FINAL PROJECT - ME184841

CREATION OF A COMPUTER TOOL FOR TRAINING PURPOSES FOR ANALYSING STATIONARY THERMODYNAMIC PROCESSES

KENWARD

NRP 5019201001

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Bachelor Degree Program - Marine Engineering

Department of Marine Engineering

Faculty of Marine Technology

Institut Teknologi Sepuluh Nopember

Surabaya

2024

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TUGAS AKHIR – ME184841

PEMBUATAN ALAT KOMPUTER UNTUK TUJUAN PELATIHAN UNTUK MENGANALISIS PROSES TERMODINAMIKA STASIONER

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BACHELOR THESIS – ME184841

CREATION OF A COMPUTER TOOL FOR TRAINING PURPOSES FOR ANALYSING STATIONARY THERMODYNAMIC PROCESSES

KENWARD

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Bachelor Degree Program

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Institut Teknologi Sepuluh Nopember

Surabaya

2024

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TASK FOR BACHELOR THESIS

Hochschule Wismar
University of Applied Sciences
Technology, Business and Design

Faculty of Engineering / Department of Maritime Studies
Richard-Wagner-Straße 31
18119 Rostock-Warnemünde
Germany

Warnemünde 15.12.2023

Task for Bachelor Thesis

Subject: Creation of a computer tool for training purposes for analysing stationary thermodynamic processes

Student:	Kenward Kenward	
Supervising Professor:	Prof. Dr.-Ing. Achmed Omar	Hochschule Wismar
Assistant Supervisor:	Prof. Dr.-Ing. Jürgen Siegl	Hochschule Wismar

The task focuses on developing a software tool to be used in seminars and exercises by students. The software tool should allow the student to design and analyse a thermodynamic process, such as a gas turbine process, in the thermodynamic diagrams and to define the associated boundary and initial conditions of the process. With the help of the tool, it should then be possible to change and adapt the self-designed process and thereby determine the influences on relevant process parameters, such as efficiency, heat flow or work. For this task it is recommended that the student is familiar with MATLAB and is well versed in applying good programming techniques.

The following aspects should be particularly considered:

- Developing of a useful graphical user interface (GUI) with at least a pressure-volume-diagram (pV-Diagram) and temperature-entropy-diagram (Ts-Diagram) and input fields for some boundary values ore limit values, such as maximum allowed pressure or maximum allowed temperature. The GUI should also have some output fields for calculation results, such as efficiency, heat flow or work.
- Through mouse input or keyboard input (or both), the operator should be able to specify a sequence of thermodynamic state changes in one of the two diagrams. The associated course of the thermodynamic process in the other diagram and the evaluation of the thermodynamic parameters should be calculated and displayed instantly. It should be possible to switch back and forth between the two diagrams while typing.
- Investigating in possible thermodynamically models for the state changes and the fluid involved.
- Use the developed software for a sensitivity analysis to create interesting training scenarios for students.

The supervising Professor reserves the rights to extend or to narrow down the scope of the task during processing. Establishing contacts with other institutions and companies must be agreed with the supervisors. The publication of the work or parts of it requires the prior permission of the supervisor. The work shall be prepared in accordance with the applicable guidelines of Hochschule Wismar for academic and scientific work. At least two consultations with the supervising Professor are required as part of the processing. The finished work is to be submitted in electronic form and in four printed copies in the organization office in Warnemünde.

Prof. Dr.-Ing. Achmed Omar

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APPROVAL SHEET

CREATION OF A COMPUTER TOOL FOR TRAINING PURPOSES FOR ANALYSING STATIONARY THERMODYNAMIC PROCESSES

FINAL PROJECT

Submitted to fulfill one of the requirements
For obtaining a degree Bachelor of Engineering at
Bachelor Degree Program of Marine Engineering
Department of Marine Engineering
Faculty of Marine Technology
Institut Teknologi Sepuluh Nopember

By: **KENWARD**
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Approved by Hochschule Wismar Germany:

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Representative : Wolfgang Busse, Dr.-Ing.

Date : 19 July 2024

Approved by Head of Marine Engineering Department:

Signature : ....

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NIP./NPP. : 197903192008011008

Date : 19 July 2024

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APPROVAL SHEET

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SURABAYA
JULY 2024

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DECLARATION OF HONOR

Hereby, I declare that:

Student Name / NRP	:	Kenward/ 5019201001
Bachelor Program	:	Marine Engineering – Double Degree
Supervisor	:	Prof. Dr.-Ing. Achmed Omar.

hereby declares that the Final Project with the title CREATION OF A COMPUTER TOOL FOR TRAINING PURPOSES FOR ANALYSING STATIONARY THERMODYNAMIC PROCESSES is the result of my own work, is original, and is written by following the rules of scientific writing.

If in the future discrepancies with this statement are found, then I am willing to accept sanctions in accordance with the provisions in force at the Institut Teknologi Sepuluh Nopember.

Rostock, 19 July 2024

Student

Kenward

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ABSTRAK

PEMBUATAN ALAT KOMPUTER UNTUK TUJUAN PELATIHAN UNTUK MENGANALISIS PROSES TERMODINAMIKA STASIONER

Nama Mahasiswa / NRP	**:**	**Kenward / 5019201001**
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Abstrak

Tesis ini menyajikan pengembangan simulator MATLAB interaktif yang dirancang untuk meningkatkan pemahaman tentang proses termodinamika di kalangan mahasiswa teknik dan profesional. Disesuaikan untuk tujuan pendidikan, simulator ini memungkinkan pengguna untuk merancang dan menganalisis proses termodinamika stasioner, seperti siklus turbin gas, menggunakan diagram termodinamika. Ini memungkinkan penyesuaian parameter kunci secara real-time, termasuk tekanan, suhu, volume, dan entropi, untuk mengamati dampaknya terhadap performa sistem. Alat ini menggabungkan prinsip-prinsip termodinamika dasar dan model matematika yang kuat untuk memastikan hasil simulasi yang akurat, menampilkan alat bantu visual seperti diagram tekanan volume p-V dan T-s entropi suhu untuk pemahaman intuitif. Pengguna dapat memasukkan batas dan kondisi awal dan menentukan urutan perubahan jalur melalui input mouse atau keyboard, dengan perangkat lunak secara instan menghitung dan menampilkan parameter proses yang relevan seperti efisiensi, panas, dan kerja. Antarmuka pengguna grafis yang mudah digunakan GUI mencakup bidang input untuk nilai batas dan bidang output untuk hasil perhitungan, mendukung peralihan yang mulus antara diagram p-V dan T-s untuk penyesuaian dan evaluasi waktu nyata. Selain itu, simulator melakukan analisis sensitivitas, menciptakan skenario pelatihan yang bervariasi untuk siswa. Alat pendidikan ini menyediakan pendekatan langsung untuk mengeksplorasi konsep termodinamika yang penting, memberdayakan pengguna untuk menganalisis dan mengoptimalkan proses termodinamika secara efektif, menjadikannya sumber daya berharga untuk pendidikan teknik dan aplikasi praktis.

Kata kunci: ***simulasi, MATLAB, termodinamika, diagram p-V, diagram T-s.***

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ABSTRACT

CREATION OF A COMPUTER TOOL FOR TRAINING PURPOSES FOR ANALYSING STATIONARY THERMODYNAMIC PROCESSES

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Abstract

This thesis presents the development of an interactive MATLAB simulator designed to enhance the understanding of thermodynamic processes among engineering students and professionals. Tailored for educational purposes, the simulator allows users to design and analyse stationary thermodynamic processes, such as gas turbine cycles, using thermodynamic diagrams. It enables real-time adjustments of key parameters, including pressure, temperature, volume, and entropy, to observe their impact on system performance. The tool incorporates fundamental thermodynamic principles and robust mathematical models to ensure accurate simulation results, featuring visual aids like pressure-volume p-V and temperature-entropy T-s diagrams for intuitive understanding. Users can input boundary and initial conditions and define sequences of path changes via mouse or keyboard inputs, with the software instantaneously calculating and displaying relevant process parameters such as efficiency, heat flow, and work. The user-friendly graphical user interface GUI includes input fields for boundary values and output fields for calculation results, supporting seamless switching between p-V and T-s diagrams for real-time adjustments and evaluations. Additionally, the simulator performs sensitivity analyses, creating varied training scenarios for students. This educational tool provides a hands-on approach to exploring essential thermodynamic concepts, empowering users to effectively analyse and optimize thermodynamic processes, making it a valuable resource for engineering education and practical applications.

Keywords: ***simulation, MATLAB, thermodynamics, p-V diagram, T-s diagram.***

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LIST OF ABBREVIATIONS

c	Compressor
COP	Coefficient of Performance
GUI	Graphical User Interface
hp	Heat Pump
m	Mass
MEP	Mean Effective Pressure
n	Polytropic Index
p	Pressure
Q	Heat
R	Gas Constant
ref	Refrigerator
s	Entropy
T	Temperature
t	Turbine
th	Thermal
V	Volume
W	Work
Z	State
ΔU	Change of Inner Energy
η	Efficiency
γ	Gamma
κ	Kappa

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CHAPTER 1 INTRODUCTION

1.1 Background of the Study

The rapid evolution of technology has significantly impacted various educational sectors, including student laboratory experiences. Traditional laboratory setups often encounter challenges such as resource limitations, accessibility constraints, and safety considerations. Integration of digital tools, such as Virtual Labs, offers a promising solution by addressing these limitations, thereby creating an innovative and engaging learning environment.

This thesis aims to develop an interactive thermodynamic process simulator using MATLAB. The objective is to create software that enables students to design and analyse thermodynamic processes using diagrams. Additionally, the software will facilitate exploration of how different parameters influence system performance, enhancing understanding of thermodynamic principles.

1.2 Problem Statement and Objectives

This thesis addresses the challenge of developing an educational simulator for analysing stationary thermodynamic processes.

Key issues include:

- Identification and integration of necessary graphical user interface GUI components, including pressure-volume p-V and temperature-entropy T-s diagrams.
- Implementation of user-friendly functionalities allowing input of process changes via mouse or keyboard, with real-time display of corresponding paths and calculation of values.
- Selection of appropriate thermodynamic models for accurate representation of state changes.
- Development of practical training scenarios for students through sensitivity analysis.

The objectives of this research are to:

- Integration of p-V and T-s diagrams into a GUI interface.
- Implementation of user-controlled input of limit values to observe their impact on thermodynamic parameters.
- Application of suitable thermodynamic models.
- Creation of effective training scenarios for student education, incorporating sensitivity analysis.

1.3 Problem Limitation

This thesis focuses on the digitization of student experiments within educational institutions, specifically addressing stationary thermodynamic processes. The scope includes technical prerequisites, remote learning challenges, and potential economic constraints. The primary audience is students in engineering disciplines, particularly those studying thermodynamics.

1.4 Research Approach

The research methodology involves an extensive literature review on stationary thermodynamic processes and their critical parameters. The software development process will adopt an iterative approach, starting with the design of an intuitive GUI and basic functionality implementation. Feedback from students and educators will guide iterative refinements, ensuring the tool's accuracy and effectiveness. The research process includes:

- Comprehensive literature review.
- Designing a GUI with p-V and T-s diagrams and input/output fields.
- Software implementation for dynamic path alterations and parameter calculations.
- User testing and iterative refinement.
- Sensitivity analysis to identify impactful training scenarios.

1.5 Research Benefit

This study aims to overcome limitations of traditional laboratories by providing an alternative that enhances hands-on learning for engineering students. The developed software tool will facilitate practical teaching of thermodynamics, improving comprehension of theoretical concepts and fostering diverse skills and knowledge.

Moreover, the tool holds potential for utilization by government agencies in engineer training, enhancing workforce competence and maintaining industry standards. By aiding research and development, the simulator can optimize technology efficiency, contribute to cost savings, and streamline product development by pre-emptively identifying design flaws.

1.6 Existing Software Tools for Thermodynamic Analysis

There are several existing software tools for thermodynamic analysis, including commercial packages like Aspen HYSYS, ANSYS Fluent, and COMSOL Multiphysics, as well as open-source tools like CoolProp and REFPROP. However, these tools are often complex and tailored for professional engineers and researchers, making them less suitable for educational purposes. This thesis aims to bridge this gap by developing a user-friendly tool specifically designed for educational use, thereby enhancing the learning experience for students studying thermodynamics.

CHAPTER 2 THERMODYNAMICS

2.1 Thermodynamic Processes, Diagrams, and Formulas

Thermodynamics is the study of energy, its transformations, and its interactions with matter. It forms a cornerstone of engineering, providing essential insights into energy conversion processes and system efficiency. Various scholars have contributed significantly to this field, offering diverse perspectives and deep analyses. For instance, Bejan et al. (2016) [1] delve into thermal design and optimization, crucial for engineering applications. Energy, encompassing both kinetic and potential forms, is central to thermodynamics. Dixon (2018) [4] illustrates the application of energy principles in fluid mechanics and turbomachinery, highlighting their practical implications. Similarly, Hill and Peterson (2012) [6] emphasize energy transformations in the context of propulsion systems, particularly relevant in aerospace engineering. Central to these fields are thermodynamic processes, which explain alterations in state variables like pressure, volume, temperature, and entropy. These processes are often represented graphically using thermodynamic diagrams, with the pressure-volume p-V and temperature-entropy T-s diagrams being paramount.

2.1.1 Thermodynamic Diagrams

The pressure-volume p-V diagram illustrates the relationship between pressure and volume throughout a process. The area beneath the curve on this diagram corresponds to the work done W by or on the system, essential for visualizing processes such as those in engines and turbines.

The temperature-entropy T-s diagram, on the other hand, portrays changes in temperature and entropy. Here, the area beneath the curve correlates to the heat transfer Q occurring during the process. This diagram proves invaluable for comprehending heat addition and rejection phases within thermodynamic cycles like Rankine and Brayton.

These graphical representations serve as indispensable tools for visualizing thermodynamic processes and understanding the intricate interplay among various state variables.

2.1.2 Fundamental Laws and Formulas

Fundamental to thermodynamics are key concepts such as the system, surroundings, and the laws governing energy. According to Çengel and Boles (2014) [3], a thermodynamic system is defined as a specific quantity of matter or a defined region in space under study. The foundational laws of thermodynamics, articulated by Engel and Reid (2019) [5], include the first and second laws, which underpin the entire discipline.

1. The First Law of Thermodynamics

   Also known as the conservation of energy. The first law of thermodynamics, or the law of energy conservation, posits that energy cannot be created nor destroyed; it can only change forms Moran et al. (2017) [8] supplement this with practical examples and problem-solving techniques.

This principle is mathematically expressed as:

$$\Delta U = Q + W \tag{2.1}$$

where ΔU is the change in internal energy, Q is the heat added to the system, and W is the work done by the system.

2. Second Law of Thermodynamics

This law states that entropy s increases for irreversible processes and remains constant for reversible processes, guiding the direction of heat transfer and the efficiency of thermodynamic cycles. The second law of thermodynamics is critical in understanding energy transformations. Saravanamuttoo et al. (2009) [9] discuss its implications in gas turbine operations, offering practical perspectives on how entropy influences engine efficiency.

2.2 Application in Educational Simulators

In developing educational simulators, it's crucial to apply thermodynamic principles effectively to create interactive tools. MATLAB serves as a powerful tool for solving complex thermodynamic problems. The MATLAB Documentation (MathWorks) [7] provides extensive resources and examples for implementing thermodynamic calculations and simulations, making it indispensable for engineers and researchers alike. These simulators should integrate graphical representations like p-V and T-s diagrams. Users can manipulate state variables such as pressure, volume, temperature, and entropy to observe immediate changes in parameters like heat and work. This real-time feedback enhances students' understanding of thermodynamic processes and their practical applications.

2.3 Fundamental Properties and Equations

Understanding the thermodynamic properties of pure substances is essential for analysing and designing thermodynamic systems. Smith et al. (2017) [10] provide comprehensive introductions to chemical engineering thermodynamics, elucidating the properties and behaviours of pure substances. Bridging the microscopic and macroscopic worlds, statistical thermodynamics employs statistical methods to understand thermodynamic properties. Callen (2006) [2] explores this approach, shedding light on the statistical nature of entropy and other thermodynamic quantities.

To illustrate the application of these principles, consider the following properties for air:

Individual gas constant $R = 287{,}2 \ \frac{J}{kg \cdot K}$

Isentropic exponent $\kappa = \frac{C_p}{C_V} = 1{,}4$

Specific heat at constant volume $C_V = \frac{R}{\kappa - 1} = 718 \ \frac{J}{kg \cdot K}$

Specific heat at constant pressure $C_p = \frac{R \cdot \kappa}{\kappa - 1} = 1005{,}2 \ \frac{J}{kg \cdot K}$

With reference conditions as:

$T_0 = 273{,}15\ K$
$p_0 = 10^5\ Pa$
$s_0 = 2243{,}07\ \frac{J}{kg \cdot K}$, Entropy zeroed at $T = -100°C$ and $p = 500\ bar$

Using the ideal gas equation

$$p \cdot V = m \cdot R \cdot T \quad (2.2)$$

Volume V can be calculated as:

$$V = \frac{m \cdot R \cdot T}{p} \quad (2.3)$$

where: p = pressure in Pa m = mass in kg

V = volume in m^3 T = temperature in K

2.3.1 Entropy Changes

Entropy s changes are given by derivation from the energy equation. Starting with the first law of thermodynamics:

$$dq + dW = du$$

$$dq + dW_V + dj = du$$

$$dq + dj - p \cdot dV = du$$

$$dq + dj = du + p \cdot dV$$

Considering $dW_V = -pdV$, and dividing by temperature T :

$$\frac{dq + dj}{T} = \frac{du}{T} + \frac{p}{T}\ dV$$

For an ideal gas and mass remains constant:

$$\frac{p}{T} = \frac{R}{V}$$

Thus, $\frac{dq+dj}{T} = ds$, as a result:

$$ds = C_V \frac{dT}{T} + R\ \frac{dV}{V}$$

Hence, integrating the above equation, the formula for calculating entropy is:

$$s_1 - s_0 = C_p \cdot ln\left(\frac{T_1}{T_0}\right) + R \cdot ln\left(\frac{V_1}{V_0}\right)$$

From the ideal gas law $p \cdot V = R \cdot T$, we can derive:

$$ln\left(\frac{V_1}{V_0}\right) = ln\left(\frac{p_0}{p_1}\right)$$, because $\frac{V_1}{V_0} = \frac{p_0}{p_1}$.

Substitute into the original equation and rearrange the equation to solve s_1:

$$s_1 = s_0 + C_p \cdot ln\left(\frac{T_1}{T_0}\right) - R \cdot ln\left(\frac{p_1}{p_0}\right) \quad (2.4)$$

2.3.2 Work and Heat Calculations

Work W and heat Q are calculated as follows:

$$\text{Work:} W = -\int_1^2 p \cdot dV \approx -\sum_{i=1}^{n} p_i \cdot dV_i = -\sum_{i=1}^{n} p_i \cdot (V_{i+1} - V_i) \quad (2.5)$$

$$\text{Heat: } Q = m \cdot \int_1^2 T \cdot ds \approx m \cdot \sum_{i=1}^{n} T_i \cdot ds_i = m \cdot \sum_{i=1}^{n} T_i \cdot (s_{i+1} - s_i) \quad (2.6)$$

The values of heat and work can be distinguished into positive and negative components. Positive work W_{in} represents work input, while negative work W_{out} represents work output. Similarly, positive heat Q_{in} represents heat input, and negative heat Q_{out} represents heat output. The total work W_{tot} and heat Q_{tot} are calculated by summing the respective components.

2.3.3 Efficiency, Coefficient of Performance COP , Carnot Efficiency, and Carnot COP

- Efficiency

The efficiency of a system is a measure of how well it converts input energy into useful work. It is a critical parameter in evaluating the performance of engines, refrigerators, and other thermal systems. The formula for efficiency η is given by:

$$\eta = \frac{W_{tot}}{Q_{in}} \quad (2.7)$$

Efficiency is typically expressed as a percentage. An efficiency of 100% $(\eta = 1)$ would indicate a perfect system where all the input heat is converted into work, which is theoretically impossible due to inevitable losses such as friction, heat dissipation, and other inefficiencies.

- The Coefficient of Performance COP

The Coefficient of Performance COP is a measure of the efficiency of refrigeration cycles and heat pumps. It describes the ratio of useful heating or cooling provided to the work input. The COP is defined differently depending on whether it is used for a heat pump or a refrigerator.
For a heat pump, the COP COP_{hp} is given by:

$$COP_{hp} = \frac{Q_{out}}{W_{tot}} \quad (2.8)$$

For a refrigerator, the COP COP_{ref} is defined as:

$$COP_{ref} = \frac{Q_{in}}{W_{tot}}$$

The COP can be greater than 1, indicating that more heat is moved than the work input, which is a characteristic of heat pumps and refrigerators due to their operation based on thermodynamic cycles. In the application, it is calculated for all working engine as COP of heat pumps.

- Carnot Efficiency and Carnot COP

  The Carnot efficiency is a theoretical maximum efficiency that a heat engine operating between two temperatures can achieve. It is derived from the Carnot cycle, which is an idealized thermodynamic cycle proposed by Sadi Carnot. The Carnot efficiency η_{Carnot} is given by:

$$\eta_{Carnot} = 1 - \frac{T_{min}}{T_{max}} \tag{2.9}$$

  The Carnot Coefficient of Performance COP is a measure of the efficiency of a heat pump or refrigeration cycle operating between two temperatures. Similar to the Carnot efficiency for heat engines, the Carnot COP is based on the Carnot cycle, an idealized thermodynamic cycle. The Carnot COP is given by:

$$COP_{Carnot} = \frac{1}{1 - \frac{T_{min}}{T_{max}}} \tag{2.10}$$

  where T_{min} and T_{max} are the minimum and maximum temperatures, respectively, within the cycle.

  The Carnot efficiency and Carnot Coefficient of Performance COP define the maximum theoretical efficiency achievable by thermodynamic cycles operating between two temperature reservoirs. These metrics underscore the critical role of temperature differentials: higher efficiency in heat engines is attainable with larger temperature differences between the hot and cold reservoirs, while better performance in heat pumps and refrigeration cycles is realized with smaller temperature differences. These principles establish fundamental limits dictated by thermodynamic laws, ensuring that real-world engines or heat pumps cannot surpass the efficiency or COP of a Carnot cycle operating between identical temperatures.

2.3.4 Calculations for State Variables

Equations of state are mathematical models that describe the state of a system under various conditions. Sonntag et al. (2015) [11] offer detailed derivations and explanations of these equations, crucial for predicting the behaviour of gases and liquids across different environments. Based on the gas law and entropy equations, we need only two out of four quantities (T, p, V, s) to calculate the other values. Here are the six cases for calculating the two unknown quantities based on two known quantities:

1. Case T and p are known, calculate V and s:

$$V = \frac{m \cdot R \cdot T}{p} \tag{2.11}$$

$$s = s_0 + C_p \cdot ln\left(\frac{T}{T_0}\right) - R \cdot ln\left(\frac{p}{p_0}\right) \tag{2.12}$$

2. Case T and V are known, calculate p and s:

$$p = \frac{m \cdot R \cdot T}{V} \tag{2.13}$$

$$s = s_0 + C_p \cdot ln\left(\frac{T}{T_0}\right) - R \cdot ln\left(\frac{p}{p_0}\right) \tag{2.14}$$

3. Case T and s are known, calculate p and V:

$$s = s_0 + C_p \cdot ln\left(\frac{T}{T_0}\right) - R \cdot ln\left(\frac{p}{p_0}\right)$$

$$R \cdot ln\left(\frac{p}{p_0}\right) = C_p \cdot \ln\left(\frac{T}{T_0}\right) - s + s_0$$

$$ln\left(\frac{p}{p_0}\right) = \frac{C_p \cdot \ln\left(\frac{T}{T_0}\right) - (s - s_0))}{R}$$

$$p = p_0 \cdot exp\left(\frac{C_p \cdot \ln\left(\frac{T}{T_0}\right) - (s - s_0)}{R}\right) \tag{2.15}$$

$$V = \frac{m \cdot R \cdot T}{p} \tag{2.16}$$

4. Case p and V are known, calculate T and s:

$$T = \frac{p \cdot V}{m \cdot R} \tag{2.17}$$

$$s = s_0 + C_p \cdot ln\left(\frac{T}{T_0}\right) - R \cdot ln\left(\frac{p}{p_0}\right) \tag{2.18}$$

5. Case p and s are known**,** calculate T and V:

$$s = s_0 + C_p \cdot ln\left(\frac{T}{T_0}\right) - R \cdot ln\left(\frac{p}{p_0}\right)$$

$$C_p \cdot ln\left(\frac{T}{T_0}\right) = s - s_0 + R \cdot ln\left(\frac{p}{p_0}\right)$$

$$ln\left(\frac{T}{T_0}\right) = \frac{s - s_0 + R \cdot ln\left(\frac{p}{p_0}\right)}{C_p}$$

$$T = T_0 \cdot \exp\left(\frac{s - s_0 + R \cdot ln\left(\frac{p}{p_0}\right)}{C_p}\right) \tag{2.19}$$

$$V = \frac{m \cdot R \cdot T}{p} \tag{2.20}$$

6. Case V and s are known**,** calculate p and T:

$$\frac{T}{T_0} = \frac{\left(\frac{p \cdot V}{m \cdot R}\right)}{\left(\frac{p_0 \cdot V_0}{m \cdot R}\right)} = \frac{p}{p_0} \cdot \frac{V}{V_0}$$

$$V_0 = \frac{m \cdot R \cdot T_0}{p_0}$$

$$s = s_0 + C_p \cdot ln\left(\frac{p}{p_0} \cdot \frac{V}{V_0}\right) - R \cdot ln\left(\frac{p}{p_0}\right)$$

$$s = s_0 + C_p \cdot ln\left(\frac{p}{p_0}\right) + C_p \cdot ln\left(\frac{V}{V_0}\right) - R \cdot ln\left(\frac{p}{p_0}\right)$$

$$s = s_0 + (C_p - R) \cdot ln\left(\frac{p}{p_0}\right) + C_p \cdot ln\left(\frac{V}{V_0}\right)$$

$$s = s_0 + C_V \cdot ln\left(\frac{p}{p_0}\right) + C_p \cdot ln\left(\frac{V}{V_0}\right)$$

$$C_V \cdot ln\left(\frac{p}{p_0}\right) = s - s_0 - C_p \cdot ln\left(\frac{V}{V_0}\right)$$

$$ln\left(\frac{p}{p_0}\right) = \frac{s - s_0 - C_p \cdot ln\left(\frac{V}{V_0}\right)}{C_V}$$

$$p = p_0 \cdot exp\left(\frac{s - s_0 - C_p \cdot ln\left(\frac{V}{V_0}\right)}{C_V}\right) \quad (2.21)$$

$$T = \frac{p \cdot V}{m \cdot R} \quad (2.22)$$

By incorporating these formulas and calculations into an educational simulator, users can gain practical experience in analysing thermodynamic processes and understanding the relationships between different state variables. This approach facilitates a deeper comprehension of the fundamental principles of thermodynamics and their applications in real-world scenarios.

2.4 Path or Process Connections

Defining the path or process of connections is crucial as it directly impacts the accuracy and reliability of calculations. The way in which points are connected can affect the flow of data leading to varying results. By clearly outlining these connections, we ensure that each step is correctly followed and integrated, minimizing errors and ensuring consistent, precise outcomes. Therefore, understanding and precisely defining these connections are essential for achieving reliable and valid outcomes in any thermodynamic calculation or system analysis.

Linear Process

In thermodynamics, the path or process connecting two states is often expressed using linear relations, which simplify complex processes and enhance the practicality of calculations. A linear relation generally takes the form of $y = mx + c$, where m is the slope and c is the intercept. For example, consider a linear path connecting two points (x_1,y_1) and (x_2,y_2).

From:

$$m = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}$$

Find c based on the case that $x = x_1$, so

$$y_1 = \frac{y_2 - y_1}{x_2 - x_1} \cdot x_1 + c$$

Solving for c, we get:

$$c = y_1 - \frac{y_2 - y_1}{x_2 - x_1} \cdot x_1$$

$$y = \frac{y_2 - y_1}{x_2 - x_1} \cdot x + y_1 - \frac{y_2 - y_1}{x_2 - x_1} \cdot x_1$$

Thus, the equation of the linear path connecting the two points can be written as:

$$y = \frac{y_2 - y_1}{x_2 - x_1} \cdot (x - x_1) + y_1$$

Examples of Linear Path Relations

Linear paths in thermodynamics can be categorized into seven types: linear pV, linear Ts, linear pT, linear ps, linear VT, linear Vs, and polytropic. For example, in the case of a linear pV path (where p and V are the two known quantities):

$$p = \frac{p_2 - p_1}{V_2 - V_1} \cdot (V - V_1) + p_1 \tag{2.23}$$

Only in case $V_2 \neq V_1$, this equation can be applied since any value divided by zero is infinity or undefined as numerical value. Similarly, the same principle applied to the others path as well.

Polytropic Process

A polytropic process is one where the pressure and volume are related by:

$$pV^n = constant$$

$$p \sim V^{-n}$$

where n is the polytropic index. The pressure-volume relation in a polytropic process is given by:

$$p = p_1 \cdot \left(\frac{V}{V_1}\right)^{-n} \tag{2.24}$$

The n can be calculated if the initial and final states are known with formula:

$$n = -\frac{log\left(\frac{p}{p_1}\right)}{log\left(\frac{V}{V_1}\right)} \tag{2.25}$$

If n is not constant, it varies within a range:

$$n_{min} < n < n_{max}$$

This calculation and its results will be displayed within the application. It allows users to determine the range of thermodynamic processes encompassed by a single process occurring between two points. The calculation formula applies only if both points are not equal. For instance:

If s is constant, then $n = \kappa = 1{,}4$.
If T is constant, then $n = 1$.
If p is constant, then $n = 0$.
If V is constant, then n is undefined /infinite.

Understanding these fundamental equations and their applications is crucial for analysing and optimizing thermodynamic processes. This knowledge, combined with practical tools for graphical representation and calculation, forms the basis for effective study and application in thermodynamics.

2.5 Elementary Thermodynamic Process

Understanding basic thermodynamic processes is fundamental to analysing energy transformations within systems. A thermodynamic process involves changes in the state variables of a system, transitioning from an initial state Z_1 to a final state Z_2. These state variables include temperature T , pressure p , volume V , and entropy s.

2.5.1 Initial and Final States

Start Point: Z_1

- Defined by T_1, p_1, V_1, s_1
- Initial Situation 1: All thermodynamic quantities corresponding with the initial state.

End Point: Z_2

- Defined by T_2, p_2, V_2, s_2
- Final Situation 2: All thermodynamical quantities corresponding with final state.

2.5.2 Path from Z_1 to Z_2

The path between the initial and final states can be defined as a function: $y = f(x)$, where y and x are elements from the set of thermodynamic quantities (T, p, V, s). The path specifies how these variables change from x_1 to x_2 and y_1 to y_2.

- Example Process: Isothermal Process

  Consider an isothermal process, where temperature remains constant $(T_1 = T_2)$. For an ideal gas, the relationship between pressure and volume for an ideal gas can be described by

$$p \cdot V = constant$$

  Thus, the path function for an isothermal process is:

$$p = \frac{constant}{V}$$

This equation illustrates the inverse relationship between pressure and volume at constant temperature, described on a p-V diagram.

2.5.3 Key Aspects of Thermodynamic Processes

State Variables:

- Temperature T : Indicates the thermal state of a system.
- Pressure p : Represents the mechanical state of the system.
- Volume V : Denotes the space occupied by the system.
- Entropy s : Measures the disorder in the system.

Heat Q and Work W :

- Heat Q : The energy transferred due to a temperature difference.
- Work W : The energy transferred due to pressure difference.

Thermodynamic Equations:

- First Law of Thermodynamics:

$$\Delta U = Q + W$$

  In a closed system, energy is conserved. According to the First Law of Thermodynamics, the change in the internal energy of the system is equal to the heat added to the system minus the work done by the system. Therefore, any changes at the inlet or outlet of the system must account for these energy exchanges to maintain the conservation of energy.

- Second Law of Thermodynamics:

  Entropy tends to increase in most processes, except for isentropic cases where there is no friction. Entropy is a special thermodynamic quantity that describes the state and evolution of a system. According to the Second Law of Thermodynamics, the total entropy of an isolated system can never decrease over time. It remains constant only in ideal, reversible processes, and increases in all real, irreversible processes. The change in entropy can be calculated using the appropriate thermodynamic formula:

$$\Delta s = f(T_1, T_2, p_1, p_2)$$

  As a result, to calculate changes in thermodynamic properties between two points, only the pressure and temperature at two points are needed, without directly applying the Second Law of Thermodynamics

Graphical Representation:

- p-V Diagram: Shows the relationship between pressure and volume. The area under the curve represents work done during the process.

- T-s Diagram: Illustrates changes in temperature and entropy. The area under the curve represents heat transfer during the process.

2.5.4 Process Examples

1. Isobaric Process (constant pressure):
   - $p = constant$
   - Work done: $W = -p\Delta V$
2. Isochoric Process (constant volume):
   - $V = constant$
   - No work is done: $W = 0$
   - Heat added increases internal energy: $Q = \Delta U$
3. Isothermal Process (constant temperature):
   - $T = constant$
   - $pV = constant$
   - Work done: $W = mRTln(\frac{V_2}{V_1})$
4. Adiabatic Process (no heat transfer):
   - $Q = 0$
   - Change in internal energy equals work done: $\Delta U = -W$
   - $pV^{\kappa} = constant$ (for ideal gases, where κ is the heat capacity ratio)
5. Polytropic Process
   - $pV^n = constant$
   - Describes a variety of processes depending on n
   - Examples:
     - $n = 0$: Isobaric (constant pressure)
     - $n = 1$: Isothermal (constant temperature)
     - $n = \kappa$: Adiabatic (no heat transfer)
   - Work done: $W = \frac{p_1 V_1 - p_2 V_2}{1-n}$

Understanding elementary thermodynamic processes involves analysing the changes in state variables from an initial to a final state, using graphical representations such as p-V and T-s diagrams, and applying fundamental thermodynamic equations. This foundational knowledge is essential for developing effective educational tools that simulate and analyse thermodynamic processes. Understanding polytropic processes helps analyse complex systems where simple processes don't apply, making it essential for studying gas behaviour under different conditions.

2.5.5 Linear Relations

1. Linear p-V Relation

   The linear p-V relation describes a thermodynamic process where pressure p and volume V are directly proportional to each other. This relationship can be expressed as:

   $$p = a_1 V + a_0 \tag{2.26}$$

   where a_1 is the proportionality constant, and a_0 is a constant.

   This type of process is often idealized and serves as a simplification in thermodynamic analyses.

2. Linear Ts Relation

   A linear Ts relation implies that temperature T and entropy s have a direct linear relationship, given by:

   $$T = a_1 s + a_0 \tag{2.27}$$

   where a_1 is the slope and a_0 is the intercept.

   This relationship is useful in idealized models of heat engines and refrigerators.

3. Linear pT Relation

   The linear pT relation indicates a direct proportionality between pressure p and temperature T , represented by:

   $$p = a_1 T + a_0 \tag{2.28}$$

   This relationship is often observed in ideal gases, where a_1 and a_0 are constants derived from the ideal gas law.

4. Linear ps Relation

   In a linear ps relation, pressure p and entropy s are linearly related:

   $$p = a_1 s + a_0 \tag{2.29}$$

   This is less common but can be used to simplify the analysis of certain thermodynamic processes.

5. Linear VT Relation

   A linear VT relation suggests that volume V and temperature T have a direct linear relationship, given by:

$$V = a_1 T + a_0 \tag{2.30}$$

   This can describe certain idealized expansion or compression processes.

6. Linear Vs Relation

   The linear Vs relation indicates that volume V and entropy s are linearly related:

$$V = a_1 s + a_0 \tag{2.31}$$

   This is useful in theoretical thermodynamic studies.

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CHAPTER 3 REALISATION OF SOFTWARE TOOL

3.1 Flowchart of Tool

The development of the software tool for educational purposes in analysing stationary thermodynamic processes followed a systematic approach. The objective was to create an effective tool that enables students to design and analyse thermodynamic cycles, such as gas turbine cycles, using graphical representations and precise boundary conditions. This process began with a thorough review of literature on thermodynamics, particularly focusing on stationary processes and their key parameters. Foundational principles were established based on definite sources such as Cengel and Boles' "Thermodynamics: An Engineering Approach" to guide the design and implementation phases.

The flowchart (Figure 1) visually explains how users interact with and utilize the software tool. This methodical approach was crucial to ensure that the tool met educational goals effectively, while also being accurate and easy to use.

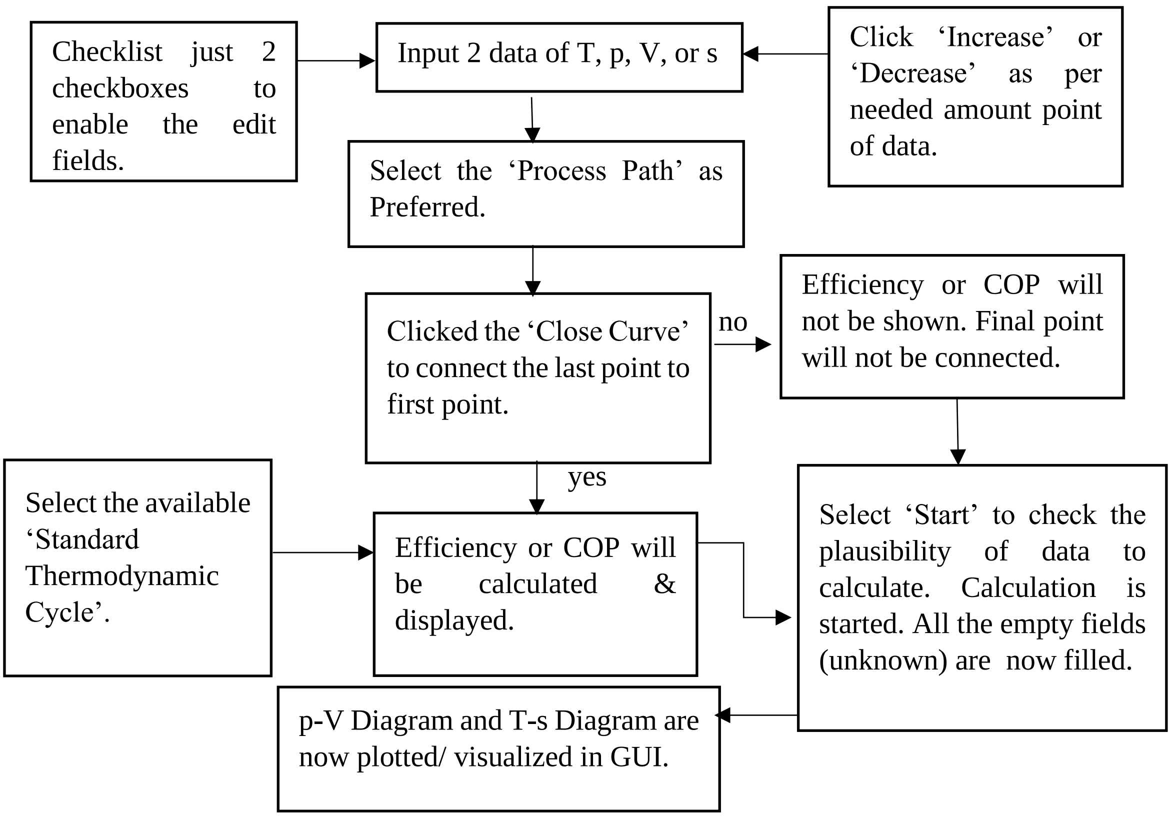


Figure 1 Tool Flowchart

3.2 Thermodynamical Part of Tool (Calculation Algorithm)

The thermodynamic component of the software tool comprises the calculation algorithms responsible for simulating and analysing thermodynamic processes. The calculation algorithms are designed to accurately predict process parameters, including efficiency, heat flow, and work, using MATLAB's computational capabilities. This ensures efficient and reliable calculation of thermodynamic properties.

The integration of validated thermodynamic models guarantees the accuracy and reliability of the software tool, providing students with a robust platform for exploring and understanding thermodynamic principles. Furthermore, the calculation algorithms are designed to be flexible and adaptable, allowing for customization and extension to accommodate various thermodynamic scenarios and educational objectives.

The core of the thermodynamic analysis tool is its calculation algorithm, which follows these steps:

1. Initialization: Initialize variables for the input and process path.
2. Data Validation: Verify that the input data is plausible for calculation.
3. Calculation and Display: Perform the necessary calculations and display all required outputs, including variables for plotting the p-V and T-s diagrams.

The thermodynamic calculation algorithms within the software tool are integral to its functionality, providing accurate simulations of thermodynamic processes. By incorporating established thermodynamic principles and leveraging MATLAB's computational power, the tool offers a valuable educational resource for students studying thermodynamics.

3.3 GUI Part of Tool and Visualization

A well-designed Graphical User Interface GUI is crucial for enhancing user interaction and experience with educational software tools in engineering disciplines. Inspired by best practices in GUI design and visualization techniques, the software tool's GUI incorporates interactive components essential for effective learning.

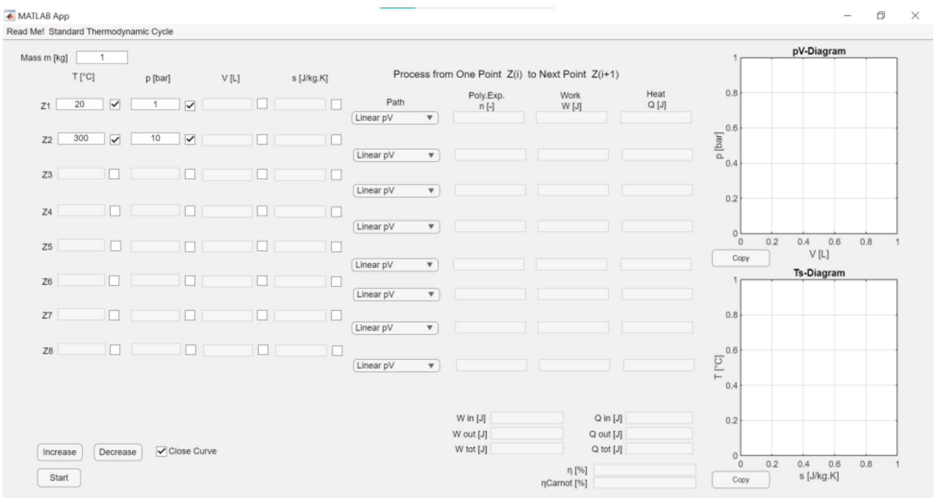


Figure 2 GUI App Design Visualization

Design and Functionality of the GUI

1. Input Fields:

   - Text Boxes: These fields allow users to input two of the thermodynamic quantities (T, p, V, s) and the mass m. The choice of which quantities to input is flexible, accommodating various process design requirements.

   - Checkboxes: The checkbox located beside the text box is utilized to enable two additional fields where the user is required to input values.

   - Dropdown Menus: Users can select the type of thermodynamic process path connection from dropdown menus. This feature simplifies the selection path and ensures that the correct equations and models are applied for the calculations.

2. Output Fields:

   - Display Fields: These disabled fields show the calculated values of the thermodynamic quantities (T, p, V, s), along with other important parameters such as the polytropic index, heat in, heat out, work in, work out, total heat, total work, efficiency, and Carnot efficiency. This comprehensive display ensures that users have access to all relevant information for their analysis.

3. Graphs:

   - p-V and T-s Diagrams: These diagrams are crucial for visualizing the process path and understanding the relationships between different thermodynamic properties. The software tool plots these diagrams based on user input, providing a clear visual representation of the process.

   - Process Path Plotting: Users can see the specific path their process follows on the p-V and T-s diagrams, enhancing their understanding of how changes in conditions affect the overall process.

   - Copy Button: Positioned beside the p-V and T-s diagrams allows the user to duplicate the displayed diagrams into a new window. Located beside the p-V and T-s diagrams enables the user to transfer the displayed diagrams into a new window, allowing for a clearer and enlarged view.

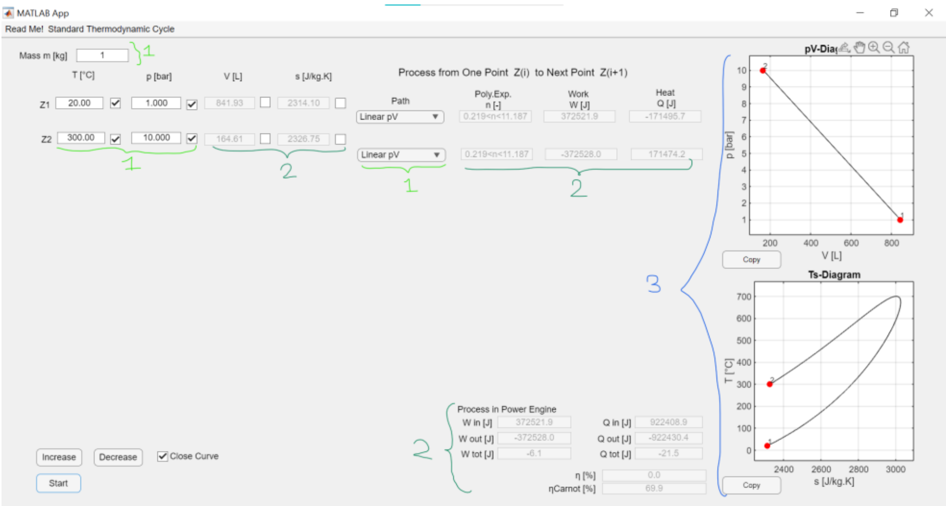


Figure 3 App Features Input, Output, and Graph (1 = Input, 2 = Output, 3 = Graph)

4. User Interaction:

- Dynamic Updates: The diagrams and output fields update automatically based on user input, providing immediate feedback. This dynamic interaction helps users see the direct impact of their changes and supports iterative learning.
- Standard Data Set: The tool includes a standard data set for thermodynamic cycles, offering a starting point for users to explore typical processes and scenarios. This feature is especially useful for educational purposes, allowing students to focus on learning the concepts without needing to input all data from scratch.
- Standard Thermodynamic Cycle: The Standard Thermodynamic Cycle involves processes within a thermodynamic system, depicted through p-V and T-s diagrams. These cycles—Diesel, Otto, Seiliger, Ericsson, Joule, Stirling, and Carnot—act as idealized models for engines and refrigeration systems, demonstrating energy conversion principles and efficiency. Data for each cycle is computed and illustrated on p-V and T-s diagrams, highlighting variations in pressure, volume, temperature, and entropy. These diagrams offer insights into thermodynamic efficiency and performance, facilitating comparisons between cycles and their engineering applications.

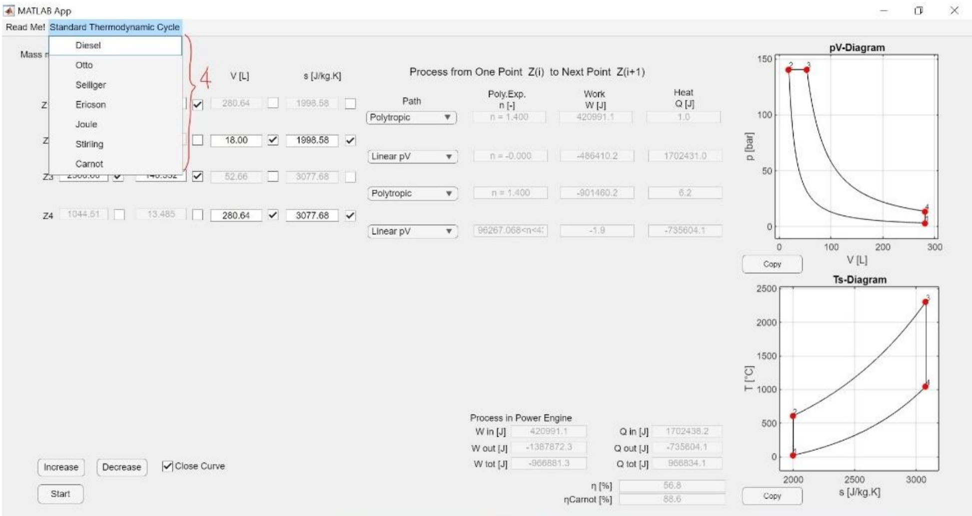


Figure 4 App Feature User Interaction

5. Additional Menu (Read Me!)

   It is recommended that users read this section to gain an understanding of the software developed in this thesis, as well as to obtain additional information regarding the application of thermodynamic concepts within the app.

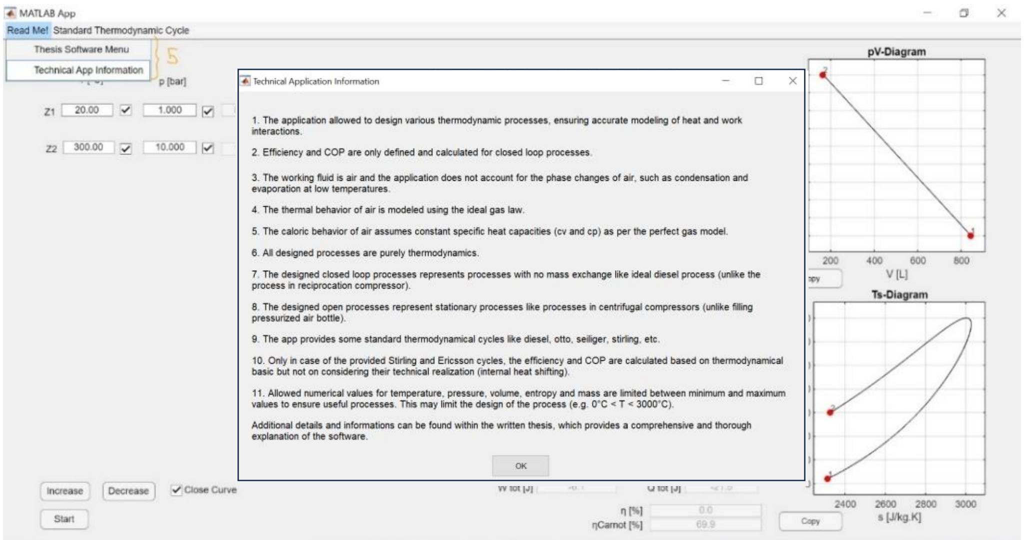


Figure 5 App Feature Read Me!

In addition to GUI design, the visualization aspect of the software tool plays a crucial role in enhancing students' understanding of thermodynamic processes. Visualization techniques offer a powerful means of conveying complex scientific concepts and fostering deeper learning experiences. By integrating GUI design principles and effective visualization techniques, the software tool offers a comprehensive platform for enhancing thermodynamics education and promoting active student engagement.

By providing students with immediate visual feedback on the effects of their actions, the software tool facilitates experiential learning and empowers students to explore the intricacies of thermodynamic processes in a hands-on manner. Through the integration of GUI design principles and effective visualization techniques, the software tool offers a comprehensive platform for enhancing thermodynamics education and promoting active student engagement.

CHAPTER 4 RESULTS

4.1 Integration of Thermodynamic Models

In the development of the software tool for analysing stationary thermodynamic processes, the integration of thermodynamic models is fundamental to ensure accurate simulations. Various thermodynamic models are explored and evaluated to determine the most suitable approach for modelling the processes. The selection of appropriate models is based on their ability to capture the underlying physics of thermodynamic systems and their compatibility with the software framework.

Investigating Thermodynamic Models

1. Ideal Gas Models

   Ideal gas models are commonly used to represent the behaviour of gases under certain conditions. These models assume that gas particles do not interact with each other and occupy negligible volume. Ideal gas laws, such as the ideal gas law equation $pV = mRT$, are employed to relate pressure, volume, temperature, and the mass of the gas. This approach simplifies the analysis of gas behaviour in various thermodynamic processes.
2. Thermodynamic Property Databases

   Thermodynamic property databases provide extensive data on the properties of substances under various conditions. These databases contain information such as specific heat capacities, enthalpies, and entropy values at different temperatures and pressures. They are valuable resources for accurately simulating thermodynamic processes involving complex substances.

Integration into the Software Tool

The chosen thermodynamic models are seamlessly integrated into the software tool's computational framework. This integration ensures that users can accurately simulate and analyse thermodynamic processes using the selected models. By incorporating reliable and validated models, the software tool provides students with a robust platform for exploring and understanding thermodynamic principles.

4.2 Provided Thermodynamic Cycle

Thermodynamic cycles are fundamental concepts in the field of thermodynamics, defining the processes that a working fluid undergoes to produce work. These cycles are used to model and analyse the performance of engines, power plants, and refrigeration systems. Understanding these cycles is essential for designing efficient and effective energy conversion systems.

4.2.1 Standard Thermodynamics Cycle

Thermodynamic cycles form the basis for the analysis and understanding of various engines and refrigerators. This thesis examines several key thermodynamic cycles: Diesel, Otto, Seiliger, Ericsson, Joule (Brayton), Stirling, and Carnot. Each cycle's explanation, function, usage, and benefits are thoroughly discussed, highlighting their unique characteristics and contributions to engineering and energy systems.

1. Diesel Cycle

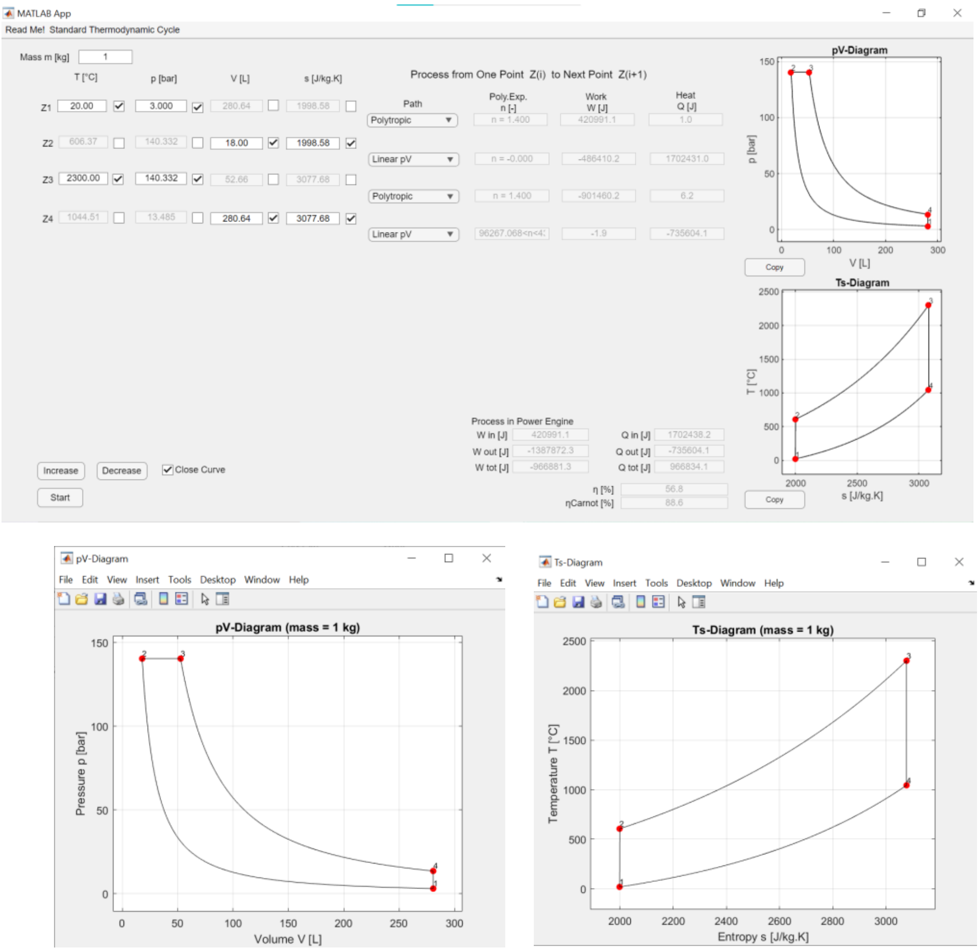


Figure 6 p-V and T-s Diagrams Diesel Cycle

The Diesel cycle, invented by Rudolf Diesel, is a thermodynamic cycle used in Diesel engines. It is characterized by the compression of air to high pressures and temperatures, followed by the injection and combustion of fuel. Diesel engines are widely used in transportation (trucks, buses, ships), power generation, and industrial machinery due to their efficiency and durability.

The Diesel cycle consists of four stages:

1) Isentropic Compression: The air is compressed adiabatically, increasing its pressure and temperature.
2) Isobaric Combustion: Fuel is injected and combusted at constant pressure.
3) Isentropic Expansion: The high-pressure gases expand adiabatically, performing work on the piston.
4) Isochoric Heat Rejection: The exhaust gases are expelled at constant volume.

Benefits:

- High Efficiency: Diesel engines have higher thermal efficiency compared to gasoline engines due to the higher compression ratio.
- Fuel Economy: Diesel fuel has a higher energy density, leading to better fuel economy.
- Durability: Diesel engines are robust and can operate under high loads for extended periods.

2. Otto Cycle

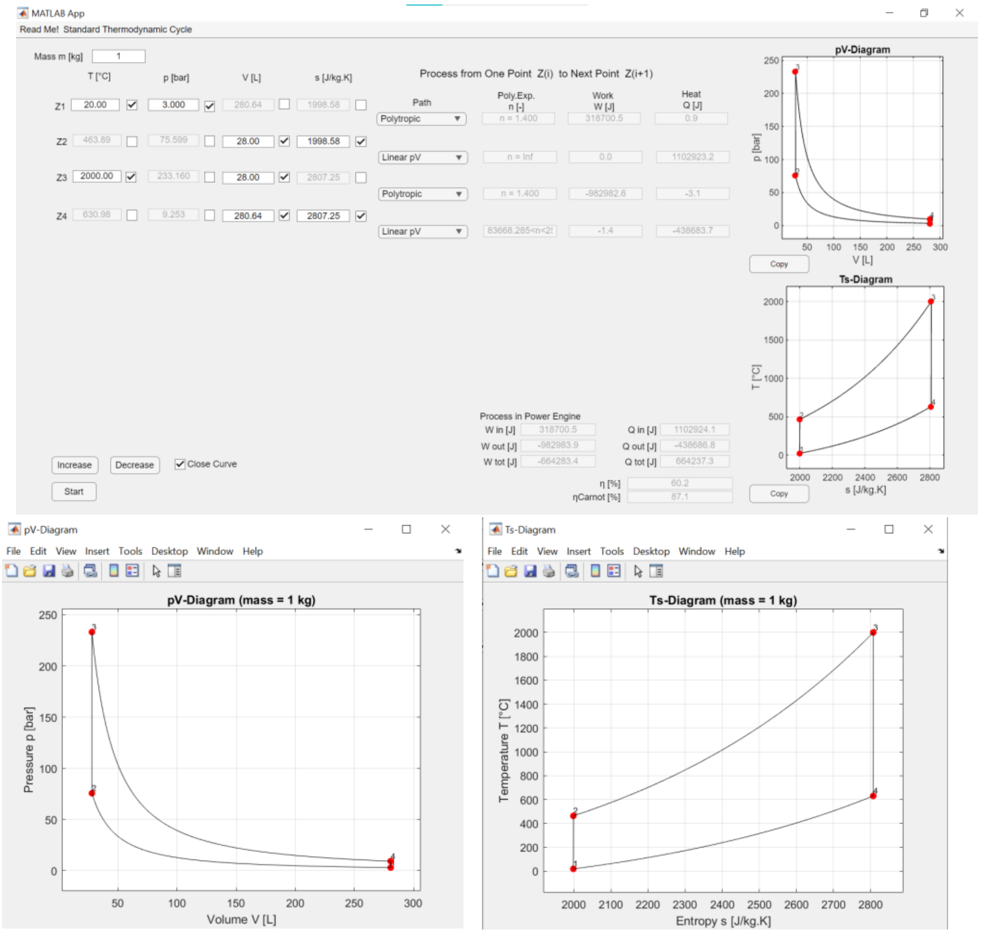


Figure 7 p-V and T-s Diagrams Otto Cycle

The Otto cycle, named after Nikolaus Otto, is the thermodynamic cycle used in gasoline engines. It involves the combustion of a fuel-air mixture within a cylinder. Otto cycle engines are commonly found in automobiles, motorcycles, and small aircraft.

The Otto cycle includes four stages:

1) Isentropic Compression: The fuel-air mixture is compressed adiabatically.

2) Isochoric Combustion: The mixture is ignited, and combustion occurs at constant volume.
3) Isentropic Expansion: The high-pressure gases expand adiabatically, driving the piston.
4) Isochoric Heat Rejection: The exhaust gases are expelled at constant volume.

Benefits:

- High Power-to-Weight Ratio: Otto engines provide a high-power output relative to their weight.
- Smooth Operation: The cycle provides smooth and continuous power output, ideal for transportation.
- Availability: Gasoline is widely available, making Otto engines convenient for everyday use.

3. Seiliger Cycle

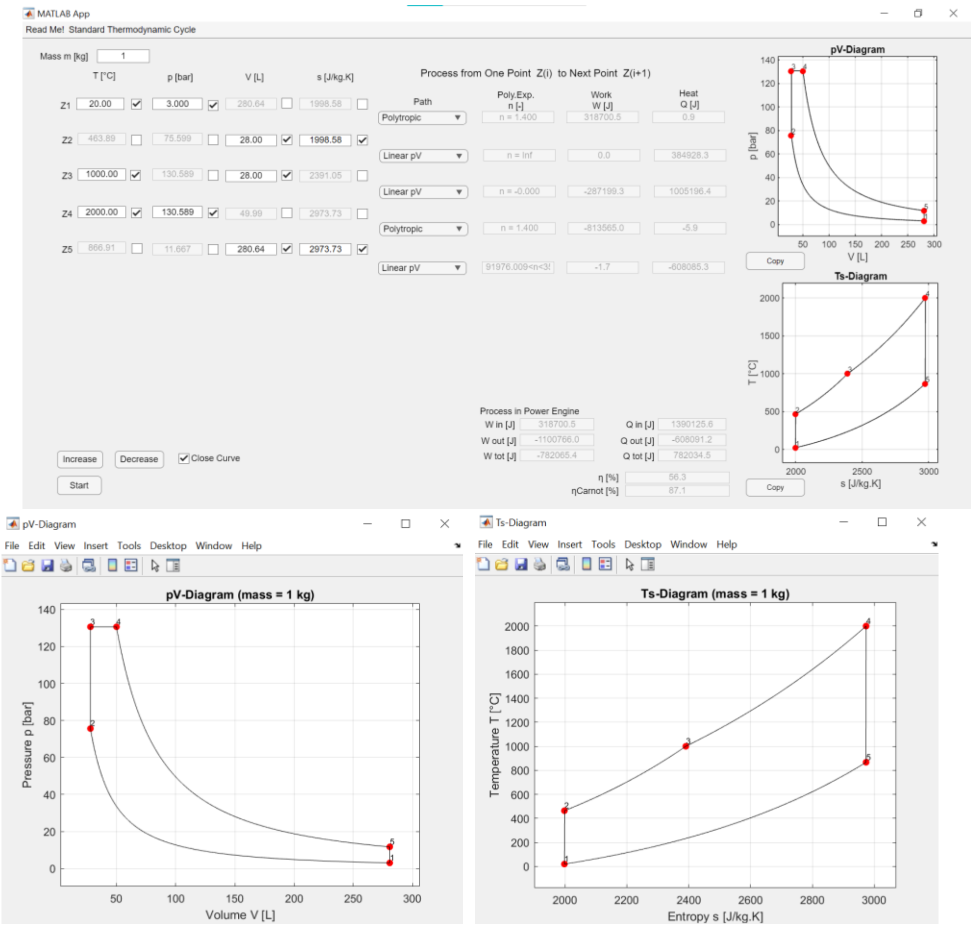


Figure 8 p-V and T-s Diagrams Seiliger Cycle

The Seiliger cycle, also known as the mixed cycle, combines elements of both the Diesel and Otto cycles. It includes isentropic compression, constant-volume combustion, and constant-pressure combustion. This cycle is used in some advanced internal combustion engines and hybrid engines to optimize performance.

The Seiliger cycle stages are:

1) Isentropic Compression: The working fluid is compressed adiabatically.
2) Isochoric Combustion: Initial combustion occurs at constant volume.
3) Isobaric Combustion: Continued combustion occurs at constant pressure.
4) Isentropic Expansion: The gases expand adiabatically, performing work.
5) Isochoric Heat Rejection: Heat is rejected at constant volume.

Benefits:

- Efficiency: By combining constant-volume and constant-pressure combustion, the Seiliger cycle can achieve higher efficiencies.
- Flexibility: It allows for better control over the combustion process, improving performance and reducing emissions

4. Ericsson Cycle

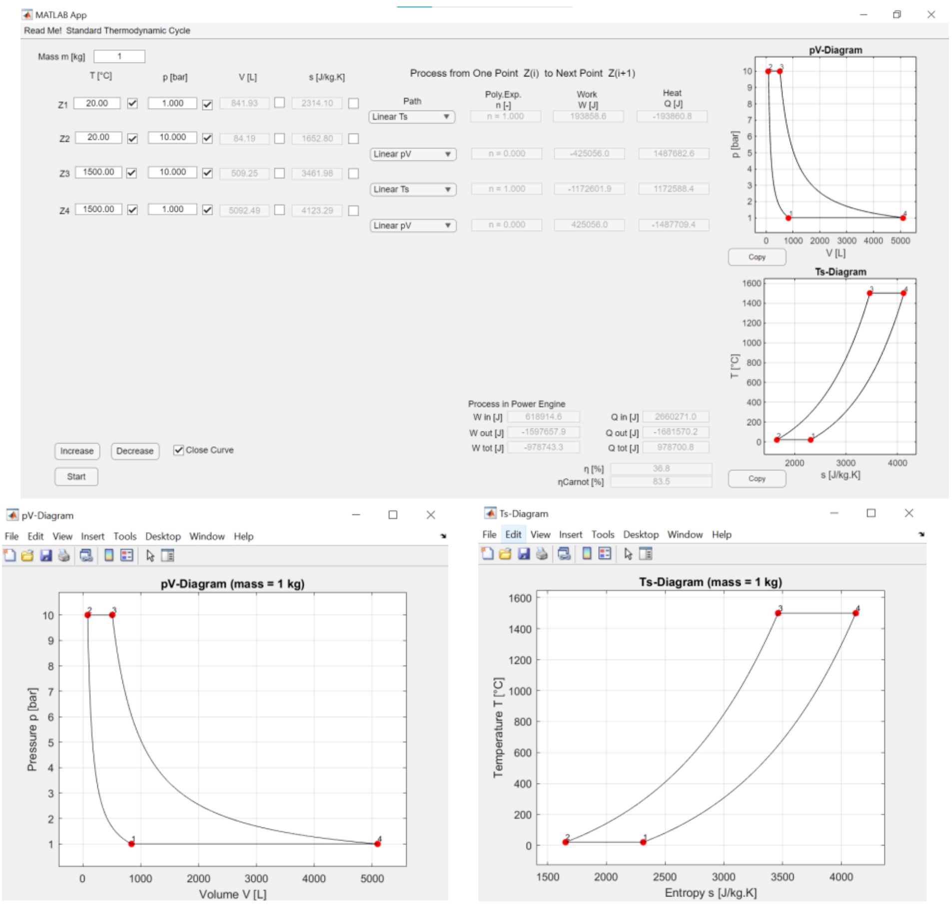


Figure 9 p-V and T-s Diagrams Ericsson Cycle

The Ericsson cycle is a thermodynamic cycle that operates with an external heat source and typically uses a regenerator to improve efficiency. It is similar to the Stirling cycle but with continuous flow of the working fluid. Ericsson cycles are used in some advanced gas turbines and cryogenic refrigeration systems.

The Ericsson cycle includes:

1) Isothermal Compression: The working fluid is compressed isothermally.
2) Isobaric Heat Addition: Heat is added at constant pressure.
3) Isothermal Expansion: The working fluid expands isothermally, performing work.
4) Isobaric Heat Rejection: Heat is rejected at constant pressure.

Benefits:

- High Efficiency: The use of isothermal processes and regeneration can achieve high thermal efficiencies.
- Versatility: It can operate with various heat sources, including solar and waste heat.

5. Joule (Brayton) Cycle

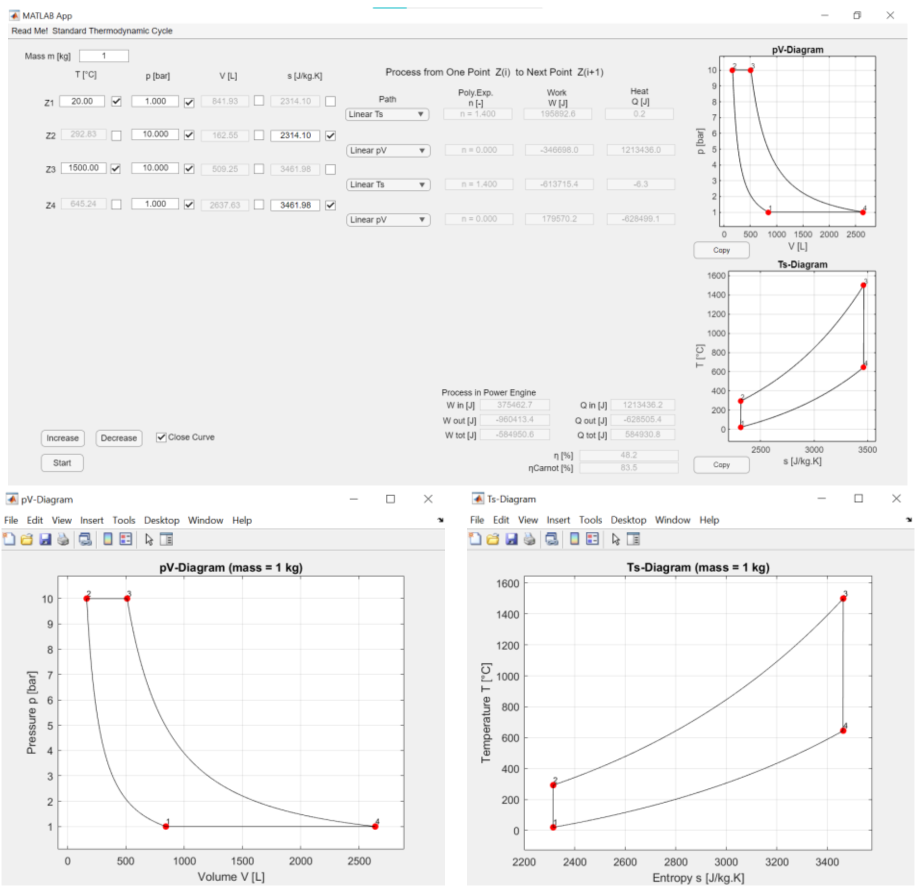


Figure 10 p-V and T-s Diagrams Joule Cycle

The Joule or Brayton cycle is a thermodynamic cycle used in gas turbines and jet engines. It involves continuous combustion and is ideal for high-speed applications. Joule cycle engines are used in jet engines, power plants, and gas turbines.

The Joule cycle consists of:

1) Isentropic Compression: Air is compressed adiabatically.
2) Isobaric Heat Addition: Fuel is burned at constant pressure.
3) Isentropic Expansion: The hot gases expand adiabatically, performing work.
4) Isobaric Heat Rejection: Heat is rejected at constant pressure.

Benefits:

- High Power Output: Suitable for high-speed and high-power applications like jet propulsion.
- Continuous Operation: Provides continuous power output, ideal for power generation.

6. Stirling Cycle

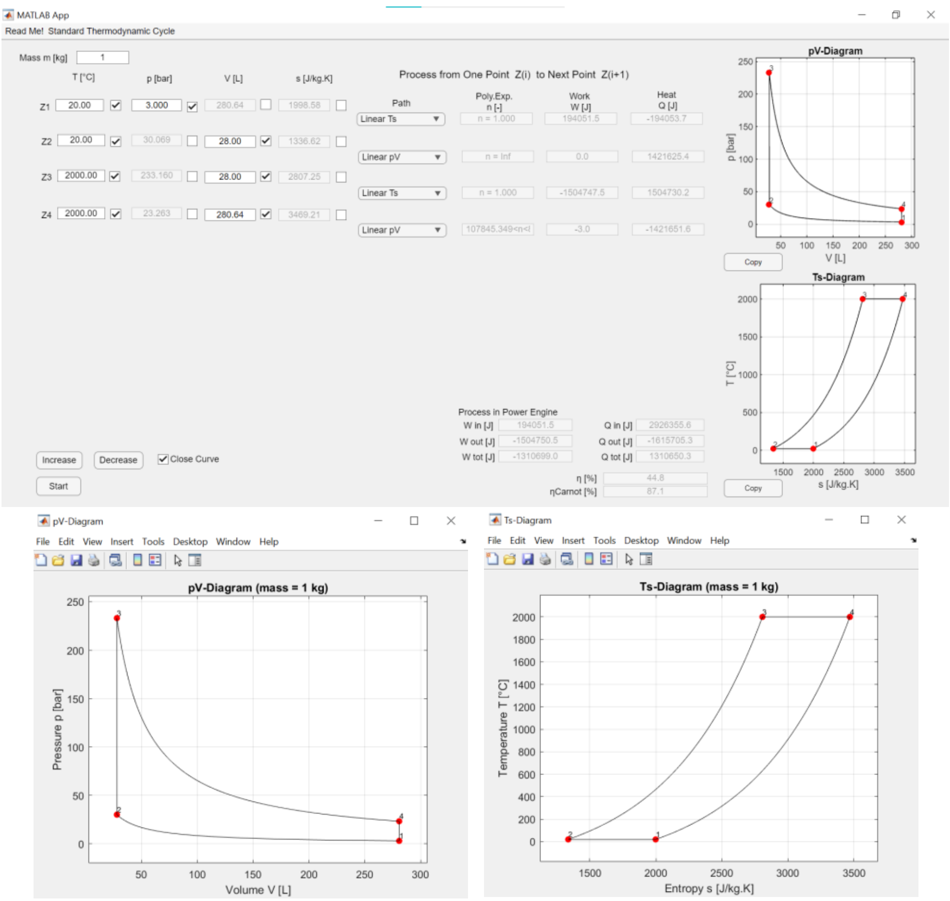


Figure 11 p-V and T-s Diagrams Stirling Cycle

The Stirling cycle is a closed-cycle regenerative heat engine that operates with an external heat source. It is known for its high efficiency and ability to use various heat sources. Stirling engines are used in low-power applications, such as solar power generation, and in situations where quiet operation is essential, like submarines.

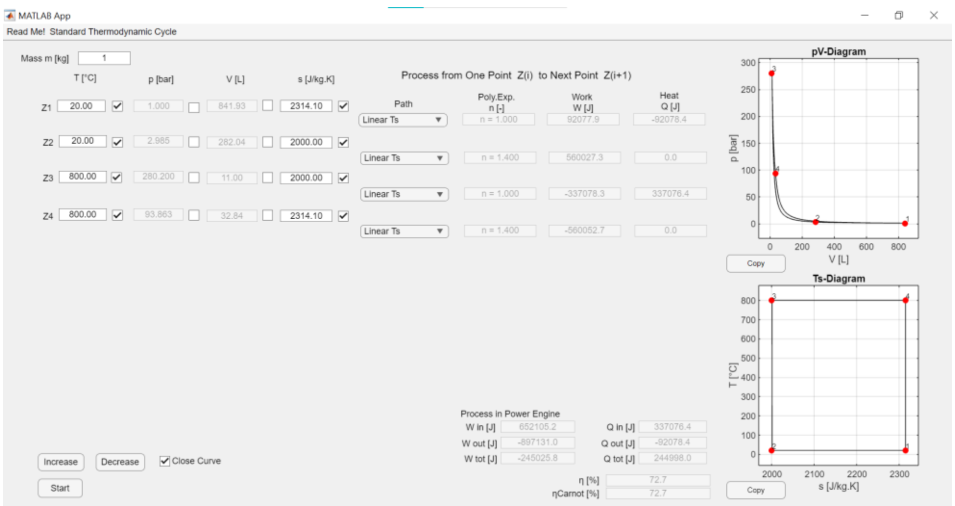
The Stirling cycle involves:

1) Isothermal Compression: The working fluid is compressed isothermally.
2) Isochoric Heat Addition: Heat is added at constant volume.
3) Isothermal Expansion: The working fluid expands isothermally, performing work.
4) Isochoric Heat Rejection: Heat is rejected at constant volume.

Benefits:

- High Efficiency: Can achieve efficiencies close to the Carnot cycle.
- Fuel Flexibility: Can use any heat source, including solar, geothermal, and waste heat.
- Quiet Operation: Ideal for applications requiring low noise levels.

7. Carnot Cycle



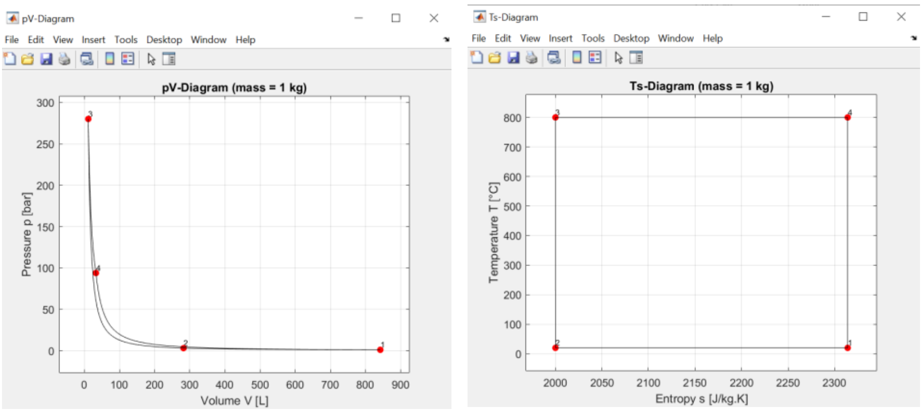


Figure 12 p-V and T-s Diagrams Carnot Cycle

The Carnot cycle is a theoretical thermodynamic cycle proposed by Sadi Carnot. It represents the maximum possible efficiency that any heat engine can achieve. While no real engine operates on the Carnot cycle, it serves as a benchmark for evaluating the efficiency of real thermodynamic cycles.

The Carnot cycle includes:

1) Isothermal Expansion: The working fluid expands isothermally, absorbing heat.
2) Isentropic Expansion: The fluid continues to expand adiabatically.
3) Isothermal Compression: The working fluid is compressed isothermally, rejecting heat.
4) Isentropic Compression: The fluid is further compressed adiabatically.

Benefits:

- Theoretical Benchmark: Defines the upper limit of efficiency for any heat engine.
- Guideline for Improvement: Helps engineers design more efficient engines by aiming to approach Carnot efficiency.

For more details on the Ericson and Stirling cycle development in MATLAB software, including challenges faced, please see Chapter 5. This chapter provides specific insights into how the cycle was implemented and addresses key technical considerations for anyone interested in replicating or extending this work.

4.2.2 Motivations on Developing Standard Thermodynamic Cycles

Developing software with pre-defined models of standard thermodynamic cycles significantly benefits both students and engineers. For students, it provides a ready-made framework, facilitating learning through interactive visualizations and dynamic diagrams. For engineers, the software streamlines the design and analysis of engines and power systems, allowing quick simulations, comparison of different cycles, and optimization of parameters.

4.2.3 Example Calculation of Mass Ratio Diesel Cycle

Accurate modelling of combustion processes is crucial for the development and optimization of various applications, including engines and industrial furnaces.

Calculating the Mass of Fuel m_f

The mass of fuel m_f can be determined using the formula:

$$m_f = \frac{Q}{Hu} \tag{4.1}$$

where:

Q is the heat energy provided,

Hu is the lower calorific value of the fuel, given as $42\ \frac{MJ}{kg}$.

Calculating Lambda λ

Lambda λ is the mass ratio of air to fuel and can be calculated using:

$$\lambda = \frac{m_a}{L_{min} \cdot m_f} \tag{4.2}$$

where:

m_a is the mass of air, assumed to be 1 kg for this calculation,

L_{min} is the stoichiometric air-fuel ratio, given as 14.

Example Calculation of Mass Ratio in the Diesel Cycle

Given the heat value between the second and third points is 1702431 J,

$$m_f = \frac{1702431\ J}{42 \cdot 10^6 \frac{J}{kg}} = 0.04\ kg$$

$$\lambda = \frac{m_a}{L_{min} \cdot m_f} = \frac{1\ kg}{14 \cdot 0.04\ kg} = 1{,}76$$

By substituting the calculated mass of fuel m_f into the lambda formula, we can determine the λ value. To illustrate the calculation, let's found out the specific value for the heat energy Q. By substituting Q into the mass of fuel formula, we derive m_f. Using this m_f value, we then calculate lambda λ. The goal is to achieve a λ value close to 1, indicating the data's precision and the model's accuracy. Deviations from unity in the λ value suggest potential inaccuracies in the input data or assumptions.

4.3 Verification of Software Functionality

Once the thermodynamic models are integrated into the software tool, thorough verification and validation procedures are conducted to ensure its functionality and accuracy.

1. **Verification Tests**

Unit Testing:

- Individual components of the calculation algorithm are tested to ensure correctness.

- Input validation routines and error handling mechanisms are validated to guarantee robustness.

Integration Testing:

- The interaction between the graphical user interface GUI and calculation components is tested.
- Data flow between different modules is evaluated to ensure seamless operation and real-time updates.

2. **Validation Tests**

Comparison with Known Results:

- The software tool's outputs are compared with known analytical solutions or benchmark problems.
- Any discrepancies between simulated results and established data are identified and addressed.

4.4 Discussion of Results

The discussion of results synthesizes findings from verification, usability testing, case studies, and test scenarios to evaluate the overall performance and effectiveness of the software tool. Key themes and patterns identified during testing are analysed to assess the tool's strengths and weaknesses. Recommendations for future enhancements and improvements are provided based on user feedback and observations, along with considerations for the tool's impact on thermodynamics education and student learning outcomes.

Key Findings

1. Accuracy and Reliability**:**
    - The tool provides almost accurate results for a wide range of thermodynamic processes.
    - Minor discrepancies with theoretical values are analysed and explained.
2. Usability:
    - Users find the tool intuitive and easy to navigate.
    - Suggestions for further improvements are noted for future iterations.
3. Educational Impact**:**
    - The tool enhances students' understanding of thermodynamic processes and the relationship between thermodynamic quantities through visualizations and real time graphical feedback.

- It serves as a valuable resource for supporting thermodynamics education in academic settings especially first part study of the course.

4. Practical Applications:
   - Engineers benefit from quick simulations and detailed analyses.
   - The tool facilitates design optimization and performance evaluation of thermodynamic systems.

4.4.1 Reason for Different Starting Pressures

In the study and application of thermodynamic cycles, the initial conditions of the working fluid play a crucial role in determining the efficiency and practicality of the cycle. One noticeable difference is that cycles such as Diesel, Otto, Seiliger, and Stirling often start at higher initial pressures (around 3 bar), while cycles like Joule (Brayton), Ericsson, and Carnot typically start at lower initial pressures (around 1 bar). This disparity in starting pressures can be attributed to various factors, including the nature of the cycle, the working conditions, and the desired outcomes in terms of efficiency and performance.

1. Diesel, Otto, Seiliger, and Stirling Cycles with Higher Initial Pressures (3 bar)

- Internal Combustion and High Compression Ratios

  Diesel, Otto, and Seiliger cycles are all internal combustion engine cycles. These cycles benefit from higher initial pressures because they rely on compressing the air-fuel mixture to a high degree before ignition. Higher initial pressures contribute to achieving higher compression ratios, which in turn improve thermal efficiency. In these cycles, starting at 3 bar helps in reaching the necessary conditions for efficient combustion and power output.

- Stirling Cycle and External Heating

  The Stirling cycle, although an external combustion engine, also starts at higher pressures to maintain a high mean effective pressure MEP throughout the cycle. This helps in achieving a greater work output per cycle. The higher initial pressure is necessary to ensure that the regenerative heating and cooling processes are effective, maintaining the cycle's high efficiency.

2. Joule (Brayton), Ericsson, and Carnot Cycles with Lower Initial Pressures (1 bar)

- Continuous Flow and Gas Turbine Applications

  The Joule (Brayton) cycle is typically used in gas turbines and jet engines, which operate under continuous flow conditions. These systems generally start at atmospheric pressure (1 bar) because they intake and compress air from the environment. Starting at 1 bar simplifies the design and integration with ambient air intake systems, making it more practical for continuous operation in various environments.

- Ericsson Cycle and External Combustion

  Similar to the Stirling cycle, the Ericsson cycle involves external heating. However, it operates on an open cycle with continuous intake and exhaust processes. Starting at 1 bar allows for straightforward integration with ambient air and continuous heat addition and rejection processes, which is essential for maintaining efficiency in a cycle that operates with isothermal processes.

- Carnot Cycle as a Theoretical Benchmark

  The Carnot cycle is a theoretical model representing the maximum possible efficiency of a heat engine operating between two temperature reservoirs. Starting at 1 bar for the Carnot cycle is a conventional choice for simplifying the theoretical analysis and making it comparable to real-world systems that often operate at atmospheric pressure. This choice underscores its role as a benchmark for evaluating the efficiency of other cycles.

4.4.2 Influence of Superheated Conditions

Superheated conditions can influence the initial pressures chosen for different cycles. In internal combustion engines (Diesel, Otto, Seiliger), the working fluid (air or air-fuel mixture) often reaches superheated states due to high compression ratios and combustion temperatures. Starting at higher pressures helps accommodate the high-temperature conditions required for efficient combustion.

In contrast, cycles like Joule (Brayton) and Ericsson, which involve continuous flow and often use air as the working fluid, manage superheated conditions differently. These cycles benefit from starting at atmospheric pressure and utilizing stages of compression and expansion to achieve the necessary temperatures for efficient operation without the need for initially high pressures.

4.4.3 Numerical Error

In the application, a numerical error has caused a slight discrepancy between the total work and heat in the closed-loop process. Originally, these values were expected to be precisely equal, but now differ by just two digits before the decimal point. Although this difference may seem small numerically, it signifies that the exact balance between work and heat cannot be achieved due to the computational error. Therefore, achieving equal values for work and heat in the tool's features is not feasible.

4.5 Analysis and Comparison of Thermodynamic Cycles: Carnot and Diesel

Students learn the fundamental principles of thermodynamics in college, acquiring the necessary theoretical knowledge. However, the application of this theory to real-life scenarios often reveals discrepancies and additional considerations. To bridge this gap in understanding, we will compare the Carnot and Diesel cycles, focusing on their p-V and T-s diagrams, as illustrated in textbooks, and simulated using MATLAB software tools.

The Carnot cycle is renowned for being the most efficient thermodynamic cycle. Figures 13 and 14 depict the p-V and T-s diagrams of the Carnot cycle from a textbook and a MATLAB simulation, respectively.

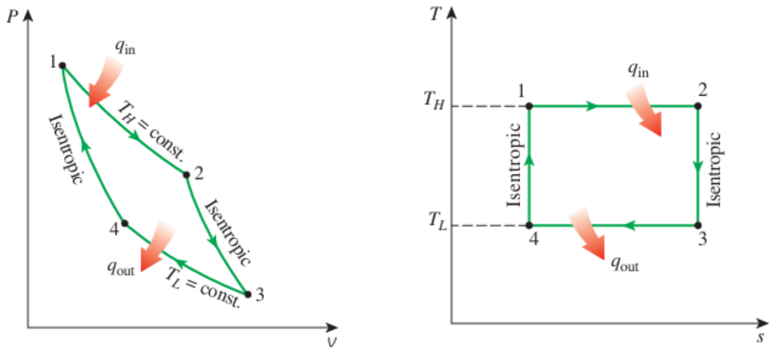


Figure 13 p-V and T-s Diagrams of Carnot Cycle (Textbook)

(Source: Çengel & Boles, 2014, p. 503)

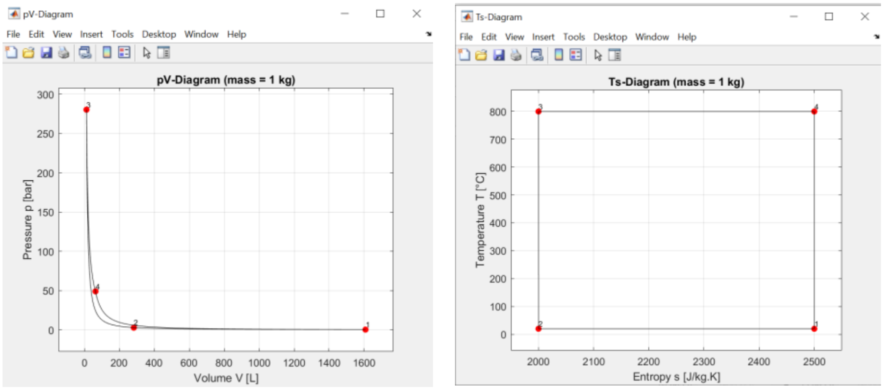


Figure 14 p-V and T-s Diagrams of Carnot Cycle (MATLAB Software Tool)

In the textbook, the diagrams are often exaggerated to facilitate understanding and visualization of the cycle's shape and processes. These diagrams illustrate the theoretical maximum efficiency that a heat engine can achieve, given by the temperature difference between the heat source and the sink. The area enclosed by the p-V diagram represents the work done by the system, which is a relatively small value due to the idealized nature of the cycle. In practical applications, various losses, such as friction, reduce the actual work output. Consequently, engines based on the Carnot cycle would require more fuel and incur higher operational costs to compensate for these losses.

The Diesel cycle, on the other hand, is less efficient than the Carnot cycle in theory. However, it generates significantly higher work output, as depicted in Figures 15 and 16, which show the p-V and T-s diagrams from a textbook and MATLAB simulation, respectively.

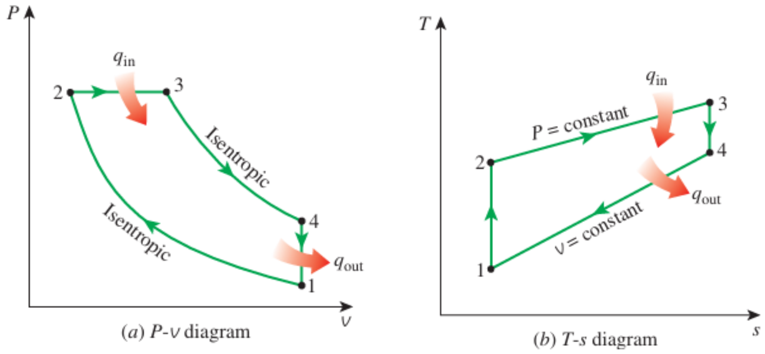


Figure 15 p-V and T-s Diagrams of Diesel Cycle (Textbook)

(Source: Çengel & Boles, 2014, p. 503)

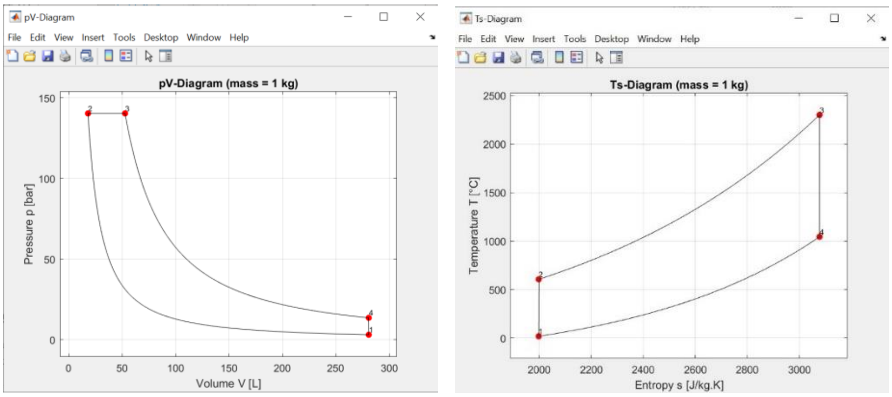


Figure 16 p-V and T-s Diagrams of Diesel Cycle (MATLAB Software Tool)

The area under the p-V diagram for the Diesel cycle represents a higher amount of work done compared to the Carnot cycle. This substantial work output helps cover the inevitable losses due to friction and other inefficiencies in a real engine. Thus, despite its lower theoretical efficiency, the Diesel cycle is more practical and cost-effective for real-world applications, as the relative impact of losses is minimized by the high-power output.

The comparison of the Carnot and Diesel cycles highlights the difference between theoretical efficiency and practical applicability. While the Carnot cycle serves as an ideal benchmark for efficiency, its practical implementation is hindered by significant losses and low work output. The Diesel cycle, although theoretically less efficient, proves more viable in real-world applications due to its higher work output and better compensation for operational losses. This analysis underscores the importance of considering practical factors alongside theoretical principles in thermodynamic applications.

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CHAPTER 5 ANALYSIS OF STANDARD PROCESS

In our pursuit of optimization and practical applicability within engineering education, we have selected the gas turbine as a case study for analysing a standard thermodynamic process. This choice is motivated by its significant relevance and widespread use in various industrial applications. Gas turbines are pivotal in power generation and propulsion systems due to their efficiency, scalability, and environmental considerations. Studying the gas turbine will provide valuable insights into thermodynamic cycles offering a foundational understanding that can be applied to broader engineering contexts and technological advancements.

5.1 Case Studies on Gas Turbine Processes

Gas turbines operate on the Brayton cycle, which consists of four primary processes: isentropic compression, isobaric combustion, isentropic expansion, and isobaric heat rejection. The performance of a gas turbine is influenced by factors such as compressor and turbine efficiencies, pressure ratios, and the properties of the working fluid. This section presents detailed case studies to illustrate these concepts.

Case Study 1: Industrial Gas Turbine for Power Generation

Diagram for Industrial Gas Turbine

Air Intake: Where ambient air enters the system.

Compressor: Increases the pressure of the air before entering the combustion chamber.

Combustion Chamber: Where fuel is burned at constant pressure.

Turbine: Converts the thermal energy of the expanding gases into mechanical energy to drive the compressor and external load.

Exhaust: Where the hot gases exit the system.

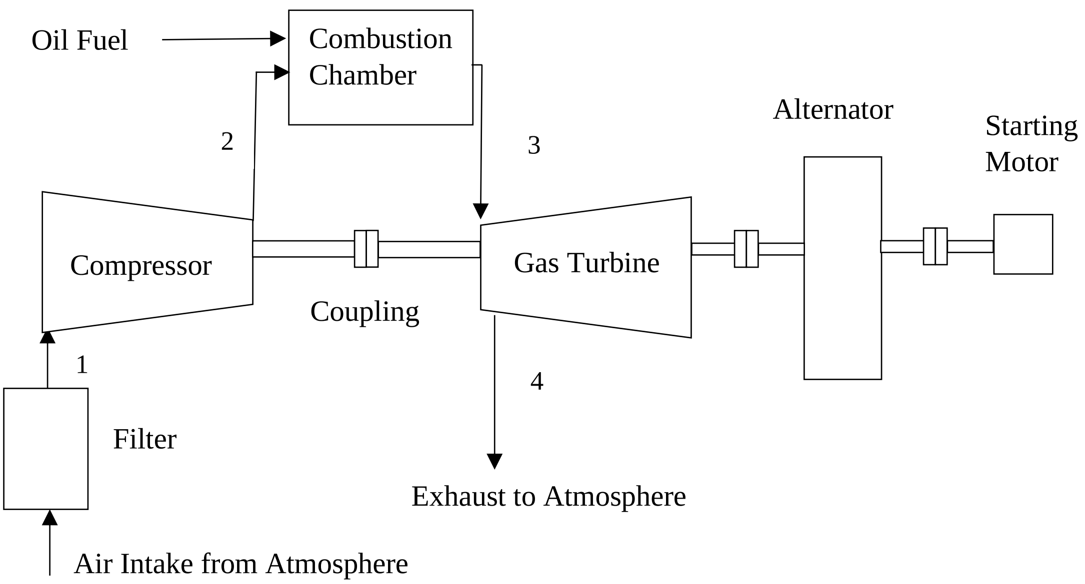

Figure 17 Gas Turbine Diagram

System Description

This case study examines an industrial gas turbine used for power generation. The turbine operates with a pressure ratio of 15:1, an inlet air temperature of 300 K, and a maximum cycle temperature of 1500 K. The compressor and turbine efficiencies are assumed to be 85% and 90%, respectively.

Performance Analysis

The analysis involves calculating the following key performance parameters:

Compressor Work W_c :

$$W_c = \frac{\frac{\gamma}{\gamma-1} \cdot R \cdot T_1 \cdot \left(\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)}{\eta_c} \quad (5.1)$$

Turbine Work W_t :

$$W_t = \frac{\gamma}{\gamma-1} \cdot R \cdot T_3 \cdot \left(\left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) \cdot \eta_t \quad (5.2)$$

Thermal Efficiency

$$\eta_{th} = \frac{|W_t - W_c|}{Q_{in}} \quad (5.3)$$

Where:

γ is the specific heat ratio (1,4 for air),

R is the specific gas constant for air,

T_1 and T_3 are the temperatures at the compressor inlet and turbine inlet, respectively,

p_1 and p_2 are the pressures at the compressor inlet and outlet, respectively,

p_3 and p_4 are the pressures at the turbine inlet and outlet, respectively

η_c and η_t are the efficiencies of the compressor and turbine.

Results and Discussion

The calculations yield the following results:

- Compressor work: 364 kJ/kg
- Turbine work: 1480 kJ/kg
- Thermal efficiency: 75,4 %

These results highlight the significant energy conversion capabilities of gas turbines, despite inherent inefficiencies in the compression and expansion processes. The thermal efficiency, although below the ideal Carnot efficiency, is typical for real-world gas turbines.

Case Study 2: Jet Engine for Aircraft Propulsion

Diagram for Jet Engine

Air Intake: Where ambient air enters the engine.

Fan/Compressor: Increases the pressure of the air before entering the combustion chamber.

Combustor: Where fuel is burned at constant pressure.

Turbine: Converts the thermal energy of the expanding gases into mechanical energy to drive the compressor and fan.

Exhaust Nozzle: Where the hot gases exit the engine to produce thrust.

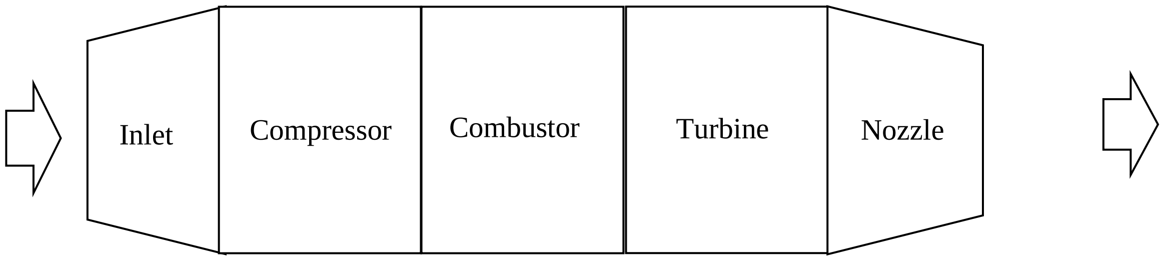

Figure 18 Jet Engine Diagram

System Description

This case study focuses on a jet engine used in commercial aircraft. The engine operates with a pressure ratio of 20:1, an inlet air temperature of 288 K, and a maximum cycle temperature of 1800 K. The compressor and turbine efficiencies are 87% and 92%, respectively.

Performance Analysis

Like the previous case study, the performance parameters are calculated using the respective equations for compressor work, turbine work, and thermal efficiency.

Results and Discussion

The calculations yield the following results:

- Compressor work: 634 kJ/kg
- Turbine work: 1074 kJ/kg
- Thermal efficiency: 40,95 %

The higher-pressure ratio and cycle temperature result in improved thermal efficiency compared to the industrial gas turbine. These improvements are essential for aircraft propulsion, where fuel efficiency and power-to-weight ratios are critical performance metrics.

5.2 Sensitivity Analysis Scenarios

Sensitivity analysis involves varying key input parameters to assess their impact on the overall performance of the gas turbine. This analysis helps identify critical factors that influence efficiency and output, guiding design improvements and operational adjustments.

Scenario 1: Varying Pressure Ratio

Analysis

The pressure ratio is varied from 10:1 to 25:1, and its effect on thermal efficiency is analysed. The relationship between pressure ratio and efficiency is given by the Brayton cycle efficiency equation:

$$\eta_{th} = 1 - \frac{1}{\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}} \qquad (5.4)$$

Results

The analysis shows that increasing the pressure ratio improves thermal efficiency. However, there is a diminishing return beyond a certain point, as mechanical and aerodynamic limitations of the compressor and turbine components come into play.

Scenario 2: Varying Inlet Air Temperature

Analysis

The inlet air temperature is varied from 250 K to 350 K. The impact on compressor work, turbine work, and thermal efficiency is evaluated. Lower inlet temperatures reduce the work required for compression, thus improving overall efficiency.

Results

The results indicate that lower inlet air temperatures lead to significant efficiency gains. This finding underscores the importance of cooling the inlet air, which is often achieved using intercoolers or air conditioning systems in practical applications.

Scenario 3: Varying Turbine Inlet Temperature

Analysis

The turbine inlet temperature is varied from 1200 K to 2000 K. Higher inlet temperatures increase the turbine work output, thereby enhancing thermal efficiency. However, material limitations and thermal stresses impose practical constraints.

Results

Increasing the turbine inlet temperature results in higher thermal efficiency, but the improvements are constrained by the material properties of turbine blades and components. Advances in high-temperature materials and cooling techniques are essential to achieve higher operating temperatures.

Discussion

The sensitivity analysis highlights the critical parameters affecting gas turbine performance. Pressure ratio, inlet air temperature, and turbine inlet temperature are key factors that influence efficiency and output. The analysis provides valuable insights for optimizing gas turbine design and operation, balancing efficiency gains with practical limitations.

The sensitivity analysis underscores the critical role of pressure ratio, inlet air temperature, and turbine inlet temperature in influencing gas turbine performance. Optimizing these parameters is crucial for maximizing efficiency while balancing operational constraints and engineering limitations. Practical applications often involve trade-offs between efficiency gains and technological feasibility, driving continuous advancements in turbine design and operational strategies. By revisiting these scenarios, we ensure a comprehensive understanding of how each parameter impacts gas turbine performance and efficiency, offering insights for future improvements in gas turbine technology and operation.

5.3 Challenges and Limitations

While the developed software tool enhances understanding and facilitates the analysis of gas turbine processes, several challenges and limitations are worth noting. These challenges are integral to both the accurate modelling of thermodynamic processes and the practical application of the tool in educational contexts. The primary challenges include:

1. Modelling Complexity: Accurately modelling thermodynamic processes in gas turbine systems is complex due to non-ideal behaviours and transient effects. These factors can significantly impact the precision of simulations and analyses.

2. Model Assumptions: The accuracy of the results is heavily influenced by the underlying thermodynamic models and assumptions. Simplifications and idealizations, often necessary for computational feasibility, can introduce errors.

3. Computational Efficiency and Usability: The efficiency of the software and the design of its user interface are critical for its usability, especially in educational settings. Slow computations and a non-intuitive interface can hinder the learning process.

Addressing these challenges requires continuous refinement and optimization of the software tool based on feedback from users and educators. By acknowledging these challenges, the aim is to enhance the utility and impact of the software tool in thermodynamics education.

5.3.1 Challenges Encountered with Stirling and Ericsson Cycles

The Stirling and Ericsson cycles present unique challenges due to their reliance on regeneration for achieving theoretical efficiencies depicted in standard thermodynamic diagrams. These cycles are characterized by their theoretical high efficiency, which approaches the Carnot efficiency. However, achieving this efficiency is contingent upon the implementation of a regenerator—a device crucial for capturing waste heat from one part of the cycle and reusing it in another.

Stirling Cycle

The inclusion of a regenerator in the Stirling cycle allows for significant heat exchange between the high-temperature and low-temperature parts of the cycle, thereby improving efficiency. However, without an effective regenerator, the cycle cannot achieve the high efficiencies depicted in theoretical models.

Challenges include:

- Designing an efficient regenerator capable of capturing and reusing waste heat.
- Accurately modelling the heat transfer processes within the regenerator.

Ericsson Cycle

Like the Stirling cycle, it relies on a regenerator to attain high efficiency. The regenerator stores heat from the isothermal expansion process and releases it during the isothermal compression process, thus reducing the net heat input required.

Challenges include:

- Integrating a regenerator that can effectively handle the heat transfer demands of the cycle.
- Ensuring the regenerator's performance is accurately reflected in the cycle's efficiency calculations.

5.3.2 Challenge Statement

The primary challenge addressed in this thesis is the difficulty of accurately modelling and analysing these cycles without a detailed and practical implementation of the regenerator. The regenerator's presence and efficiency are critical to the accurate depiction of these cycles, as shown in thermodynamic diagrams and models.

Due to the complexity of designing and integrating an efficient regenerator, as well as the need for extensive experimental validation, this aspect has proven to be beyond the scope of the current thesis. Addressing the full implementation and analysis of the regenerator within the Stirling and Ericsson cycles requires a dedicated investigation that involves both theoretical modelling and practical experimentation.

5.3.3 Future Work

Given the time constraints and the scope of the current work, a comprehensive analysis of the regenerator's impact on these cycles is postponed. This important topic is recommended for future research, which could form the basis of another thesis. Future work should focus on:

- Theoretical Modelling: Develop detailed theoretical models of regenerators, considering various design configurations and materials.
- Experimental Validation: Conduct experiments to validate the performance of regenerators and their impact on cycle efficiency.

- Simulation Integration: Integrate validated regenerator models into simulations of Stirling and Ericsson cycles to provide a more accurate depiction of their performance.
- Comparative Analysis: Perform comparative analyses of different regenerator types and configurations to identify optimal designs for specific applications.

By deferring this complex problem to future research, the current thesis maintains focus on achievable objectives and lays the groundwork for advancements in understanding these cycles.

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CHAPTER 6 CREATE AND ANALYSIS OF NON-STANDARD PROCESS

The chapter aim is to explore and analyse non-standard thermodynamic processes, allowing students to construct arbitrary cycles and investigate their thermodynamic properties. Through an interactive application, students can manipulate these cycles graphically, observing how adjustments affect efficiency and performance metrics. Initially, two distinct processes, labelled as Process A and Process B, are introduced to illustrate the variability in thermodynamic cycles and demonstrate how different configurations impact efficiency and operational characteristics. This approach equips students with practical insights into the complexities of non-standard cycles and their relevance in engineering contexts.

In theoretical thermodynamics, two hypothetical processes are often used to illustrate key concepts about work and efficiency. These processes, while not practical for real engines, serve as valuable educational tools. Process A demonstrates a scenario where the total work output is very large, but the efficiency is extremely low. Due to its low efficiency, this process is not feasible for practical applications, and no manufacturer would design an engine based on it. Process B, on the other hand, exemplifies a situation with very high efficiency but very low total work output. Despite its high efficiency, the minimal work produced makes this process impractical for real-world engines, and manufacturers would avoid designing such an engine. By studying these two extreme cases, students can gain a deeper understanding of how manipulation of different parameters affects the overall performance and feasibility of thermodynamic processes. This exercise helps illustrate the trade-offs between work and efficiency, enhancing comprehension of fundamental thermodynamic principles.

The blue line graph (after the manipulation) serves as the baseline or starting point for both processes A and B. This initial graph provides essential data that forms the foundation for interpreting subsequent manipulations and changes shown in the plotted graphs. By referring to the blue line graph, analysts can effectively track how the data has been modified or transformed over time or through different conditions in both processes. This comparison allows for a detailed understanding of the trends, variations, or impacts depicted in the manipulated graphs, offering insights into the progression or transformation of the data from its original state for both processes A and B.

6.1 Initial Process A

Process A is defined to investigate the effects of altering the shape of the p-V diagram on work and efficiency. Initially represented as a rectangular process on the p-V diagram, variations in its shape and dimensions are studied to understand their impact on thermodynamic performance.

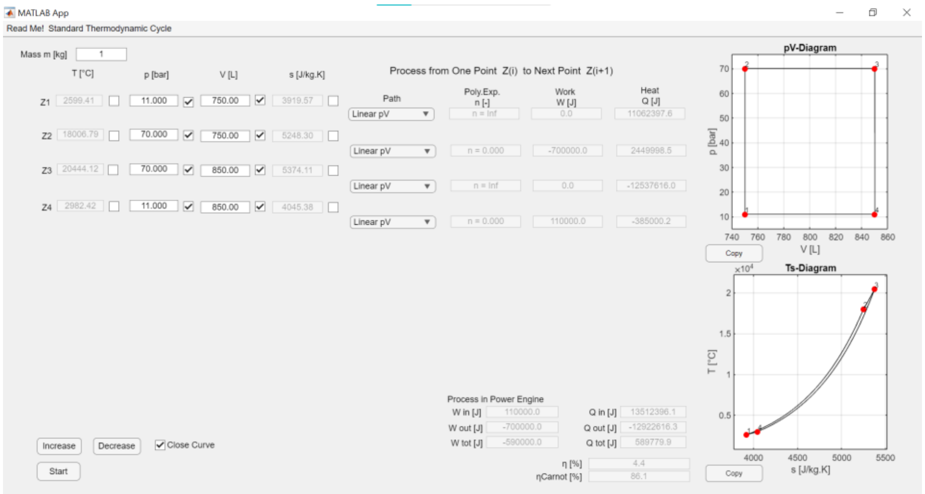

Figure 19 Initial Process A

- First Manipulation: Stretching in Volume Direction

This manipulation involves adjusting the volume axis of the p-V diagram while narrowing the pressure range. Initially, the diagram spanned a wide range of pressures and volumes. After manipulation, the pressure range was reduced, while the volume range was expanded. This adjustment allows us to observe how changes in volume impact work output and efficiency while maintaining a narrower range of pressure values for analysis. By focusing on these changes, students can better understand the relationship between volume and work output, and how efficiency is affected by variations in pressure and volume within thermodynamic processes.

Table 1 First Manipulation Data of Process A

Process A		Initial	First Manipulation
p [bar]	1	11	21
	2	70	60
	3	70	60
	4	11	21
V [L]	1	750	700
	2	750	700
	3	850	900
	4	850	900

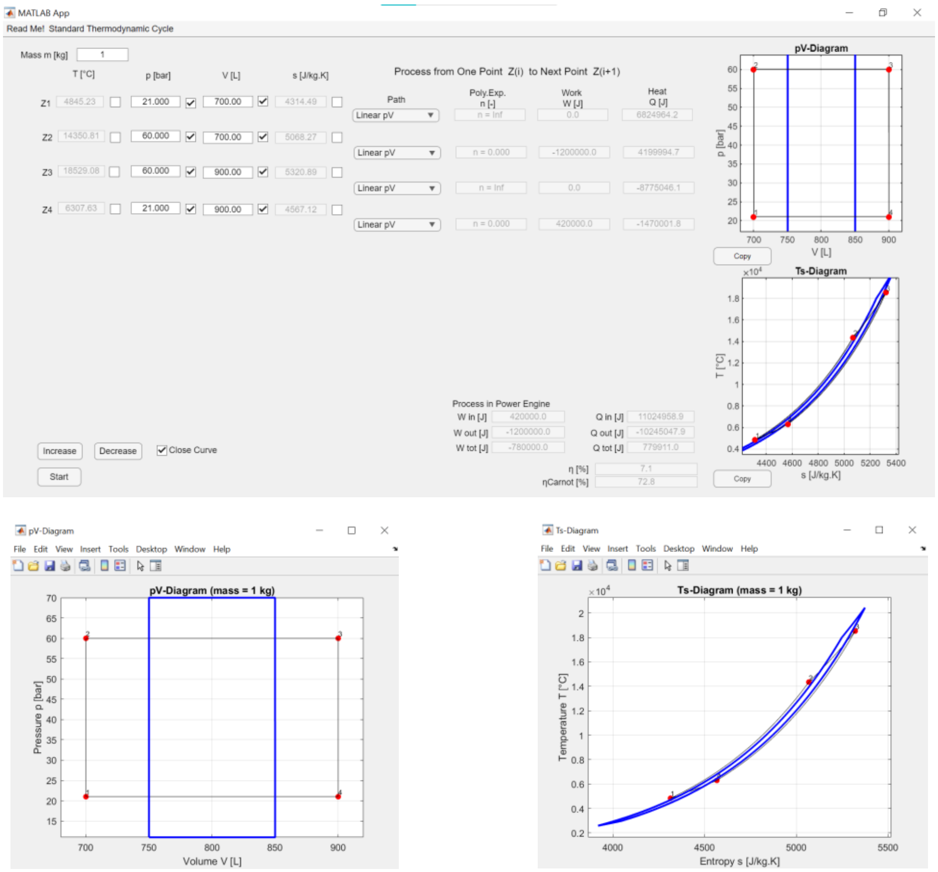

Figure 20 Process A First Manipulation

- Second Manipulation: Stretching in Pressure Direction

Here, the pressure axis of the p-V diagram is adjusted while narrowing the volume range. After manipulation, the pressure range was expanded, while the volume range was reduced. This adjustment allows us to analyse how variations in pressure influence work output and efficiency, while maintaining a constant volume for comparative analysis. By focusing on these changes, students can better understand the relationship between pressure and work output, and how efficiency is affected by variations in pressure and volume within thermodynamic processes.

Table 2 Second Manipulation Data of Process A

Process A		Initial	Second Manipulation
p [bar]	1	11	1
	2	70	80
	3	70	80
	4	11	1
V [L]	1	750	775
	2	750	775
	3	850	825
	4	850	825

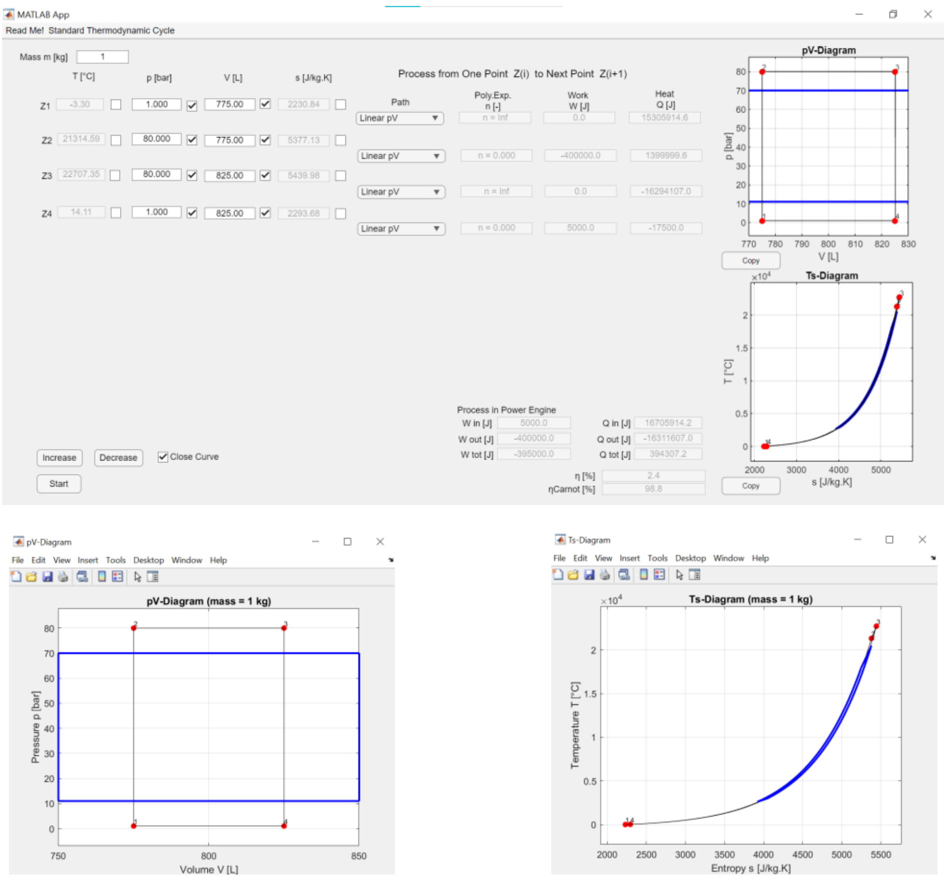

Figure 21 Process A Second Manipulation

- Third Manipulation: Stretching in Clockwise Direction

  This manipulation involves proportionally stretching both the pressure and volume axes of the p-V diagram in a clockwise direction. This adjustment maintains the proportional relationship between pressure and volume while expanding their ranges. By doing so, we can systematically examine how simultaneous variations in pressure and volume impact thermodynamic performance. This focused analysis specifically aims to elucidate changes in efficiency under varying conditions of pressure and volume within the system. Through this approach, students can gain a deeper understanding of how adjustments in both pressure and volume influence the efficiency of thermodynamic processes.

Table 3 Third Manipulation Data of Process A

Process A		Initial	Third Manipulation
p [bar]	1	11	1
	2	70	60
	3	70	80
	4	11	21
V [L]	1	750	700
	2	750	775
	3	850	900
	4	850	825

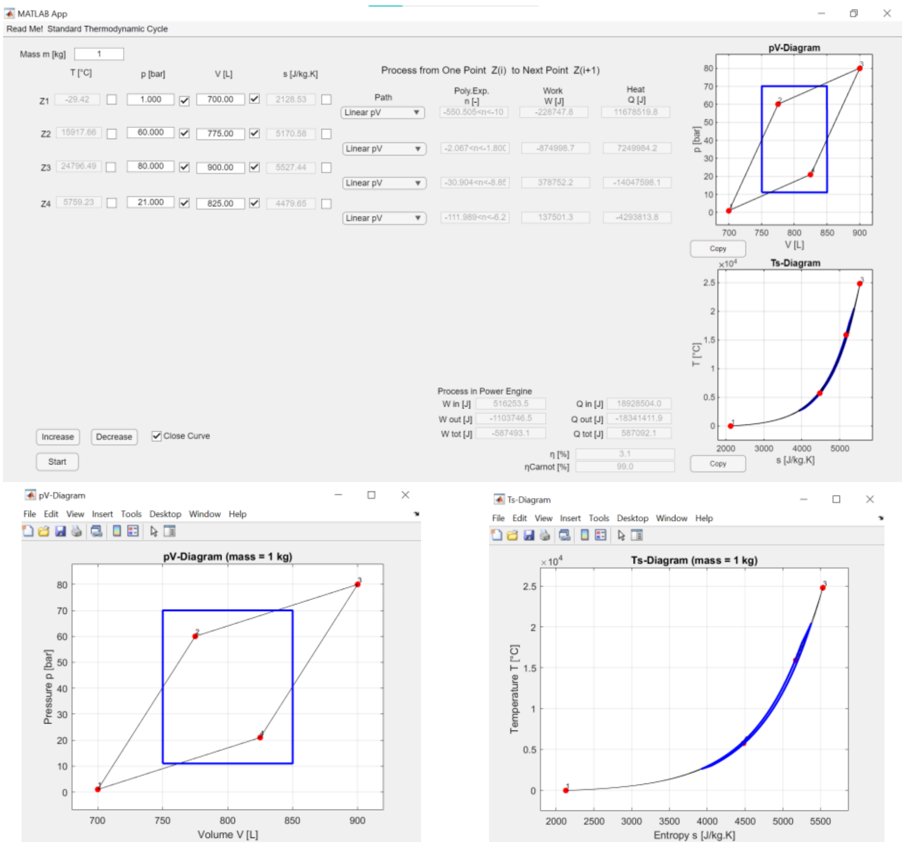

Figure 22 Process A Third Manipulation

- Fourth Manipulation: Stretching in Counter-Clockwise Direction

In this scenario, the pressure and volume axes of the p-V diagram are adjusted counter-clockwise while maintaining their proportional relationship. This manipulation explores how coordinated changes in pressure and volume influence both work output and efficiency in thermodynamic systems. Studying these variations helps illustrate how adjustments in pressure and volume interact to affect the overall performance of engines and other thermodynamic processes, essential for optimizing practical applications in engineering.

Table 4 Fourth Manipulation Data of Process A

Process A		Initial	Fourth Manipulation
p [bar]	1	11	21
	2	70	80
	3	70	60
	4	11	1
V [L]	1	750	775
	2	750	700
	3	850	825
	4	850	900

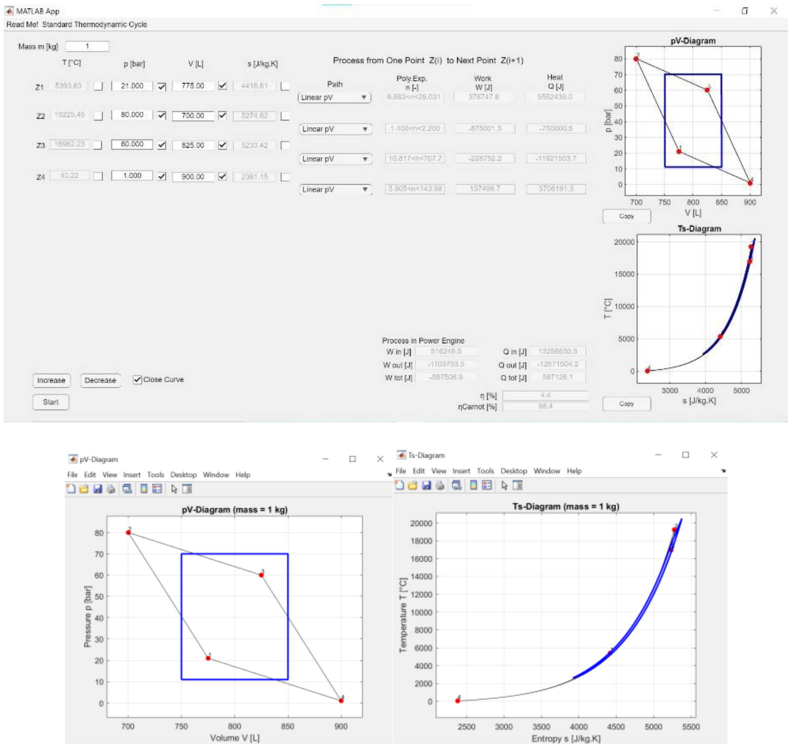

Figure 23 Process A Fourth Manipulation

This chapter systematically explores how manipulating the geometric properties of the p-V diagram shapes influence the thermodynamic behaviour of processes. By stretching the diagram to alter both pressure and volume while maintaining their proportional relationship, we observe how these changes impact work output and efficiency. This analysis is crucial for understanding the practical implications of non-standard cycles in engineering applications and identifying optimal conditions that maximize efficiency in thermodynamic systems.

6.2 Initial Process B

Process B is defined to explore the thermodynamic effects of altering the shape of the T-s diagram, contrasting with Process A's focus on the p-V diagram. Initially represented as a rectangular process on the T-s diagram, Process B allows for the examination of how variations in its shape and dimensions influence thermodynamic performance.

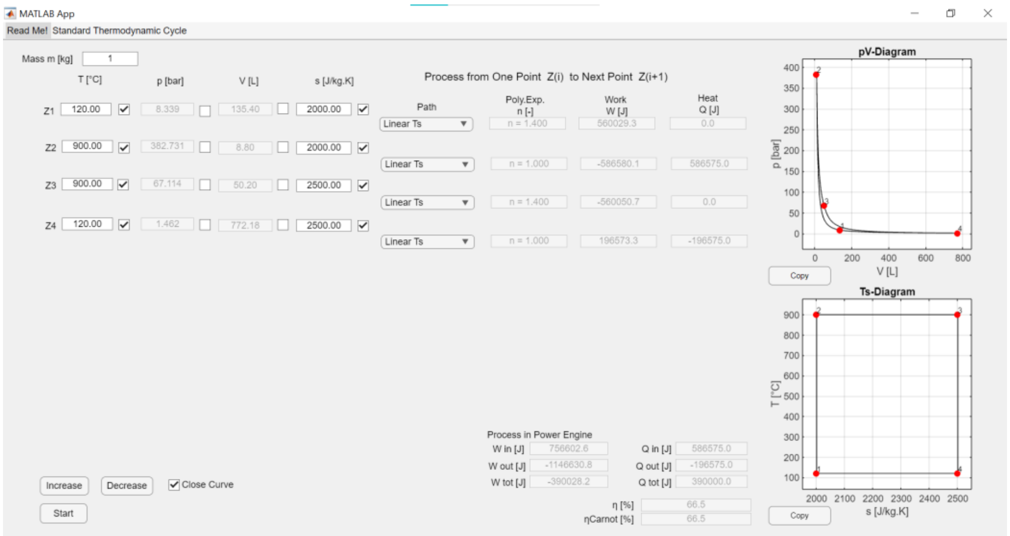

Figure 24 Initial Process B

- First Manipulation: Stretching in Entropy Direction

This manipulation involves adjusting the entropy axis of the T-s diagram while allowing temperature to vary. By stretching the diagram in the entropy direction, the range of entropy values is expanded. This adjustment enables a focused examination of how changes in entropy influence work output and efficiency within the thermodynamic system. Despite temperature fluctuations across a reduced range, the expanded entropy axis facilitates a detailed analysis of thermodynamic performance based on entropy variations.

Table 5 First Manipulation Data of Process B

Process B		Initial	First Manipulation
T [°C]	1	120	220
	2	900	800
	3	900	800
	4	120	220
s [J/kg·K]	1	2000	1750
	2	2000	1750
	3	2500	2750
	4	2500	2750

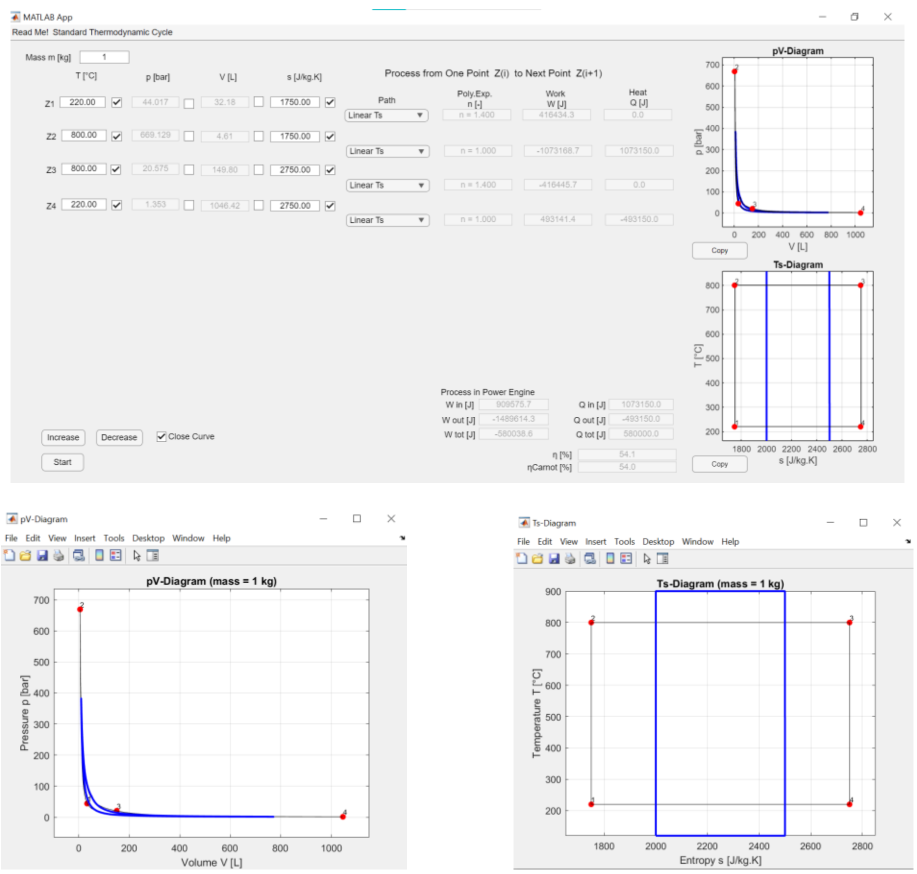

Figure 25 Process B First Manipulation

- Second Manipulation: Stretching in Temperature Direction

Here, the temperature axis of the T-s diagram is adjusted while allowing entropy to vary. Stretching the diagram in the temperature direction expands the temperature range while observing changes in entropy within a constrained range. This manipulation facilitates an analysis of how variations in temperature affect work output and efficiency. By expanding the temperature axis while maintaining a limited entropy range, the impact of temperature variations on thermodynamic processes can be systematically examined.

Table 6 Second Manipulation Data of Process B

Process B		Initial	Second Manipulation
T [^{o}C]	1	120	20
	2	900	1000
	3	900	1000
	4	120	20
s [J/kg·K]	1	2000	2125
	2	2000	2125
	3	2500	2375
	4	2500	2375

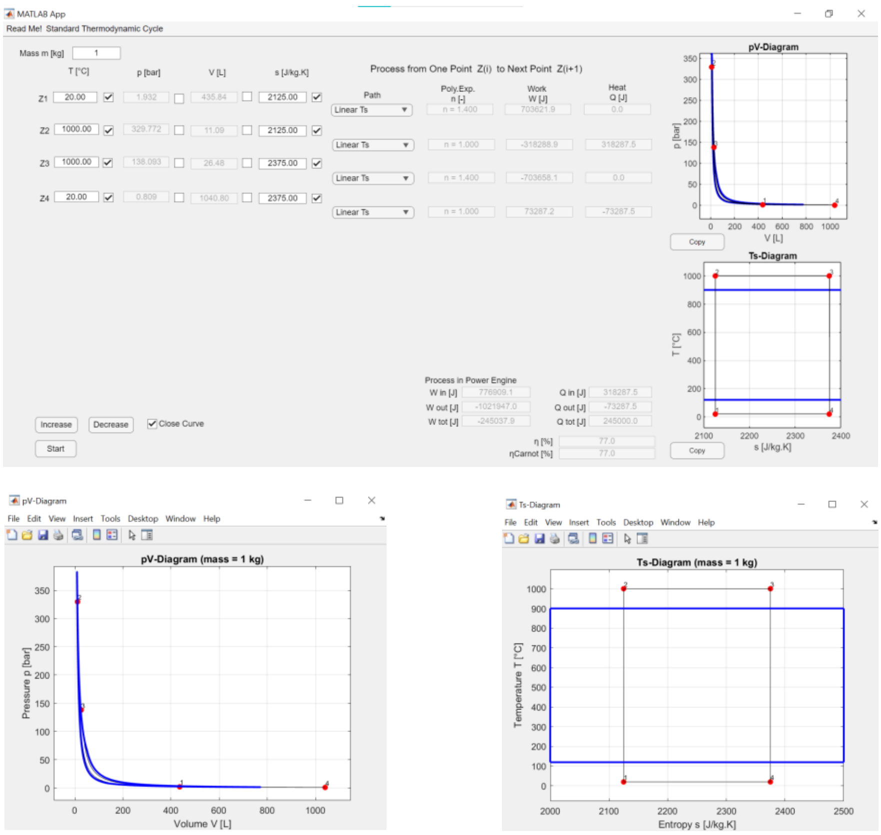

Figure 26 Process B Second Manipulation

- Third Manipulation: Stretching in Clockwise Direction

This manipulation involves stretching both the entropy and temperature axes of the T-s diagram in a clockwise direction, preserving their proportional relationship. By expanding the diagram in this manner, the combined variations in entropy and temperature are analyzed to understand their collective influence on thermodynamic performance. This approach allows for a comprehensive examination of how changes in both entropy and temperature interact to affect work output and efficiency across the system.

Table 7 Third Manipulation Data of Process B

Process B		Initial	Third Manipulation
T [^{o}C]	1	120	20
	2	900	800
	3	900	1000
	4	120	220
s [J/kg·K]	1	2000	1750
	2	2000	2125
	3	2500	2750
	4	2500	2375

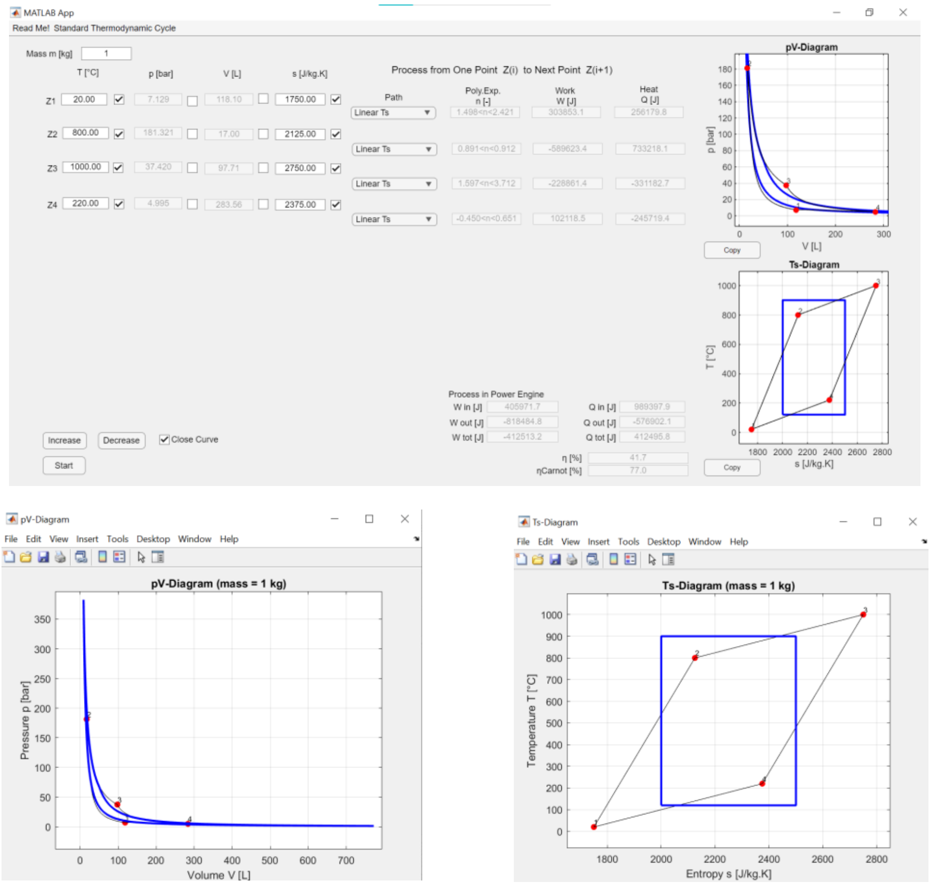

Figure 27 Process B Third Manipulation

- Fourth Manipulation: Stretching in Counterclockwise Direction

In this scenario, the entropy and temperature axes of the T-s diagram are adjusted in a counterclockwise manner while maintaining their proportional relationship. This manipulation explores the effects of counterclockwise variations in entropy and temperature on work output and efficiency within the thermodynamic system. By stretching the diagram in this direction, while preserving their relative proportions, it facilitates a detailed exploration of how alterations in both entropy and temperature individually and collectively impact thermodynamic performance.

Table 8 Fourth Manipulation Data of Process B

Process B		Initial	Fourth Manipulation
T [°C]	1	120	20
	2	900	800
	3	900	1000
	4	120	220
s [J/kg·K]	1	2000	1750
	2	2000	2125
	3	2500	2750
	4	2500	2375

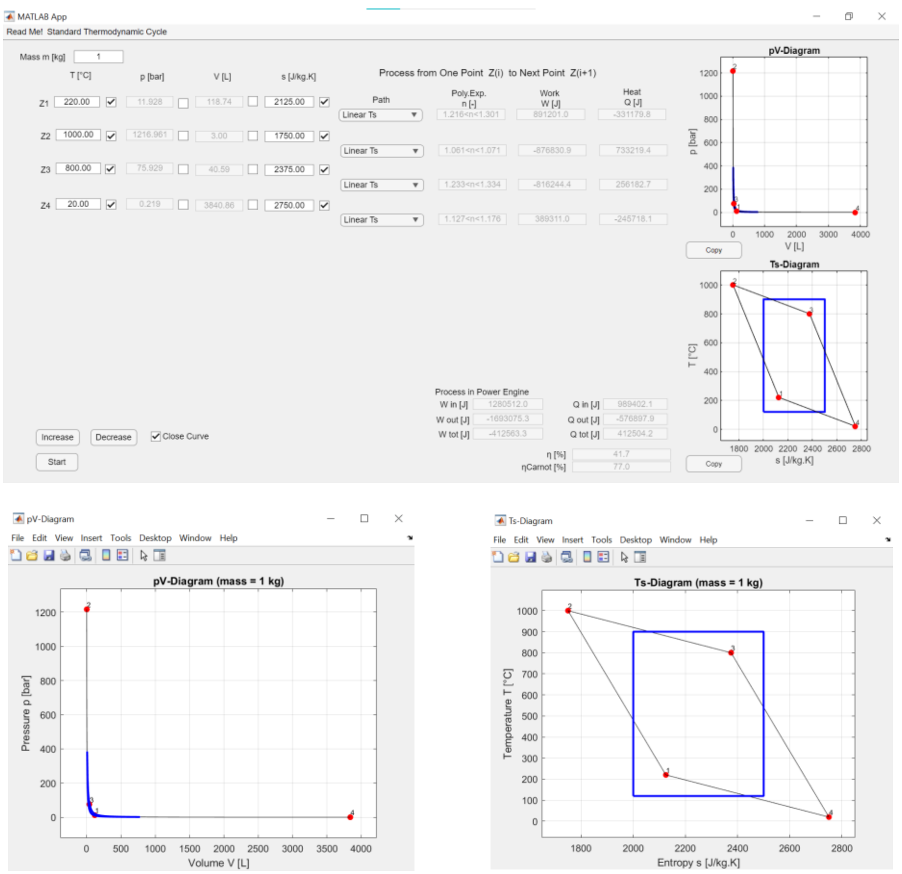

Figure 28 Process B Fourth Manipulation

By systematically exploring these manipulations, this chapter aims to provide insights into how the geometric properties of the T-s diagram shape influence the thermodynamic behaviour of processes. This analysis is essential for understanding the practical implications of non-standard cycles in engineering applications.

6.3 Overview of Process A and B Analysis with Discussion

The table below provides a detailed comparison of all conclusions and efficiency data from both processes A and B, capturing the results before and after manipulations were applied. It showcases how each process performed initially, highlighting any variations or improvements observed following the manipulations. This comprehensive analysis allows for a clear understanding of the impact these manipulations had on the efficiency and outcomes of the processes, facilitating informed decision-making based on the presented data.

Table 9 All Results of Process A and Process B

Data	A		B	
Process Manipulation	W_{tot} [kJ]	η [%]	W_{tot} [kJ]	η [%]
Initial	590	4,4	390	66,5
First	780	7,1	580	54,1
Second	395	2,4	245	77
Third	587	3,1	413	41,7
Fourth	588	4,4	413	41,7

Based on the analyses of processes A and B shown in table above, it is evident that process B exhibits higher efficiency compared to process A. This finding indicates that a rectangular shape defined on the p-V diagram does not yield as high efficiency as observed on the T-s diagram. Among the four manipulations or stretches conducted on the initial process, process A achieves its highest efficiency during the first manipulation, while process B reaches its peak efficiency during the second manipulation. It is important to note, however, that despite process B demonstrating higher efficiency, it generates less work output than process A. Therefore, the choice between optimizing for work output or efficiency depends on the specific requirements of the application.

CHAPTER 7 CONCLUSION AND RECOMMENDATION

7.1 Conclusion

In conclusion, the development of this educational simulator for analysing stationary thermodynamic processes marks a significant advancement in engineering education, effectively addressing the problem statement and objectives outlined. The software provides students with an interactive platform to explore complex thermodynamic concepts dynamically. By integrating GUI components such as p-V and T-s diagrams, the tool facilitates the visualization of thermodynamic processes and enhances parameter manipulation.

This simulator empowers students by enabling them to specify and instantly evaluate thermodynamic parameters, fostering a deeper understanding through interactive learning experiences. By engaging in practical thermodynamic analysis and process design, students gain valuable skills essential for tackling real-world engineering challenges. The implementation of user-friendly functionalities allows input of process changes via mouse or keyboard, with real-time display of corresponding paths and calculation of values, fulfilling the research objectives.

The case studies on gas turbine processes underscore the tool's versatility and effectiveness in simulating and assessing various operational scenarios. Leveraging thermodynamic models and visualization techniques, students gain insights into gas turbine behaviour and performance, enhancing their comprehension of fundamental thermodynamic principles. Furthermore, the thorough exploration and analysis of non-standard thermodynamic cycles emphasize how changes in the shapes of p-V and T-s diagrams affect thermodynamic performance.

Through the study of processes A and B, students gain insights into how different cycle configurations impact efficiency and work output. These findings underscore the importance of tailoring thermodynamic cycles to optimize either work output or efficiency, depending on specific operational needs in engineering applications. This understanding is crucial for maximizing the performance of thermodynamic systems in real-world scenarios.

In summary, the objectives of integrating p-V and T-s diagrams into a GUI, implementing user-controlled input for limit values, applying suitable thermodynamic models, and creating effective training scenarios through sensitivity analysis have been successfully achieved. This educational simulator serves as a powerful tool for enhancing students' learning experiences and preparing them for real-world engineering challenges.

7.2 Future Enhancement and Recommendations

Moving forward, several enhancements and recommendations can further elevate the educational impact and usability of the simulator:

1. Expansion of Thermodynamic Models: Investigate additional models to support a broader range of analyses and educational goals effectively.

2. Improved User Interaction: Enhance user interaction features and GUI design for a more intuitive and seamless user experience.
3. Integration of Advanced Simulation Techniques: Incorporate advanced techniques like transient analysis and dynamic simulations to simulate real-world thermodynamic processes more accurately.
4. Feedback Mechanisms: Establish mechanisms for gathering user and educator feedback to continuously refine and improve the software tool based on educational needs.
5. Integration with Educational Platforms: Integrate the tool with existing educational platforms or learning management systems to facilitate seamless incorporation into curriculum delivery and assessment processes.

Addressing these enhancements will not only improve the simulator's functionality but also enrich students' learning experiences in thermodynamics, preparing them comprehensively for practical engineering challenges.

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