INTERACTIVE MODELING AND SIMULATION OF THE OTTO THERMODYNAMIC CYCLE

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Abstract: This paper presents the development process of an interactive numerical model for the analysis of the Otto thermodynamic cycle. The model is implemented in MATLAB and enables the computation of thermodynamic state variables, pressure-volume diagrams, and thermal efficiency as functions of the operating parameters. The proposed approach allows an investigation of the influence of the compression ratio on engine performance and provides a clear visualization of the thermodynamic processes involved. The application serves both as an educational tool and as a basis for further numerical investigations of internal combustion engine cycles.

Keywords: Otto cycle, thermodynamic modeling, numerical simulation, internal combustion engine, thermal efficiency, MATLAB

1. INTRODUCTION

The Otto cycle represents a fundamental theoretical model used for the analysis of thermodynamic processes in spark-ignition engines. It describes a sequence of four idealized transformations: isentropic compression of the air-fuel mixture, constant-volume heat addition, isentropic expansion, and constant-volume heat rejection. Although based on simplifying assumptions, the model provides a solid foundation for understanding the fundamental thermodynamic behavior of internal combustion engines.

This paper aims to develop an interactive numerical model of the Otto cycle, implemented in the MATLAB environment, which enables the simulation and visualization of the main thermodynamic processes involved. The developed application allows the determination of the key cycle parameters, the generation of the pressure-volume (p-V) diagram, and the evaluation of the thermal efficiency as a function of the compression ratio. Through this approach, the user can analyze the influence of input parameters on cycle performance, making the application a useful educational and research tool for the study of spark-ignition engines.

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2. THERMODYNAMIC MODEL OF THE OTTO CYCLE

The Otto cycle model is widely used in scientific literature due to its simplicity and its ability to highlight the influence of key operating parameters, such as the compression ratio, combustion temperature, and specific heat ratio, on engine performance.

2.1. Basic assumptions of the Otto cycle

The theoretical model of the Otto cycle is based on the following fundamental assumptions:

- the working fluid is treated as an ideal gas;
- the compression and expansion processes are assumed to be isentropic;
- the combustion and heat rejection processes are considered to occur at constant volume;
- the thermodynamic properties of the working fluid, particularly the specific heat ratio, are assumed to remain constant;
- friction losses, heat transfer to the cylinder walls, and other irreversible effects are neglected.

These assumptions allow the derivation of simplified analytical relations suitable for analyzing the general behavior of the cycle.

2.2. Description of the Otto cycle processes

The ideal Otto cycle consists of four fundamental thermodynamic processes, represented on the pressure-volume (p-V) diagram:

Isentropic compression (1-2)

During this process, the air-fuel mixture is compressed from the initial volume V_1 to the minimum volume V_2. The transformation is assumed to be isentropic, and the corresponding relations are given by:

$$T_2 = T_1 \cdot \varepsilon^{k-1} \tag{1}$$

$$p_2 = p_1 \cdot \varepsilon^{k} \tag{2}$$

where $\varepsilon = \frac{V_1}{V_2}$ is the compression ratio, and k is the adiabatic exponent.

Constant-volume heat addition (2-3)

During this stage, the combustion of the air-fuel mixture takes place and is modeled as a constant-volume process. The temperature and pressure increase due to the supplied thermal energy:

$$T_3 = T_2 + \frac{Q_{in}}{c_v} \tag{3}$$

$$p_3 = p_2 \cdot \frac{T_3}{T_2} \tag{4}$$

where Q_{in} is the heat added to the system.

Isentropic expansion (3-4)

In this phase, the combustion gases expand isentropically, performing mechanical work on the piston. The governing relations are:

$$T_4 = T_3 \cdot \left(\frac{1}{\varepsilon}\right)^{k-1} \tag{5}$$

$$p_4 = p_3 \cdot \left(\frac{1}{\varepsilon}\right)^{k} \tag{6}$$

Constant-volume heat rejection (4-1)

The final process corresponds to the rejection of heat to the surroundings at constant volume, bringing the system back to its initial thermodynamic state and completing the cycle.

2.3. Thermal efficiency of the Otto cycle

The thermal efficiency of the Otto cycle is defined as the ratio between the useful mechanical work and the heat supplied during the combustion process:

$$\eta = \frac{W_{\text{net}}}{Q_{\text{in}}} \tag{7}$$

For the ideal Otto cycle, this expression can be simplified as a function of the compression ratio:

$$\eta = 1 - \frac{1}{\varepsilon^{k-1}} \tag{8}$$

This relationship highlights the significant influence of the compression ratio on the thermal efficiency of the cycle and represents a fundamental criterion for evaluating the performance of Otto-cycle engines.

3. NUMERICAL MODELING AND IMPLEMENTATION OF THE OTTO CYCLE

3.1. General description of the numerical model

The numerical model developed in this study aims to analyze the thermodynamic behavior of the Otto cycle through a computational approach. The application was implemented in the MATLAB environment and was designed to allow flexible modification of the input parameters, as well as real-time visualization of the resulting thermodynamic processes. This approach facilitates a clear understanding of the influence of operating parameters on the performance of the cycle.

3.2. Structure and functionality of the application

The developed application features an interactive graphical user interface that enables the user to input the main parameters of the Otto cycle, such as the compression ratio, initial temperature, and supplied heat. Based on these inputs, the application automatically computes the corresponding thermodynamic state variables.

Figure 1 illustrates the graphical user interface of the application, which includes input fields for parameter definition, output sections for numerical results, and graphical representations of the thermodynamic cycle. The interface is designed to support an intuitive analysis of the system behavior and to facilitate the evaluation of the influence of key parameters on the overall performance of the cycle.

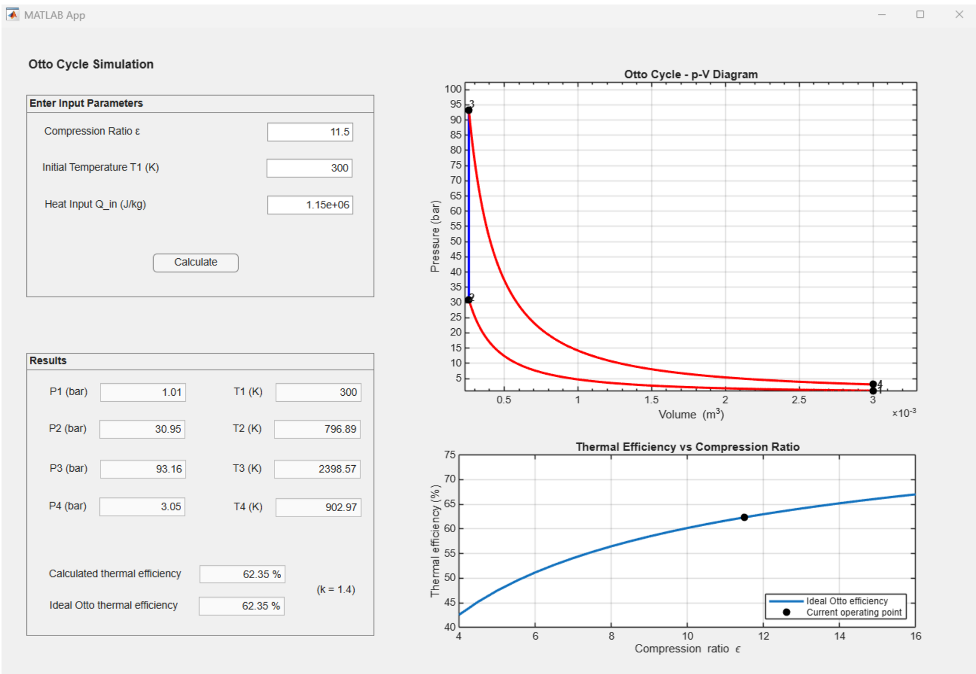

Fig.1. Graphical user interface of the Otto cycle simulation application

3.3. Numerical Implementation of the Otto cycle

The numerical model implemented in this study is based on the classical thermodynamic relations corresponding to the ideal Otto cycle. The calculation of the thermodynamic states is performed sequentially, starting from the initial conditions and applying the specific relations associated with each transformation.

The main parameters considered in the simulation include the compression ratio, the initial temperature, and the adiabatic exponent. Based on these inputs, the pressure and temperature values at the characteristic points of the cycle are determined. The obtained data are subsequently used to generate the pressure-volume diagram and to evaluate the thermal efficiency of the cycle.

Figure 2 presents the pressure-volume diagram corresponding to the Otto cycle, highlighting the sequence of the four fundamental processes. The shape of the curve confirms the theoretical behavior of the cycle, while the variations in pressure and volume reflect the influence of the input parameters on the thermodynamic process.

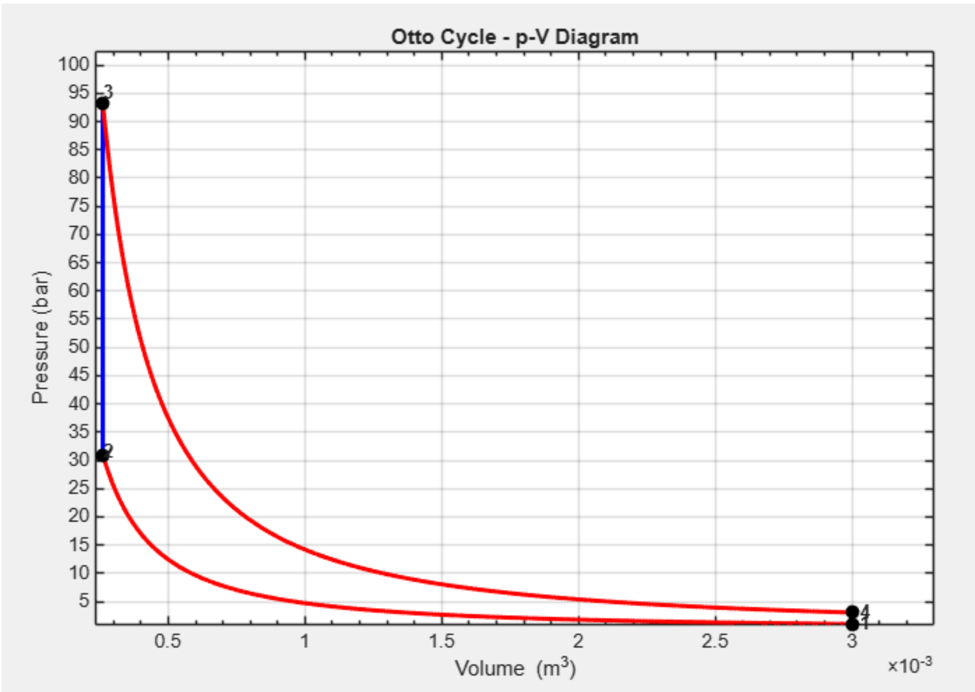

Fig. 2. Pressure-volume diagram of the Otto cycle obtained through numerical simulation

3.4. Analysis of numerical results

The obtained results highlight the dependence of the cycle performance on the compression ratio. An increase in the compression ratio leads to higher maximum pressure and temperature values, as well as to an improvement in thermal efficiency. Figure 3 illustrates the variation of thermal efficiency as a function of the compression ratio. The resulting curve confirms the theoretical trend according to which the efficiency increases with the compression ratio, although with progressively diminishing gains at higher compression ratios.

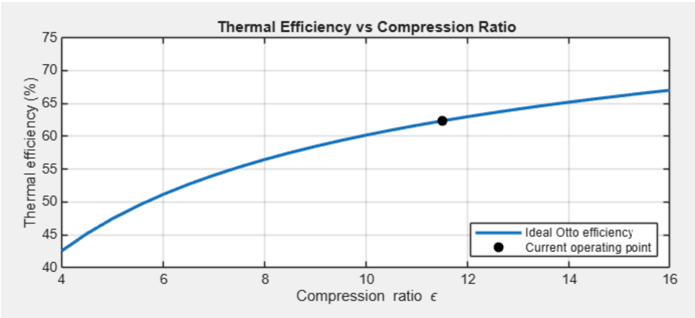

Fig. 3. Variation of the thermal efficiency as a function of the compression ratio

The obtained results demonstrate the validity of the proposed numerical model and its relevance for the analysis of Otto cycle performance. The developed application provides an effective tool for both educational purposes and preliminary studies in the field of internal combustion engines.

4. RESULTS AND DISCUSSION

This section presents and analyzes the results obtained through the implementation of the numerical model of the Otto thermodynamic cycle using the developed MATLAB-based application. The analysis aims to highlight the thermodynamic behavior of the cycle, to validate the correctness of the theoretical model, and to emphasize the influence of the main operating parameters on engine performance.

4.1. Results of the Otto cycle simulation

For a representative set of input parameters - compression ratio $\varepsilon = 11.5$, initial temperature $T_1 = 300$ K, and heat input $Q_{in} = 1.15 \times 10^6$ J/kg - the application generates the complete p-V diagram of the Otto cycle, as illustrated in Figure 2.

The diagram clearly illustrates the four fundamental thermodynamic processes:

- **1-2:** isentropic compression, characterized by an increase in pressure and temperature as the volume decreases;
- **2-3:** constant-volume heat addition, associated with the combustion process and a rapid rise in pressure;
- **3-4:** isentropic expansion, during which the working fluid performs mechanical work;
- **4-1:** constant-volume heat rejection, corresponding to the exhaust phase of the cycle.

The shape of the resulting curve accurately reflects the theoretical behavior of the ideal Otto cycle, confirming the correctness of the numerical implementation.

4.2. Analysis of the characteristic parameters of the cycle

For the analyzed case, the main thermodynamic parameters are presented in Figure 1 (corresponding to the values displayed in the application):

- The maximum pressure reached during the thermodynamic cycle exceeds 93 bar, which is a realistic value for a spark-ignition engine operating under idealized conditions.
- The maximum temperature at state 3 confirms the intensity of the combustion process and is consistent with the theoretical values expected for a high compression ratio.
- The difference between temperatures T_2 and T_4 highlights the amount of useful energy converted into mechanical work.

These results demonstrate the consistency of the model and validate the assumptions adopted in the development of the application.

4.3. Analysis of thermal efficiency

An essential aspect of the present study is the analysis of the thermal efficiency of the Otto cycle. Within the developed application, the efficiency is calculated both using the theoretical relation and by evaluating the ratio between the useful mechanical work and the heat supplied to the system.

The "Thermal Efficiency vs. Compression Ratio" plot highlights the monotonic increase of efficiency with increasing compression ratio. This trend confirms the theoretical behavior of the Otto cycle and emphasizes the significant role of the compression ratio in enhancing the performance of spark-ignition engines.

For the analyzed case ($\varepsilon \approx 11.5$), the calculated thermal efficiency reaches approximately 62-63%, a value that falls within the theoretical limits of the ideal Otto cycle and validates the correctness of the numerical implementation.

4.4. Remarks on the numerical implementation

The developed application provides an intuitive and interactive representation of the Otto cycle, allowing:

- rapid modification of input parameters;
- immediate visualization of the effects on pressure, temperature, and efficiency;
- direct comparison between ideal behavior and simulated operating conditions.

5. CONCLUSIONS

In this study, a numerical analysis of the Otto thermodynamic cycle was carried out through the development and implementation of a dedicated computational model integrated into an interactive MATLAB-based application. The main objective was to investigate the thermodynamic behavior of the cycle and to highlight the influence of key parameters on the performance of spark-ignition engines.

An important aspect of the study concerns the analysis of the effect of the compression ratio ε on thermal efficiency. The numerical results demonstrate a monotonic increase in efficiency with increasing compression ratio, in full agreement with the theoretical relationship of the ideal Otto cycle. The graphical representation of this dependence provides an intuitive understanding of the phenomenon and highlights the practical limitations imposed by real engine operating conditions.

The developed application represents a flexible educational and research tool, allowing rapid modification of input parameters and immediate visualization of their impact on the main thermodynamic quantities. The intuitive graphical interface, together with the graphical representations of the p-V cycle and efficiency variation, facilitates a clear understanding of the physical processes involved in internal combustion engines.

In conclusion, this work demonstrates the usefulness of numerical modeling in the analysis of thermodynamic cycles and highlights the potential of dedicated software tools to support both educational activities and research in the field. Future developments may include extending the model to account for real losses (such as heat transfer and friction), incorporating more advanced combustion models, or adapting the application for the analysis of other thermodynamic cycles, such as the Diesel or Sabathé cycles.

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