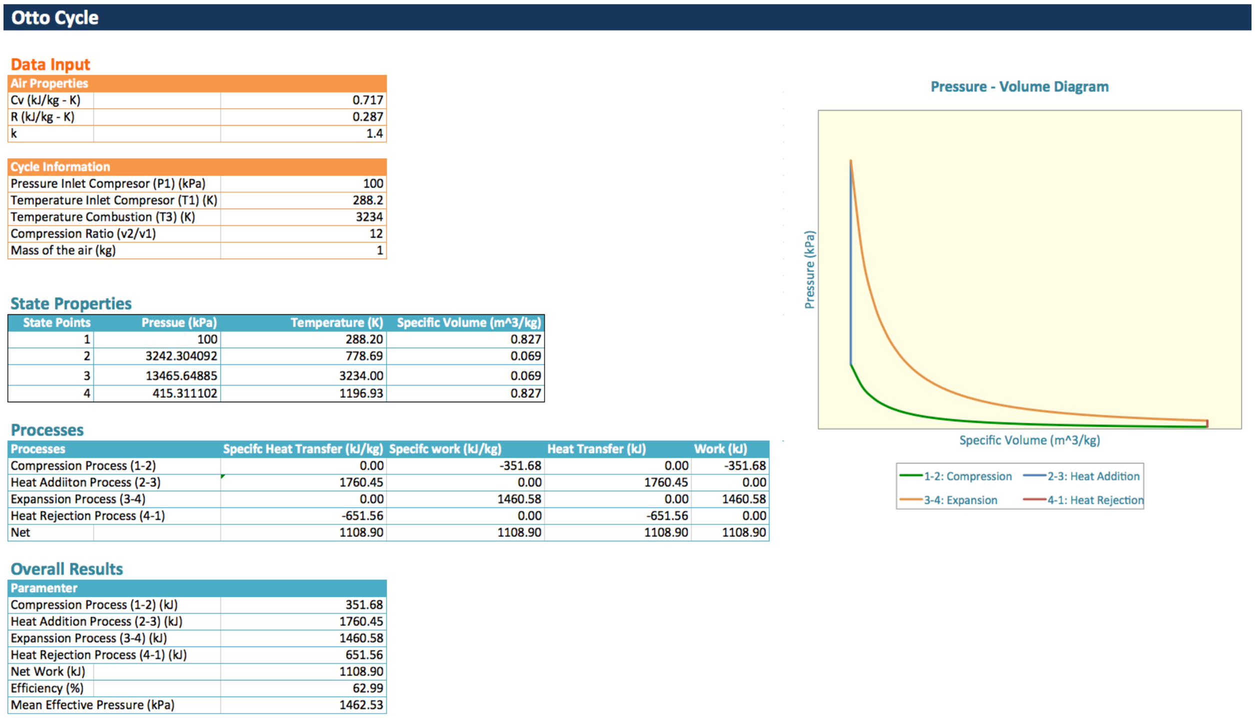
Processes

Processes	Specifc Heat Transfer (kJ/kg)	Specifc work (kJ/kg)	Heat Transfer (kJ)	Work (kJ)
Compression Process (1-2)	0.00	-478.26	0.00	-478.26
Heat Addiiton Process (2-3)	1799.95	514.53	1799.95	514.53
Expanssion Process (3-4)	0.00	1063.15	0.00	1063.15
Heat Rejection Process (4-1)	-700.53	0.00	-700.53	0.00
Net	1099.42	1099.42	1099.42	1099.42

Overall Results

Paramenter	
Compression Process (1-2) (kJ)	478.26
Heat Addition Process (2-3) (kJ)	1799.95
Expanssion Process (3-4) (kJ)	1063.15
Heat Rejection Process (4-1) (kJ)	700.53
Net Work (kJ)	1099.42
Efficiency (%)	61.08
Mean Effective Pressure (kPa)	1552.50

Figure 4. Display for Diesel Cycle Model



Otto Cycle

Data Input

Air Properties	
Cv (kJ/kg - K)	0.717
R (kJ/kg - K)	0.287
k	1.4

Cycle Information	
Pressure Inlet Compresor (P1) (kPa)	100
Temperature Inlet Compresor (T1) (K)	288.2
Temperature Combustion (T3) (K)	3234
Compression Ratio (v2/v1)	12
Mass of the air (kg)	1

State Properties

State Points	Pressue (kPa)	Temperature (K)	Specific Volume (m^3/kg)
1	100	288.20	0.827
2	3242.304092	778.69	0.069
3	13465.64885	3234.00	0.069
4	415.311102	1196.93	0.827

Processes

Processes	Specifc Heat Transfer (kJ/kg)	Specifc work (kJ/kg)	Heat Transfer (kJ)	Work (kJ)
Compression Process (1-2)	0.00	-351.68	0.00	-351.68
Heat Addiiton Process (2-3)	1760.45	0.00	1760.45	0.00
Expanssion Process (3-4)	0.00	1460.58	0.00	1460.58
Heat Rejection Process (4-1)	-651.56	0.00	-651.56	0.00
Net	1108.90	1108.90	1108.90	1108.90

Overall Results

Paramenter	
Compression Process (1-2) (kJ)	351.68
Heat Addition Process (2-3) (kJ)	1760.45
Expanssion Process (3-4) (kJ)	1460.58
Heat Rejection Process (4-1) (kJ)	651.56
Net Work (kJ)	1108.90
Efficiency (%)	62.99
Mean Effective Pressure (kPa)	1462.53

Figure 5. Display with input parameters same as Example 1 but with CR =12

Figures 3 and 5 show that, utilizing this computational tool, useful process data can be calculated instantly. This allows student groups to quickly examine how process parameters may affect the overall cycle, and this can be used for students to actively respond to conceptual questions by independently processing information. For instance, students could be tasked to explain the effect that compression ratio has on thermal efficiency of the Otto cycle and can quickly determine that, by increasing the CR from 10 to 12, the thermal efficiency is also increased from 60% to 63%. Furthermore, a quick study (Example 3) where compression ratio is varied from 5 to 15 utilizing the computational tool, while other parameters remain constant with values corresponding to those from Fig. 3, shows that efficiency increases from 47.5% to 66.2% with the increase in CR. Thus, students can autonomously determine that increasing compression ratio increases thermal efficiency, and then validate their findings by examining the course text. The process could be further developed by plotting the incremental increases of CR vs. thermal efficiency, shown in Fig. 6. The same analysis could be performed for any other system parameter to determine the effect of the variation of this parameter on the system performance.

Example 3.
Using temperature and pressure input values for an Otto cycle from Example 1, vary the CR from 5 to 15 to determine the effect on the cycle thermal efficiency.

The results are presented in Figure 6. This shows that for an Otto Cycle, efficiency is increased as CR is increased. Since the Otto cycle is an ideal cycle, the efficiency values shown in Fig. 6 are higher than would be expected for a real SI cycle. For the Otto cycle, the efficiency varies from about 48% to 63% at a high CR of 15. An actual SI engine could be approximated as[8]

$$\eta_{actual} = 0.85 \cdot \eta_{th,otto} \tag{19}$$

Thus, the efficiency of an actual SI engine could be expected to be within 40% and 55% for the selected CR and inlet conditions.

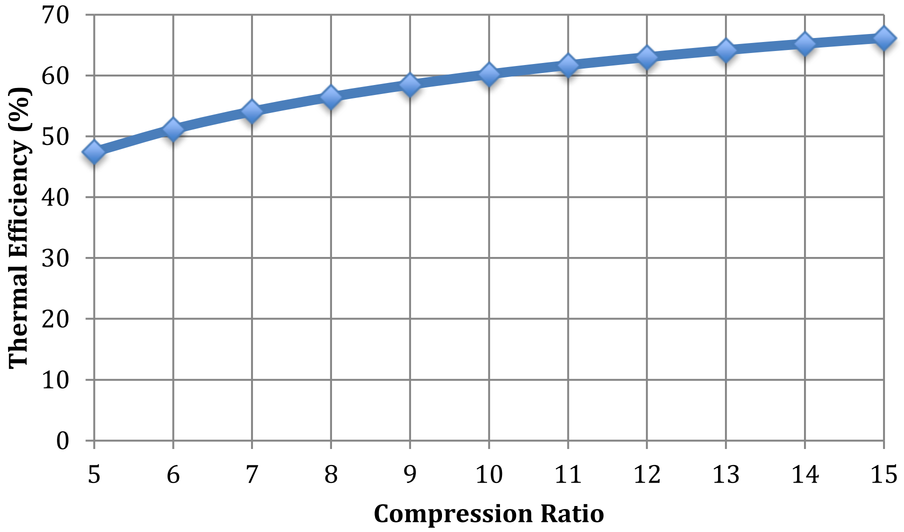


Figure 6. Plot of Parametric Study

Conclusions

Computational tools to model Otto and Diesel cycles have been developed using Microsoft Excel. Microsoft Excel is utilized because it is readily available software for undergraduate mechanical engineering students. These tools, combined with the previously developed Brayton Cycle computational tool, present a broad set of computational tools for analyzing gas power cycles. Utilization of these tools in the classroom can help to promote a student-centered learning environment and allow for more detailed problem-based learning classroom models in thermodynamics courses.

References

1. A. A. Knizley and P. J. Mago, "Implementation of Computational Tools in Energy-Related Mechanical Engineering Courses," in *2014 ASEE Southeast Section Conference*, Macon, GA, March 2014.

2. R. Luck and P. J. Mago, "Use of Mathcad and Excel to Enhance the Study of Psychrometric Processes for Buildings in an Air Conditioning Course," in *2012 ASEE Southeast Section Conference*, Starkville, MS, April 2012.

3. B. K. Hodge, "Using Mathcad to Enhance the Effectiveness of the Wind Energy Topic in an Alternate Energy Sources Course," in *Proceedings of the 2007 ASEE Annual Conference*, 2007.

4. B. K. Hodge and W. G. Steele, "A Survey of Computational Paradigms in Undergraduate Mechanical Engineering Education," *Journal of Engineering Education*, vol. 91, pp. 415-417, 2002.

5. R. M. Felder and R. Brent, "Navigating the Bumpy Road to Student-Centered Instruction," *College Teaching*, vol. 44, no. 2, pp. 43-47, 1996.

6. K. A. Smith, S. D. Sheppard, D. W. Johnson and R. T. Johnson, "Pedagogies of Engagement: Classroom-Based Practices," *Journal of Engineering Education*, vol. 94, pp. 87-101, 2005.
7. C. Borgnakke and R. E. Sonntag, Fundamentals of Thermodynamics, 7th ed., Hoboken, NJ: John Wiley & Sons, 2009.
8. W. W. Pulkrabek, Engineering Fundamentals of the Internal Combustion Engine, Second Edition ed., Upper Saddle River, NJ: Pearson Prentice-Hall, 2004.

Alta A. Knizley

Alta Knizley is an instructor in the Mechanical Engineering Department at Mississippi State University. She obtained her Ph.D. in Mechanical Engineering from Mississippi State University in 2013. She has an avid interest in undergraduate education and a strong background in energy-related course curriculum.

Pedro J. Mago

Pedro J. Mago is Department Head and PACCAR Chair Professor for the Mechanical Engineering Department at Mississippi State University. He teaches undergraduate courses in thermodynamics, air conditioning, power generation systems as well as graduate courses in advanced heat transfer. Dr. Mago is the author of more than 140 archival journal articles and conference papers.