Thermodynamic Modeling and Matlab-based Simulation of a Stirling Engine for Micro-Scale Power Generation

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Abstract: *The Stirling engine represents one of the most promising technologies for the efficient conversion of thermal energy into mechanical work, due to its ability to operate with almost any heat source and to achieve theoretical efficiencies approaching the Carnot cycle. This article aims to provide a detailed study of the Stirling cycle, the development of a mathematical model, numerical simulation using MATLAB and the analysis of the engine performance as a function of the main thermodynamic parameters, with special emphasis on applications in micro-power generation. A distinctive aspect of this study lies in the comprehensive treatment of the polynomial dependence of specific heat in all thermodynamic processes, enabling a more accurate representation of real gas behavior compared to idealized classical models. The mathematical model is formulated using the fundamental laws of thermodynamics and the ideal gas equation, as well as the well-known Schmidt model for the analytical description of pressure and volume throughout the cycle. A numerical simulation is then performed in MATLAB, where the work per cycle is calculated, p–V and T–s diagrams are generated, and the theoretical efficiency is evaluated for different operating temperatures and pressures. The simulation results show that increasing the temperature difference and average gas pressure significantly increases the mechanical output of the engine and the power output, while an efficient regenerator significantly improves the overall performance and brings the engine closer to Carnot efficiency. The study shows that the Stirling engine has significant potential for sustainable power generation systems, while the developed modeling and simulation framework provides a solid foundation for further experimental development and design optimization.*

Keywords*: STIRLING ENGINE, THERMODYNAMIC MODELING, MATLAB SIMULATION, MATLAB GUI.*

1. Introduction

The growing global demand for sustainable and efficient energy conversion technologies has renewed interest in external combustion systems, such as Stirling engines. First introduced in the 19th century and later formalized by Walker, Senft, Organ and other seminal authors [1–4], the Stirling engine operates in a closed regenerative thermodynamic cycle, capable of achieving efficiencies approaching the ideal Carnot limit. Its ability to utilize a wide range of heat sources, including fossil fuels, industrial waste heat, geothermal sources and solar radiation, makes the Stirling engine an attractive candidate for modern distributed energy applications, particularly in low-emission and high-reliability micro-generation systems [5,6].

Fig. 1 *Stirling Engine CAD Model [7].*

A distinctive feature of the Stirling cycle is its completely closed working fluid cycle, in which energy is transferred through expansion and compression processes separated in space by heat exchangers. Recent literature emphasizes the importance of regenerator design, dead volume minimization, and accurate thermodynamic modeling for predicting the behavior of the real cycle [8, 9]. Modern studies have further incorporated numerical simulation tools such as MATLAB [10] to evaluate the performance of the system under different conditions, enabling detailed analyses of p–V, T–s, and instantaneous pressure evolution [11]. Advances in computational modeling have also allowed researchers to incorporate non-ideal behaviors, including heat losses, pressure drops, regenerator inefficiencies, and, as highlighted in this study, the temperature-dependent (polynomial) variation of specific heat capacities, which provides a more realistic representation of the thermophysical properties of real gases over a wide temperature range.

Solar-powered, low-temperature differential Stirling engines have been of particular interest due to their simplicity, safety, and low cost of utilizing renewable thermal energy [12, 13]. Studies by Kongtragool et al. [12], and Shazly et al [9], demonstrate the feasibility of using solar radiation as the primary heat source, enabling micro-CHP and stand-alone power units for remote locations.

2. Methodology

The methodology of this study integrates classical thermodynamic theory with advanced numerical simulation techniques to develop a comprehensive and accurate model of the Stirling engine cycle. The engine is treated as a closed, regenerative thermodynamic system operating with an ideal working gas, following the fundamental approaches of Walker, Senft, Organ and Reader & Hooper [1–4]. Several standard engineering assumptions are adopted to simplify the modeling process without compromising physical accuracy. The working fluid is assumed to obey the ideal gas law throughout the cycle, and all processes are treated as internally reversible, with expansion and compression modeled as ideal isothermal transformations and heat transfer along isochores estimated using temperature-dependent thermodynamic properties. Kinetic and potential energy changes are neglected due to their negligible contribution to thermodynamic energy interactions, and the regenerator is modeled using an efficiency factor that considers real, non-ideal heat transfer. The heater, cooler, and regenerator are treated as separate control volumes to capture the spatial distribution of temperature and heat exchange mechanisms.

A central element of the methodology is the use of a temperature-dependent polynomial representation of specific heat capacities. To achieve high-fidelity modeling over a wide temperature range, the NASA seven-term polynomial formulation is employed, following the procedures reported in Shazly et al. [7].

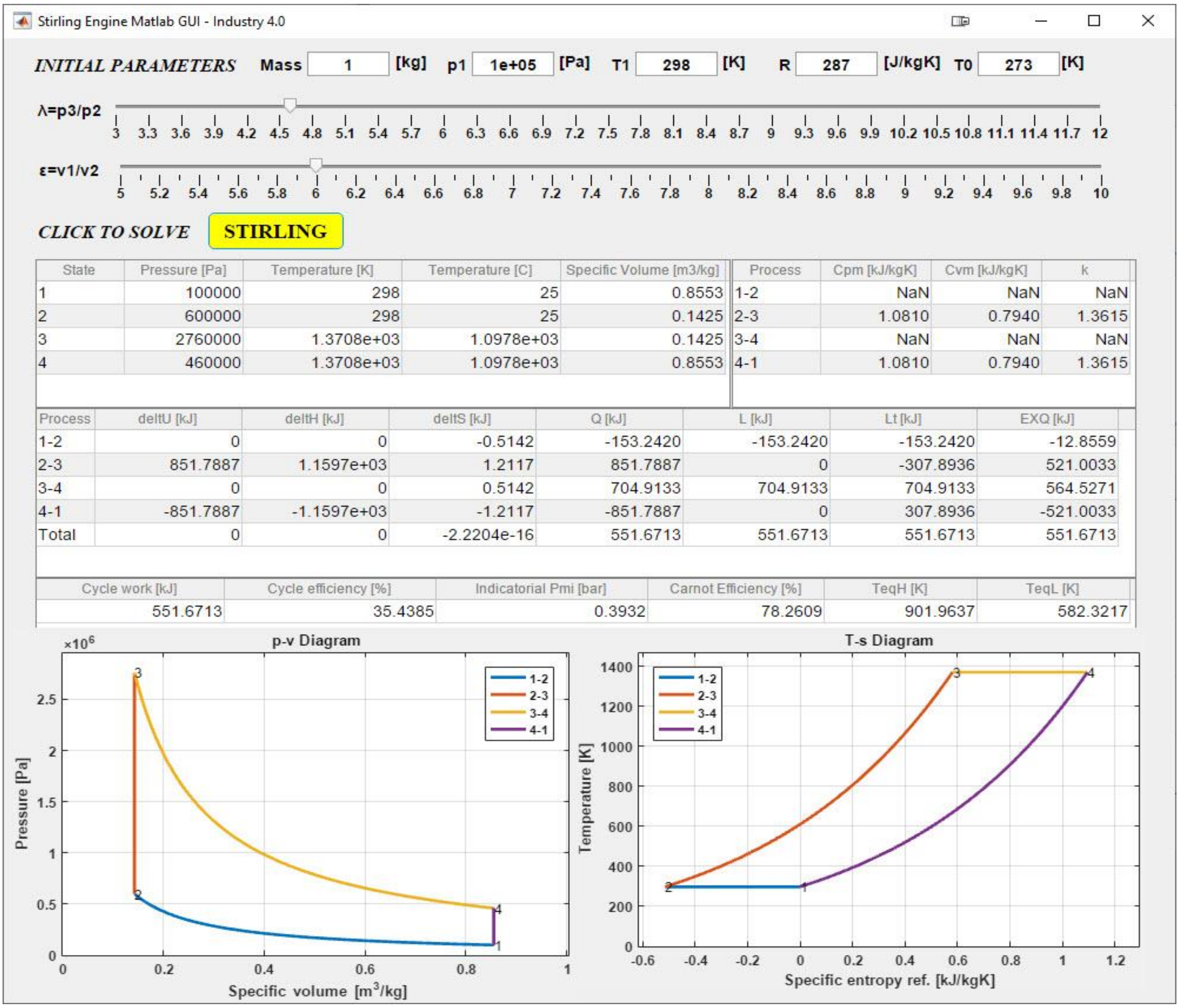
This approach allows accurate computation of Cp(T), Cv(T), enthalpy, and entropy as functions of temperature by integrating the polynomial expressions. In contrast to simplified constant-k models commonly found in classical analyses, this formulation provides a more realistic depiction of real-gas behavior and directly influences the accuracy of energy balances along the isochoric processes. The resulting thermodynamic representation yields more reliable estimates of work, heat transfer, and efficiency, particularly at elevated operating temperatures.

To determine the instantaneous pressure throughout the cycle, the Schmidt analytical model is adopted [6]. This model assumes sinusoidal piston–displacer kinematics and provides a closed-form expression for the pressure as a function of the engine's geometric characteristics, dead volumes, phase angle between piston and displacer, and heater and cooler temperatures. It allows the construction of continuous pressure–volume diagrams and captures dynamic variations that extend beyond the idealized Stirling cycle. The model's analytical nature ensures numerical stability and computational efficiency, making it suitable for iterative simulations and parametric studies.

All thermodynamic formulations are implemented in MATLAB, which serves as the main tool for numerical simulation [10]. The software calculates state properties such as temperature, pressure, enthalpy, and entropy for each process, and generates the corresponding p–V and T–s diagrams. Users specify initial conditions including the working gas mass, hot and cold side temperatures, volume ratio, and geometric parameters of the model. MATLAB then evaluates temperature-dependent specific heats, calculates heat interactions along isochores, determines the work produced by each isothermal process, and constructs the full pressure profile using the Schmidt model. Key performance indicators such as net cycle work, heat input, and thermal efficiency are obtained by integrating the pressure–volume curve and evaluating the energy balances for each transformation. The implementation also allows comparative analysis between models with constant and variable specific heats, enabling the assessment of the impact of real gas thermodynamic behavior on engine performance. Through this integrated methodology, combining thermodynamic fundamentals, polynomial-based property estimation, dynamic pressure modeling, MATLAB simulation, and prototype-oriented design, the study creates a powerful framework for accurately analyzing and improving the performance of Stirling engines intended for micro-scale power generation.

3. Results

The Stirling Engine MATLAB graphical interface provides an interactive environment for simulation, visualization, and thermodynamic analysis of ideal Stirling engine cycles, integrating mathematical modeling with modern digital concepts of Industry 4.0 for engineering education, research, and design optimization.



State	Pressure [Pa]	Temperature [K]	Temperature [C]	Specific Volume [m3/kg]
1	100000	298	25	0.8553
2	600000	298	25	0.1425
3	2760000	1.3708e+03	1.0978e+03	0.1425
4	460000	1.3708e+03	1.0978e+03	0.8553

Process	Cpm [kJ/kgK]	Cvm [kJ/kgK]	k
1-2	NaN	NaN	NaN
2-3	1.0810	0.7940	1.3615
3-4	NaN	NaN	NaN
4-1	1.0810	0.7940	1.3615

Process	deltU [kJ]	deltH [kJ]	deltS [kJ]	Q [kJ]	L [kJ]	Lt [kJ]	EXQ [kJ]
1-2	0	0	-0.5142	-153.2420	-153.2420	-153.2420	-12.8559
2-3	851.7887	1.1597e+03	1.2117	851.7887	0	-307.8936	521.0033
3-4	0	0	0.5142	704.9133	704.9133	704.9133	564.5271
4-1	-851.7887	-1.1597e+03	-1.2117	-851.7887	0	307.8936	-521.0033
Total	0	0	-2.2204e-16	551.6713	551.6713	551.6713	551.6713

Cycle work [kJ]	Cycle efficiency [%]	Indicatorial Pmi [bar]	Carnot Efficiency [%]	TeqH [K]	TeqL [K]
551.6713	35.4385	0.3932	78.2609	901.9637	582.3217

Fig. 2 *Thermodynamic analysis of ideal Stirling engine cycles.*

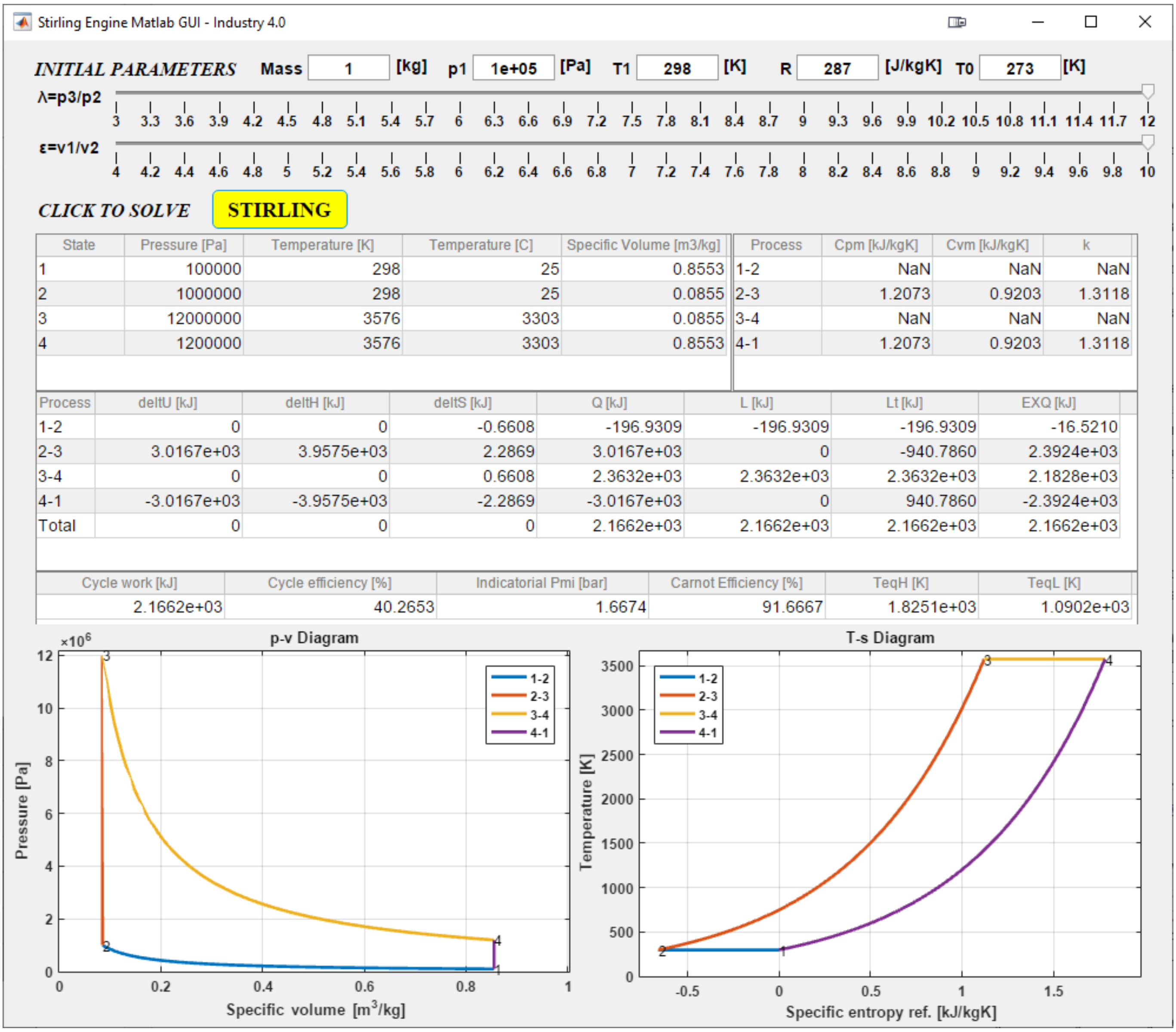


Fig. 3 *Thermodynamic analysis of ideal Stirling engine cycles (maximum volume ratio (ε) and pressure ratio (λ))*

The images below show an advanced version of the MATLAB graphical interface of the Stirling engine, displaying the results of multiple simulations of the Stirling cycle with different parameter values. The left graph illustrates the p–V diagram, each of which corresponds to a complete thermodynamic cycle for different combinations of volume ratio (ε) and pressure ratio (λ). The characteristic shape of the Stirling cycle loop is evident in all cases, with higher values of λ and ε producing wider loops and higher maximum pressures. The right graph presents the corresponding T–s diagrams, where the isothermal and isochoric segments of the cycle become more pronounced as the temperature levels increase. The curves demonstrate the impact of changing the parameters on entropy generation and thermal load.

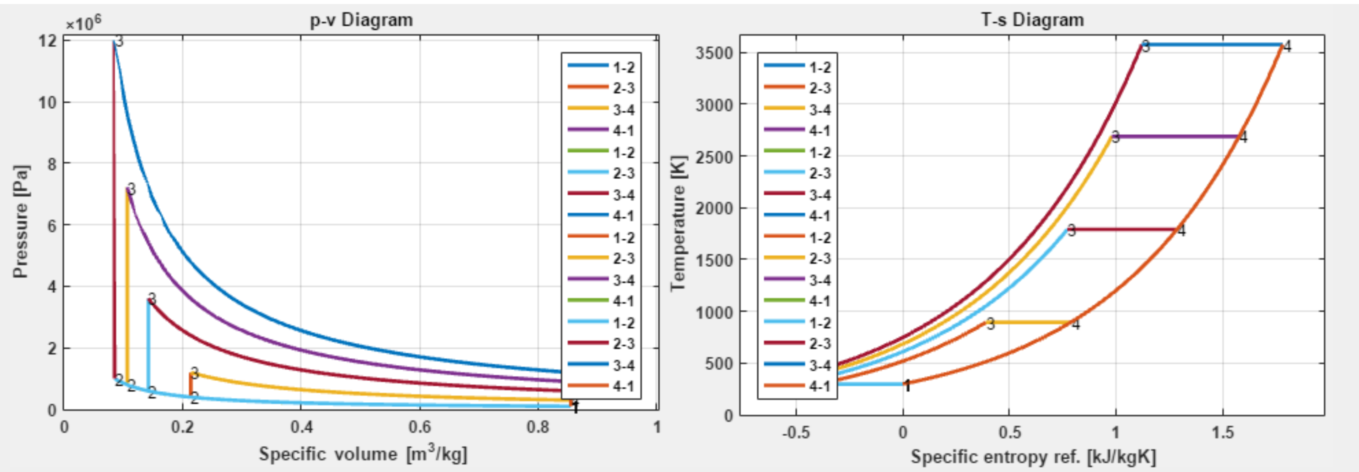


Fig. 4 *Stirling Engine p–V and T–s diagrams of multiple Stirling cycle simulations with varying parameter values.*

The graphical user interface (GUI) was fully coded in MATLAB App Designer [10], providing a clear and intuitive layout where users can enter all relevant thermodynamic parameters, run numerical simulations, and visualize p–V and T–s diagrams in real time. The program architecture is based on fundamental thermodynamic principles [1-6], including the ideal gas law and energy balance equations for each process of the Stirling cycle: isothermal expansion (1–2), isochoric regeneration (2–3), isothermal compression (3–4), and isochoric heat rejection (4–1).

In the control panel, users can specify initial parameters such as the mass of the working gas, the initial pressure and temperature, the pressure and volume ratios (λ and ε), and the universal gas constant (R). Once these parameters are entered, the user starts the calculation by clicking "STIRLING", which activates the computer solver built into the GUI.

The central table dynamically displays state properties (pressure, temperature, specific volume, enthalpy, entropy, and internal energy) in all four thermodynamic states, along with process-related variables such as heat transfer (Q), work (L), enthalpy change (Δh), internal energy change (Δu), and entropy change (Δs). These data are calculated numerically using logarithmic and exponential relationships for each process, ensuring physical consistency and high computational accuracy.

The interface automatically generates two main graphical outputs, the p–V diagram, illustrating the cyclic behavior of pressure versus specific volume, clearly showing the closed thermodynamic loop. The closed area corresponds to the net work output per cycle, and the T–s diagram, showing the evolution of temperature in relation to specific entropy, highlighting the reversible nature of the ideal cycle, and allowing comparison with the reference Carnot efficiency.

The bottom section of the GUI summarizes the cycle performance metrics, including, Cycle Work [kJ], Thermal Efficiency [%], Mean Indicated Pressure (Pmi) [bar], Equivalent Carnot Efficiency [%], Average Effective Temperatures of the Heater (TeqH) and Cooler (TeqL).

The Stirling Engine's MATLAB graphical user interface can be used in a wide range of academic and research applications, serving as a powerful tool for both teaching and advanced analysis. It is particularly well-suited for academic teaching and demonstration of closed-loop thermodynamic processes, allowing students to visualize and understand the energy transformations within the Stirling cycle.

Beyond its analytical capabilities, the software has strong educational integration potential, functioning as a didactic platform for thermodynamics, energy systems, and sustainable engineering curricula, fully aligned with the principles of the digital transformation of Industry 4.0 laboratories.

4. Conclusions

This original MATLAB-based simulation environment demonstrates a successful fusion of theoretical modeling, computer automation, and graphical representation, embodying the principles of digital transformation in engineering education. Through its versatility and precision, the MATLAB Stirling Engine GUI stands as an innovative tool for advancing the understanding and design of high-efficiency thermodynamic systems.

The Stirling engine represents a thermodynamic system characterized by high theoretical efficiency, capable of approaching the Carnot limit due to its operation based on the temperature difference between the heat source and the heat sink. Its externally heated configuration allows flexible use of various thermal energy sources, including renewable and waste heat, while maintaining low emissions and high reliability.

The simplified mathematical modeling approach, founded on the ideal gas law and the division of the working space into hot and cold chambers, provides a clear insight into the pressure and volume variations throughout the thermodynamic cycle. The resulting p–V diagram displays a closed loop whose enclosed area represents the net work output, confirming the energy-conversion capability of the engine.

Numerical simulations performed in MATLAB enable detailed investigation of how key operational parameters, such as hot and cold temperatures, mean working pressure, and compression ratio affect the indicated work and overall efficiency. These simulations constitute an essential tool for parametric optimization and facilitate direct comparisons with other thermodynamic cycles under similar boundary conditions.

To improve accessibility and usability in academic environments, the final version of this tool will also be compiled into a standalone .exe application for Windows. This executable version will allow students and academic staff to use the software without the need for a MATLAB license, making it fully distributable in teaching labs, classrooms, training sessions, and distance learning platforms. Creating a dedicated executable file ensures faster performance, higher stability, and seamless integration with the Windows operating system, transforming this GUI into a practical and widely accessible tool for education and research.

5. References

1. Walker, G. "*Stirling Engines*". Oxford: Clarendon Press, (1980).
2. Senft, J. R. "*An Introduction to Stirling Engines*". Moriya Press. (1993).
3. Organ, A. J. "*Thermodynamics and Gas Dynamics of the Stirling Cycle Machine*". Cambridge University Press. (1992).
4. Reader, G. T., & Hooper, C. "*Stirling Engines*". Longman Group Limited. (1983).
5. Çengel, Y. A., & Boles, M. A. "*Thermodynamics: An Engineering Approach. 8th ed*". New York: McGraw-Hill; (2015)
6. Schmidt, "*Schmidt Analysis for Stirling engines*." (1972).
7. https://www.3dcadbrowser.com/3d-model/stirling-engine-38917
8. Ana C. Ferreira, Ricardo F. Oliveira, Manuel L. Nunes, Luís B. Martins, and Senhorinha F. Teixeira *"Modelling and Cost Estimation of Stirling Engine for CHP Applications", (2014).*
9. J.H. Shazly, A.Z. Hafez, E.T. El Shenawy, M.B. Eteiba. *Simulation, design and thermal analysis of a solar Stirling engine using MATLAB.* Energy Conversion and Management. (2014).
10. MATLAB Documentation. "*MATLAB & Simulink for Numerical Simulation of Thermodynamic Cycles*". MathWorks; (2025).
11. Gjeta, A., Alcani, M., Dorri, A., "*The Influence of Thermodynamic Parameters on Internal Combustion Engines and the Graphical Presentation of Cycles Diagrams Using Matlab*". Lecture Notes on Multidisciplinary Industrial Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-48933-4_28, (2024).
12. Kongtragool, B., & Wongwises, S. "*A review of solar-powered Stirling engines and low-temperature differential Stirling engines*". Renewable and Sustainable Energy Reviews, 7(2): 131–154. (2003).
13. F. Formosa and G. Despesse, "*Analytical model for Stirling cycle machine design*" Energy Convers. Manag., vol. 51, no. 10, pp. 1855–1863, Oct. (2010).