Development of a Web-based IC Engine Simulator (WICES)

Vinod Matham, Kendrick Aung

Department of Mechanical Engineering
Lamar University, Beaumont, Texas 77710

Abstract

Internal Combustion (IC) engines have been in use for over a century in many applications such as transportation and energy generation. In the Department of Mechanical Engineering at Lamar University, IC engine course is an elective course for senior students specializing in energy and thermal fluid area. One of the main obstacles in teaching an IC Engine class to undergraduate students is the lack of computational tools that enhance and improve the learning process of students. With the widespread availability of multi-media software and hardware tools, development and integration of web-based tools to the undergraduate curriculum becomes essential. This paper discusses the development of a web-based IC Engine Simulator (WICES) to be used in an undergraduate IC Engine class. The simulator is written in Java language for easy use and portability. The simulator can be used to predict performance of IC engines using gasoline, diesel, methane, and hydrogen as fuels. Physical models for heat release, friction, heat transfer, and pollutant emissions were included in the simulator. The results of the simulator can be displayed in both text and graphical format. The text outputs include the engine power, torque, efficiency, and other parameters. The variation of these parameters with operating variables such as engine speed, equivalence ratio, and compression ratio can be displayed in graphical plots.

Nomenclature

Alphabet

A_{head}	Cylinder head area (cm^2)
A_{piston}	Piston crown area (cm^2)
A_w	Exposed cylinder area (cm^2)
A_{wall}	Cylinder bore area (cm^2)
a	Weibe efficiency factor
b	Cylinder bore (cm)
ca	Crank radius (cm)
$fmep_{total}$	Total friction mean effective pressure (kPa)
h_g	Heat transfer coefficient of the wall (W/cm^2 K)

l	Connecting rod length (cm)
m	mass of the cylinder charge
N	Engine speed (rpm)
n	Weibe form factor
P	Cylinder pressure (kPa)
Q_{in}	Heat input to the cycle (J)
Q_w	Heat transfer to the cylinder wall (J)
R	Ratio of connecting rod length to crank radius
r	Compression ratio
s	Stroke (cm)
T_g	Temperature of the cylinder gas (K)
T_w	Temperature of the cylinder wall (K)
U	Piston speed (cm/s)
V	Cylinder volume (cm^3)
V_d	Displacement volume (cm^3)
x_b	mass fraction of burned gas in the cylinder
y	Exposed cylinder wall height (cm)

Greek

γ	Specific heat ratio
θ	Crank angle (degree)
θ_s	Crank angle at the start of heat release (degree)
θ_d	Burn duration of heat release (degree)

Introduction

Increasing popularity of the Internet and widespread availability of computers have resulted in the use of World Wide Web (WWW) as a teaching medium in engineering education [1, 2]. Thus, more and more educators have developed web-based teaching and evaluation tools to facilitate and improve the learning process of students [3, 4]. In this paper, the development of a web-based IC Engine Simulator (WICES) was discussed and presented.

Internal Combustion (IC) engines have been the prime movers of choice for energy generation and transportation for many decades. Although the advent of new energy conversion systems such as fuel cells may replace some industrial applications of IC engines, IC engines are still expected to be the mainstay of our energy generation and transportation needs for foreseeable future. As a result, knowledge of IC engines is essential for mechanical engineering students. In the Department of Mechanical Engineering at Lamar University, an IC engine course is one of the electives for senior students specializing in energy and thermal fluid area.

The course was developed to demonstrate fundamental principles of IC engines with emphasis on modern developments in the area. The textbook is Engineering Fundamentals of the Internal Combustion Engine by Willard Pulkrabek [5]. Students were also encouraged to use web-based resources and computational tools to carry out analysis and design calculations. One of the main obstacles in teaching an IC Engine class to undergraduate students is the lack of computational tools that enhance and improve the learning process of students. With the widespread availability of multi-media software and hardware tools, development and integration of web-based tools to the undergraduate curriculum becomes essential.

A few web-based IC engine modules are already available for use. In previous offerings of the course, the instructor asked the students to use the modules from the Colorado State University web site [6]. The website covers three topical areas of IC engines based on the textbook by Professors Allan Kirkpatrick and Ferguson from Colorado State University. There are multiple applets available for calculation of different aspects of IC engines. However, a comprehensive applet or simulation that considers fluid mechanics, heat transfer and combustion is not available. The results of the simulations cannot be retrieved as a text file to be processed as needed even though the results can be viewed as plots on the web site. Thus, the present simulator tries to address these needs in a single java-based program.

This paper addresses that need by developing a web-based IC Engine Simulator (WICES). The main objective is to develop a web-based engine simulator that is suitable for an undergraduate IC Engine class.

Model development

The numerical simulation was based on the models of heat release, pumping losses and friction losses, heat transfer from the cylinder gases to the cylinder wall, and pollutant emission. Mass burning rate of the fuel was modeled by the finite heat release model, a differential model of an engine power cycle in which the heat addition was specified as a function of the crank angle [7]. The mass fraction of the burned gas in the cylinder, x_b, was typically represented by a Weibe function as in Eq. (1)

$$x_b(\theta) = 1 - \exp\left[-a\left(\frac{\theta - \theta_s}{\theta_d}\right)^n\right] \tag{1}$$

where θ is the crank angle, θ_s is the start of heat release, θ_d is the duration of heat release, n is the Weibe form factor, and a is the Weibe efficiency factor. The values of a = 5 and n = 3 were used as they were reported to fit well with the experimental data [8]. The Weibe function was plotted as a function of crank angle in Fig. 1.

The rate of pressure rise in the cylinder depended on the rate of heat release. The rate of heat release as a function of crank angle was obtained by differentiating Eq. (1) with respect to crank angle, θ, and multiplied the resulting derivative with the total heat input to the cycle as given in Eq. (2)

$$\frac{dQ}{d\theta} = Q_{in}\frac{dx_b}{d\theta} \tag{2}$$

where Q_{in} is the total heat input to the cycle, the product of the mass of fuel in the cylinder and the lower heating value of the fuel.

Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition

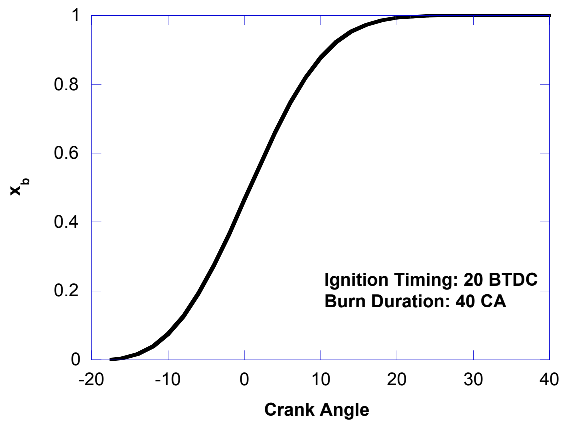

Fig. 1 Plot of the Weibe Function Representing the Mass Burning Rate

The heat input, Q_{in}, is calculated by the product of the mass of fuel and the lower heating value (LHV) of the fuel. For fuel blends such as gasoline/ethanol or gasoline/methanol, the LHV of the mixture was determined by

$$LHV_{mix} = \Sigma\, x_i\, LHV_i \qquad (3)$$

where x_i and LHV_i are the mass fraction and the lower heating value of fuel i. The heating values of the fuels were taken from Pulkrabek [5].

The processes inside the cylinder were modeled based on the first law of thermodynamics and the single zone model. The properties of the gas mixture such as pressure and temperature inside the cylinder are assumed to be uniform. The single zone model provides the cylinder pressure as a function of crank angle by the relation

$$\frac{dP}{d\theta} = -\gamma \frac{P}{V}\frac{dV}{d\theta} + \frac{\gamma - 1}{V}\left(\frac{dQ}{d\theta}\right) \qquad (4)$$

where P is the cylinder pressure, V is the cylinder volume, γ is the specific heat ratio. The cylinder volume, V, as a function of crank angle, θ, is given by [8]

$$V(\theta) = \frac{V_d}{r-1} + \frac{V_d}{2}\left[R + 1 - \cos\theta - \left(R^2 - \sin^2\theta\right)^{1/2}\right] \qquad (5)$$

where V_d is the displacement volume, r is the compression ratio, and R is given by

$$R = \frac{2l}{s} \qquad (6)$$

where l is the length of the connecting rod and s is the stroke of the cylinder. The equation (4) was integrated with respect to crank angle using fourth order Runge-Kutta method [9]. The computations of the cylinder properties started with the specified values of pressure and temperature at the beginning of the compression, which were specified by the user. Using the calculated cylinder pressure, the work done is evaluated using the relation:

$$\delta W = pdV \tag{7}$$

The total work done for the cycle was obtained by integrating Eq. (7) over one cycle. The cylinder temperature, T, was obtained by using the ideal gas equation of state

$$PV = mRT \tag{8}$$

where R is the gas constant of the mixture. The properties of the reactants and products were calculated considering the variation of properties with respect to temperature. Thermo-physical properties such as specific heat and enthalpy were taken from CHEMKIN database [12]. Equilibrium chemistry was used to predict the formation of NO_x. The opening and closing of intake and exhaust valves, flow through the intake valves and exhaust valves, the flow processes in the intake manifold and the exhaust pipe were not considered in the model.

Heat transfer from the gases to the cylinder wall can have significant effects on the performance of the engine. Thus, the heat transfer model by Woschni [10] was included in the present model. The equation (4) was therefore modified to include the wall heat transfer term as follows:

$$\frac{dP}{d\theta} = -\gamma \frac{P}{V}\frac{dV}{d\theta} + \frac{\gamma - 1}{V}\left(\frac{dQ}{d\theta}\right) - \frac{dQ_w}{d\theta} \tag{9}$$

where Q_w is the heat transfer to the wall. The rate of heat transfer at any crank angle to the exposed cylinder wall at an engine speed, N, is given by

$$\frac{dQ_w}{d\theta} = h_g(\theta) A_w(\theta)\left(T_g(\theta) - T_w\right)/N \tag{10}$$

where h_g is the heat transfer coefficient, A_w is the exposed cylinder area, T_g is the temperature of the cylinder gas and T_w is the cylinder wall temperature. In the simulator, the temperature of the cylinder wall is assumed to be 400K. The exposed cylinder area, A_w, as a function of crank angle is given by Eq. 10 [7],

$$A_w(\theta) = A_{wall} + A_{head} + A_{piston} = \pi\, b\, y + \frac{\pi}{2} b^2 \tag{11}$$

where A_{wall} is the cylinder bore area, A_{head} is the cylinder head area, A_{piston} is the piston crown area assuming a flat cylinder head, b is the cylinder bore and y is the exposed cylinder wall height. The exposed cylinder wall height, y, is given by [7]

$$y = a + l - \left[\left(l^2 - a^2 \sin^2 \theta \right)^{1/2} + a \cos\theta \right] \tag{12}$$

where a is the crank radius, which is half of the cylinder stroke. The cylinder wall heat transfer coefficient, h_g, is based on the correlation by Woschni [10]

$$h_g = 3.26 P^{0.8} U^{0.8} b^{-0.2} T^{-0.55} \tag{13}$$

where U is the piston speed. The residual gas fraction was determined according to the procedure described by Ferguson and Kirkpatrick [7]. Mechanical friction and pumping losses were also included in the model. Two models were implemented to predict the friction losses and pumping losses. The detailed model takes into account mechanical friction, pumping, and accessories while a simplified model considered the total friction loss as a function of engine speed. The detailed model was based on Patton [11] and the simple model was based on the following relation [7] where the total friction loss was represented as friction mean effective pressure ($fmep_{total}$):

$$fmep_{total} = a + b\left(\frac{N}{1000}\right) + c\left(\frac{N}{1000}\right)^2 \tag{14}$$

where a = 94.8, b = 2.3, c = 4.0, and N is the engine speed in rpm.

Description of the Simulator

The simulator is written in Java programming language as it allows seamless integration with the Internet and the web browser. In addition, only a web browser is needed to execute the simulator. Java, developed by the Sun Microsystems, has become very popular because of the many features designed to make it operate on the Internet. With this language one can "write once and run anywhere" [13]. Developers can write full-fledged applications in Java, whose architecture is much like C and C++. It is freely available from the Sun Microsystems website (http://java.sun.com/).

Java can be used to create two types of programs: applications and applets. An application is a program that runs on the computer, under the operating system of that computer. An application created using Java is more or less like C or C++. Java's ability to create applets is what makes it more important. An applet is an application designed to transmit over the Internet and executed by a Java-compatible Web browser. An applet is a tiny Java program; dynamically downloaded across the network, just like an image, sound file or video clip. In other words, an applet is an intelligent program that can react to user input and dynamically change. The present simulator is written as a Java applet for portability and compactness.

The simulator can be used to predict performance of IC engines using different fuels. The user can choose either liquid or gaseous fuels: liquid fuels (gasoline, diesel, methanol, ethanol, gasoline/methanol, gasoline/ethanol) and gaseous fuels (methane, hydrogen, methane/hydrogen).

Physical models for heat release, friction, heat transfer, and pollutant emissions (NO_x) were included in the simulator as discussed in the model development section.

The input data to the simulator can be divided into three parts: engine geometry, thermodynamics, and operating parameters. Input data for engine geometry include bore, stroke, length of the connecting rod, and compression ratio. Thermodynamics parameters are the intake conditions (pressure and temperature), and exhaust pressure. Operating parameters are engine speed, fuel, equivalence ratio, spark timing, and spark duration. If friction losses are to be considered in detail, more parameters concerning the crankshaft, the camshaft, and drive accessories are needed as input. Figure 2 shows the opening screen of the WICES. As can be seen from Fig. 2, the user can input the values of the parameters and choose a set of fuels provided. At present, the calculations are limited to the set of fuels provided in the calculator.

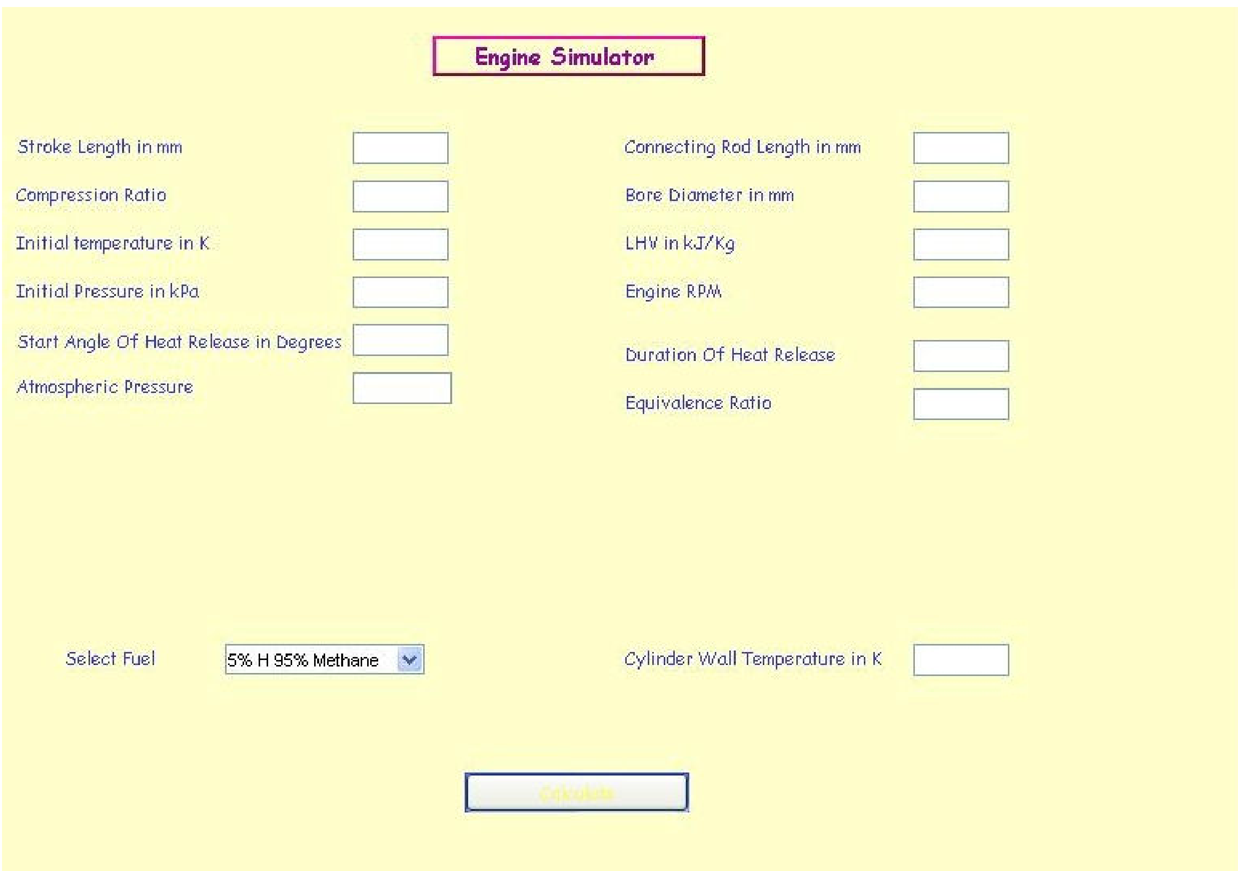

Fig. 2 Opening Screen Shot of the WICES

The results of the simulator can be displayed in both text and graphical format. The text outputs include the engine power, torque, efficiency, and other parameters. The variation of these parameters with operating variables such as engine speed, equivalence ratio, and compression ratio can be displayed in graphical plots. The text results can be saved in a file for later processing. The plot of cylinder pressure versus cylinder volume for a sample run is shown in Fig. 3. The results of the simulation were imported and plotted in Microsoft Excel.

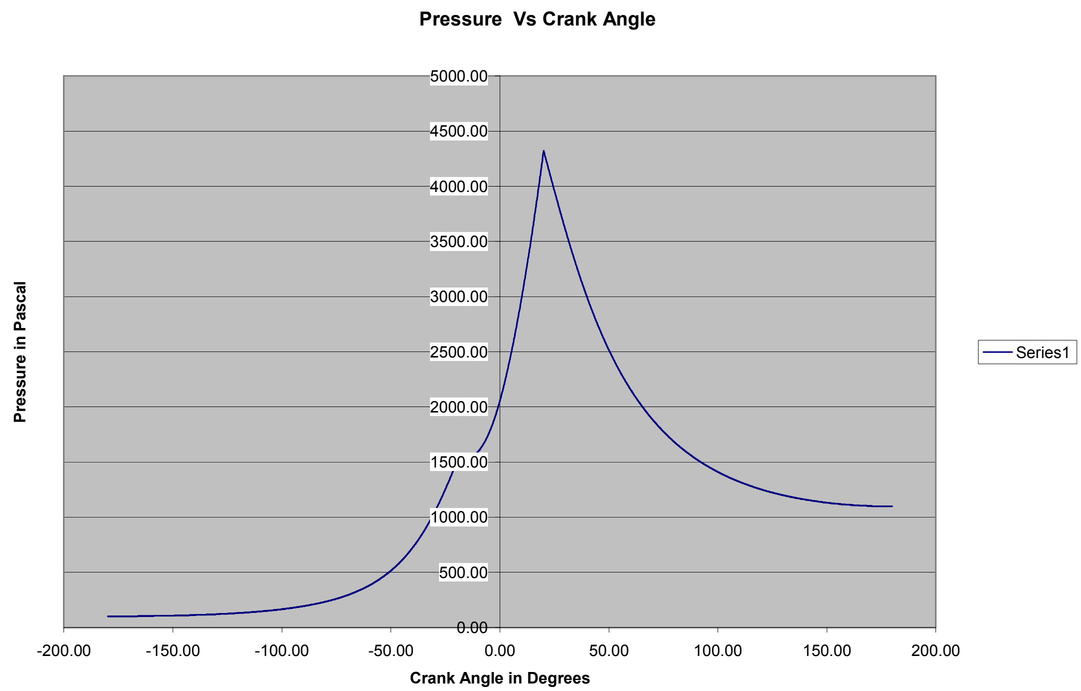

Fig. 3 Pressure vs. Volume Plot of a Sample Run

Distribution and Future Direction

Currently, the simulator is undergoing beta testing at Lamar University. Once the testing is over, the simulator will be hosted on the web site of the Mechanical Engineering Department at Lamar University. It will also be made freely available to users for downloading once they register with the author through e-mail.

The present simulator is based on a single zone model for burning of fuels. Multi-zone burning models and fluid mechanics models for flow through the values and exhaust systems will be incorporated in future versions of the simulator.

Bibliography

1. Ham, F.E., Militzer, J., and Bemfica, A. (1998). *CFDnet: Computational Fluid Dynamics on the Internet*. http://www.cfdnet.com.
2. Bhattercharjee, S., 2003, "Thermodynamics Expert System (TEST)," Prentice Hall.
3. Haque, M. E., "Web-based Visualization Techniques for Structural Design Education," Proceedings of the 2001 ASEE Annual Conference, 2001.
4. Ranga, K., and Gramoll, K., "3-D Finite Element Analysis on the Internet using Java and VRML," Proceedings of the 2000 ASEE Annual Conference, 2000.
5. Pulkrabek, W. W., 1997, "Engineering Fundamentals of the Internal Combustion Engine," Prentice Hall, New Jersey
6. http://www.engr.colostate.edu/~allan/engines.html.

7. Ferguson, C. R., and Kirkpatrick, A. T., 2001, "Internal Combustion Engines," John Wiley & Sons, New York.
8. Heywood, J., 1988, "Internal Combustion Engine Fundamentals," McGraw-Hill, New York.
9. Chapra, S. C., and Canale, R. P., 2001, "Numerical Methods for Engineers: With Software and Programming Applications," 4th Edition, McGraw-Hill, New York.
10. Woschni, G., 1967, "A Universally Applicable Equation for the Instantaneous Heat Transfer Coefficient in the Internal Combustion Engine," SAE paper 670931.
11. Patton, K. J., Nitchke, R. G., and Heywood, J. B., 1989, "Development and Evaluation of a Friction Model for Spark Ignition Engines," SAE paper 890836.
12. "CHEMKIN Database", Sandia National Laboratory.
13. Lea, R., Matsuda, K., and Miyashita, K., 1996, "Java for 3D and VRML worlds," 1st Edition, New Riders, Indianapolis.

Biography

VINOD MATHAM is a graduate student in the Department of Mechanical Engineering at Lamar University. He joined Lamar University in January 2003 and is expected to receive his Master of Engineering Science degree in May 2005. This paper is based on his Masters thesis.

KENDRICK AUNG is an assistant professor in the Department of Mechanical Engineering at Lamar University. He received his Ph.D. degree in Aerospace Engineering from University of Michigan in 1996. He is an active member of ASEE, ASME, AIAA and Combustion Institute. He has published over 50 technical papers and presented several papers at national and international conferences.