DESIGN AND DEVELOPMENT OF TURBOCHARGER BASED BRAYTON CYCLE

A Final Year Project Report
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In Partial Fulfillment
of the Requirements for the Degree of
Bachelor of Mechanical Engineering

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ABSTRACT

This study investigated the design and development of a high-efficiency Brayton cycle engine, prioritizing a compact footprint. This objective focuses on three key areas: turbocharger selection, combustor design, and comprehensive performance analysis.

The selection of the turbocharger involved a rigorous evaluation of available models to identify the option delivering the optimal pressure ratio and airflow for the desired power output. Subsequently, the combustor design opted for a non-premixed configuration, offering advantages in terms of fuel versatility and potential NOx emission reduction. Using SolidWorks software, a simpler and optimized 3D model was created, prioritizing efficient fuel-air mixing and stable flame propagation within the compact constraints.

To gain detailed insights into the non-premixed combustion process, the project utilized advanced ANSYS simulations. These simulations enabled profound analysis of critical parameters such as temperature distribution, pollutant formation, and overall combustion efficiency.

In conclusion, this project successfully demonstrated the feasibility of developing a simple, compact, and potentially highly efficient Brayton cycle engine by employing a carefully selected turbocharger and a well-designed non-premixed combustor. Further refinements and experimental testing are recommended to validate the simulation results and further optimize the design for real-world applications.

ACKNOWLEDGMENTS

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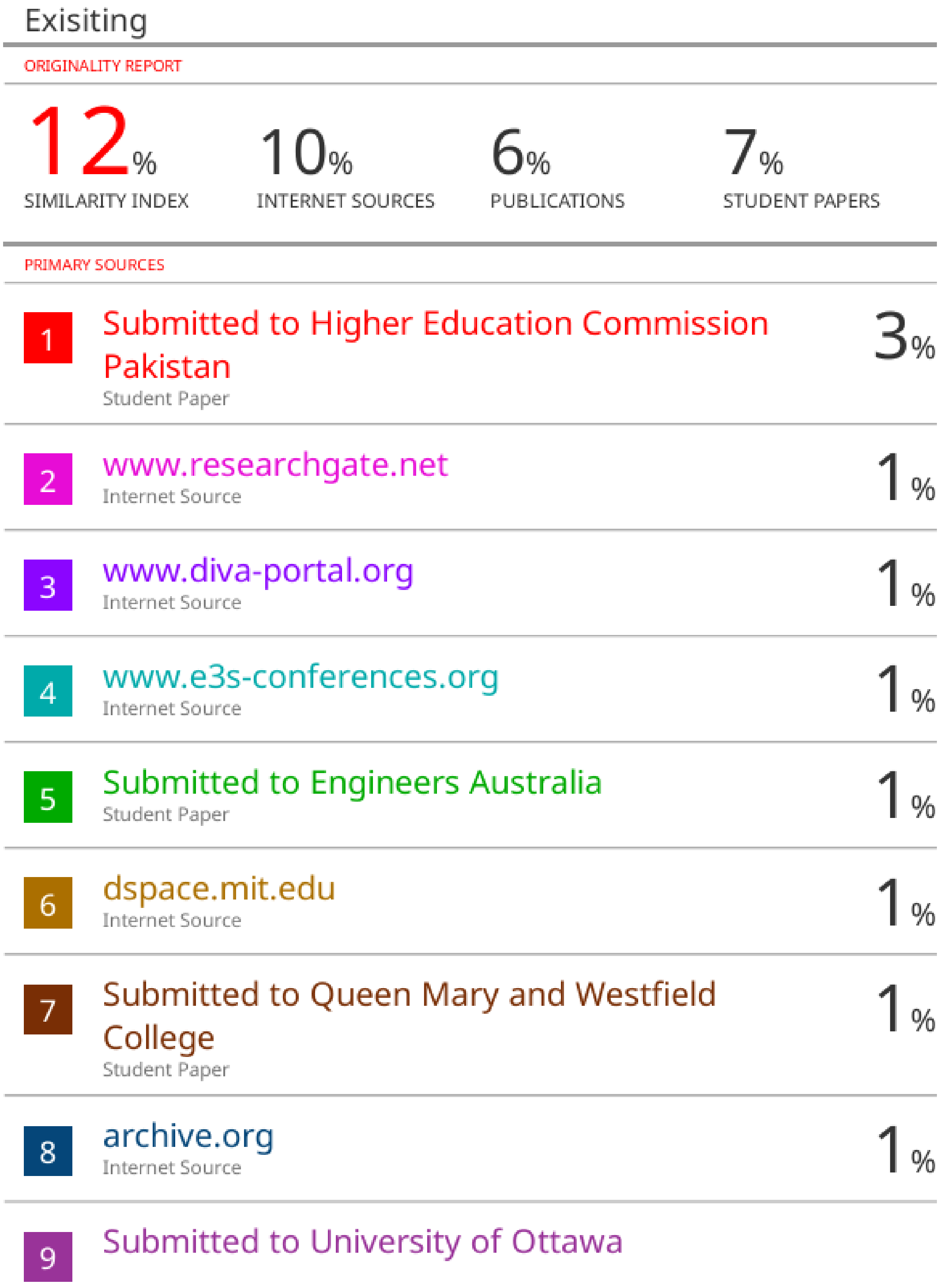

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ABBREVIATIONS

APU’s	Auxiliary Power Units
GPU’s	Ground Power Units
CFD	Computational Fluid Dynamics
CAD	Computer Aided Drawing
3D	Three dimensional
TKE	Turbulence Kinetic Energy
SDR	Specific Dissipation Rate

CHAPTER NO.1 INTRODUCTION:

TURBOCHARGER-BASED BRAYTON CYCLE - A STEP TOWARDS LOCALIZED MICRO GAS TURBINE TECHNOLOGY

1.1 Brayton Cycle

Brayton cycle is an open, constant-pressure cycle involving four thermodynamic processes:

1. **Isentropic compression:** Air drawn from the environment experiences adiabatic compression, increasing its pressure and temperature without heat transfer.
2. **Isobaric heat addition:** The compressed air enters a combustion chamber where fuel is injected and burned. The combustion process occurs at constant pressure, raising the temperature significantly.
3. **Isentropic expansion:** The stifling air expands through a turbine, performing work as its pressure and temperature decrease adiabatically.
4. **Isobaric heat rejection:** The exhaust air passes through a heat exchanger, releasing heat to the environment before returning to the compressor, completing the cycle.

1.1.1 Significance of the Brayton Cycle:

The Brayton cycle, with its inherent versatility and potential for high thermal efficiency, has long served as the cornerstone of various power generation and propulsion systems. From the mighty jet engines propelling airplanes to the efficient gas turbines powering large-scale electricity grids, the Brayton cycle's ability to convert thermal energy into mechanical work has earned it a prominent place in the engineering landscape. However, scaling this technology down to smaller applications often presents significant challenges.

1.1.2 Challenges in Miniaturization:

Miniaturizing a traditional Brayton cycle setup introduces several hurdles:

- **Component Selection:** Dedicated gas turbines and compressors designed for smaller scales can be expensive and difficult to source, particularly within resource-constrained markets like Pakistan.

- **Efficiency Concerns:** Achieving high thermal efficiency in smaller systems demands meticulous component matching and minimizing parasitic losses, proving complex and crucial for success.
- **System Complexity:** Integrating specialized components into a compact, functional system further adds to the design and fabrication challenges.

1.1.3 Turbochargers: A Promising Alternative:

A turbocharger is essentially a miniature gas turbine, where exhaust gas spins a turbine wheel connected to a compressor. The compressor then crams more air into the engine, allowing for more fuel burn and more power.

Intriguingly, this design can be flipped: by feeding compressed air into the turbine, we can extract useful work. That's the crux of the microturbine idea - using readily available turbochargers as the core of miniaturized power generators.

Emerging from the automotive realm, turbochargers offer an intriguing prospect for overcoming these hurdles. These compact, self-contained units, primarily utilized for boosting internal combustion engine performance, exhibit several characteristics that make them potential candidates for a miniaturized Brayton cycle implementation:

- **Readily Available:** Turbochargers are mass-produced for the automotive industry, leading to wider availability and potentially lower costs compared to dedicated gas turbine components.
- **Integrated Design:** Combining a compressor and turbine within a single unit simplifies the system layout and reduces complexity.
- **Robust Construction:** Built to withstand the demanding conditions of automotive engines, turbochargers offer inherent durability and reliability.

1.1.4. Pakistani Context and Project Significance:

Within the context of Pakistan, where access to specialized gas turbine components might be limited, leveraging readily available turbochargers for a miniaturized Brayton cycle holds strategic significance:

- **Technological Advancement:** This project explores an innovative approach to miniaturization, potentially leading to more accessible and affordable micro gas turbine technology.

- **Resource Utilization:** By utilizing existing local resources like turbochargers, the project promotes self-reliance and reduces dependence on specialized imported components.
- **Potential Applications:** Successful development could pave the way for diverse applications in Pakistan, including:
    - Micro combined heat and power (CHP) systems for distributed power generation in remote areas.
    - Waste heat recovery from industrial processes to improve energy efficiency.
    - Small-scale power generation for off-grid communities.

1.2 Problem Statement: Developing a Cost-Effective, Locally Sustainable, and Multi-Fuel Microturbine based on Turbocharger Design

Pakistan's rapidly growing energy demand necessitates innovative solutions beyond traditional power plants. Microturbines, based on the efficient Brayton cycle, offer promising potential for distributed power generation in remote areas, microgrids, and industrial applications. However, current challenges hinder their widespread adoption:

1.2.1. Lack of Local Manufacturing: Existing microturbines are primarily imported, increasing costs, and limiting accessibility. The absence of indigenous manufacturing expertise creates a barrier to scaling and customization based on local needs and resources.

1.2.2. Cost-Effectiveness: Current microturbine technologies are often expensive, making themunaffordable for many potential users, particularly in developing economies like Pakistan. Highinitial investment costs limit their deployment, hindering widespread adoption.

1.2.3. Limited Multi-Fuel Capability: Many available microturbines primarily rely on natural gas, creating an operational vulnerability in regions like Pakistan with fluctuating gas supply. The lack of flexibility to utilize readily available alternative fuels like biogas or renewable hydrogen reduces their potential contribution to a sustainable energy mix.

1.3 Project Objectives and Expected Outcomes

This project aims to address the challenges of miniaturizing the Brayton cycle by utilizing a readily available automotive turbocharger.

- **Design and fabricate a combustion chamber:** Develop a combustion chamber compatible with the chosen turbocharger, ensuring efficient fuel combustion and heat transfer, tailored to selected fuel type (discuss chosen fuel and its rationale).
- **Integrate the combustion chamber with the turbocharger:** Create a closed-loop Brayton cycle system where the compressor outlet feeds the combustion chamber, and the chamber's output drives the turbine.
- **Evaluate the system performance:** Analyze the system's thermal efficiency, power output, and emissions characteristics through comprehensive testing and data analysis.
- **Assess the project's feasibility and limitations:** Consider the practicality of utilizing turbochargers in Brayton cycles within the Pakistani context, including cost, resource availability, scalability, and future development potential.

CHAPTER NO. 2 LITERATURE REVIEW

2.1 Advancement in Research

Beyond the general introduction outlined above, consider incorporating the following details.

- **Detailed Design of Combustion Chamber:** Elaborate on the design process of your combustion chamber, including material selection, geometric considerations, fuel injection methods, and heat transfer optimization strategies. Include relevant calculations and diagrams to illustrate your design choices.
- **Integration and System Layout:** Discuss the challenges and solutions involved in integrating the combustion chamber with the chosen turbocharger. Explain the system layout, including interconnecting components, control mechanisms, and safety features.
- **Testing and Performance Analysis:** Describe the testing procedures employed to analyze the system's performance. Present your findings on thermal efficiency, power output, emissions characteristics, and any observed limitations. Provide graphs, charts, and tables to effectively showcase your results.
- **Feasibility Assessment and Future Potential:** Discuss the broader implications of your project. Analyze the project's economic and technical feasibility within the Pakistani context, considering cost, resource availability, potential applications, and opportunities for further development.

Here are some research papers which are being referred to for literature review for the above-mentioned requirements and understanding the depth of project requirements and outcomes.

2.2 PRELIMINARY DESIGN OF A COMBUSTION CHAMBER FOR MICROTURBINE BASED IN AUTOMOTIVE TURBOCHARGER

Aiming to reduce development costs, this research proposes a microturbine combustion chamber design based on an existing automotive turbocharger. The reverse flow configuration leverages the readily available turbocharger while adhering to space constraints. By adapting established design methods for microturbines and employing computational tools, the authors present a conceptual design with key dimensions and specifications. While the study demonstrates the potential of this approach, further refinement, performance validation, and emission control considerations are needed for a fully functional microturbine.

2.3 Design, Fabrication, and Performance of a Gas-Turbine Engine from an Automobile Turbocharger

Padilla's paper details the design, fabrication, and performance analysis of a miniature gas turbine engine built using an automobile turbocharger. This project, focused on educational purposes and potential small-scale power generation, utilized an open Brayton cycle with a custom combustion chamber connecting the turbocharger's compressor and turbine. While the prototype achieved modest efficiency (5%) and power output (0.2 kW) using compressed air, it demonstrated the feasibility of repurposing readily available components for gas turbine applications. Moreover, the paper highlights the project's educational value and acknowledges limitations like open cycle configuration and measurement challenges, paving the way for further exploration and development in this domain.

2.4 Design of an Automobile Turbocharger Gas Turbine Engine

This research suggests a microturbine combustion chamber design based on an existing automobile turbocharger in an effort to save development costs. Taking advantage of the readily available turbocharger, the reverse flow design conserves space. The authors offer a conceptual design with important dimensions and specifications by utilizing computational tools and applying well-established design procedures for microturbines. Even though the study shows the promise of this strategy, more development, performance verification, and emission control concerns are required before a microturbine can be completely operational.

2.5 Converting an automobile turbocharger into a micro gas turbine.

Usman Butt's paper investigates converting an automobile turbocharger into a micro gas turbine, utilizing its affordability and accessibility for educational and potentially small-scale power generation. The design features a custom combustion chamber for efficient fuel combustion and integrates with the turbocharger for a closed Brayton cycle. While achieving high engine speeds and demonstrating feasibility, the research acknowledges the absence of a recuperator for efficiency improvement and highlights potential applications like micro combined heat and power systems. This work paves the way for further exploration of readily available components in micro gas turbine development, offering affordable and accessible technology advancements.

2.6 Combustion chamber design and performance for micro gas turbine application

In this paper, Enagia et al. looked into the design and performance analysis of a combustion chamber specifically crafted for micro gas turbine applications. While access to the full details necessitates the full text or a more detailed description, the title hints at the study's likely coverage. The authors potentially discuss specific design choices for the chamber, encompassing its geometry, materials, fuel injection methods, and other crucial aspects tailored for micro gas turbines. Furthermore, the paper might present experimental or computational results assessing the chamber's performance in terms of combustion efficiency, stability, emissions characteristics, and its impact on the overall micro gas turbine system's performance. Finally, the authors could explore the applicability of their design to diverse micro gas turbine applications, considering factors like power generation, waste heat recovery, or specific industrial requirements.

2.7 Literature review findings and areas of improvements

Our project aims to address the critical challenges by developing a microturbine based on a locally available, cost-effective turbocharger design with multi-fuel capability. This innovation holds the potential to:

- Reduce dependence on imported technology and promote local manufacturing expertise.
- Significantly lower the initial investment cost, making microturbines accessible to a wider range of users.
- Increase operational flexibility by enabling adaptation to various fuel sources, including readily available biogas and renewable hydrogen, fostering a cleaner and more sustainable energy landscape.

By successfully realizing this project, we aim to contribute to Pakistan's energy security, promote local technological advancement, and pave the way for a more sustainable and accessible power generation infrastructure.

CHAPTER 3: METHODOLOGY

The project consists of completely mechanical components. It has three main parts i.e., Turbine, Compressor, and a Combustion Chamber. In this project we will be working on the design and as well as fabrication of the Turbocharger-based Brayton Cycle. Firstly, a basic turbocharger was finalized as per the requirements, then designing, analyzing, and prototyping was done to verify its mechanisms and then finally assembling of the turbocharger with the Combustion Chamber.

3.1 Brayton's Cycle

Most of the modern-day power generation systems are based on Brayton cycle which involves the following processes:

- Isentropic Compression
- Constant pressure heat addition
- Isentropic Expansion
- Constant pressure heat rejection

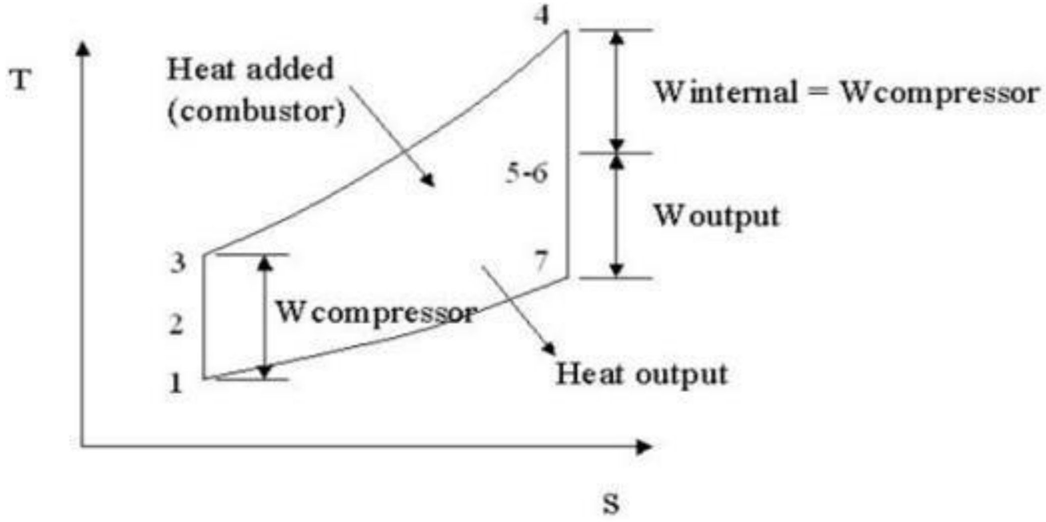


Figure 1: T-s Diagram of Brayton Cycle

As mentioned previously, the turbocharger which resembles a Gas turbine in many ways offers a great opportunity to develop low-cost, micro-turbines. The advantage of using turbocharger for this project is that we have readily available, aligned, coupled, and mounted on single shaft compressor and turbine. A suitable combustion chamber with a proper fuel injection and ignition system when assembled with a turbocharger can be used for variety of power applications of APU's and GPU's.

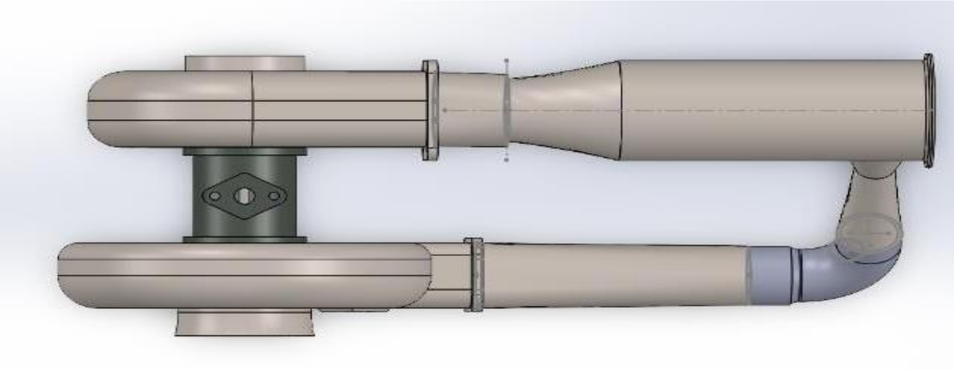


Figure 2: Microturbine's layout

So, for the design and development of turbocharger-based Brayton Cycle we went through the following processes.

- Turbocharger Selection
- Designing of Combustion Chamber
- Combustion Analysis
- Design optimization according to performance curves.

3.2 Turbocharger Selection

Most automotive turbochargers can easily be converted into a self-sustained gas turbine engine. However, the choice may vary depending upon the specific application. For our project, we opted for a larger turbo Garret GT-2502[1] because of its compact design, reliability and availability and affordability, being a Diesel engine turbocharger [2] it has maximum service life given this application. Garret GT-2502 uses a traditional wastegate design to regulate boost pressure. Modern advancements in turbocharger technology have been driven by two key factors emission regulations and rising fuel costs, particularly in diesel engine applications. One of the most impactful strategies to account for both emission reduction and performance improvement in diesel engines lies in precisely controlling the fuel-to-air ratio.

Figure 3: Garret GT-2502 Turbocharger

3.3 Designing of Combustion Chamber

A combustion chamber for the Garrett GT2502 turbocharger was designed in SolidWorks, prioritizing optimal fuel-air mixing, complete combustion, and structural integrity. Initial design parameters included fuel type, target power output, and relevant combustion principles. Based on the existing designs and analyzing flow characteristics an annular type of combustion chamber was selected because of its high efficiency and low emissions.

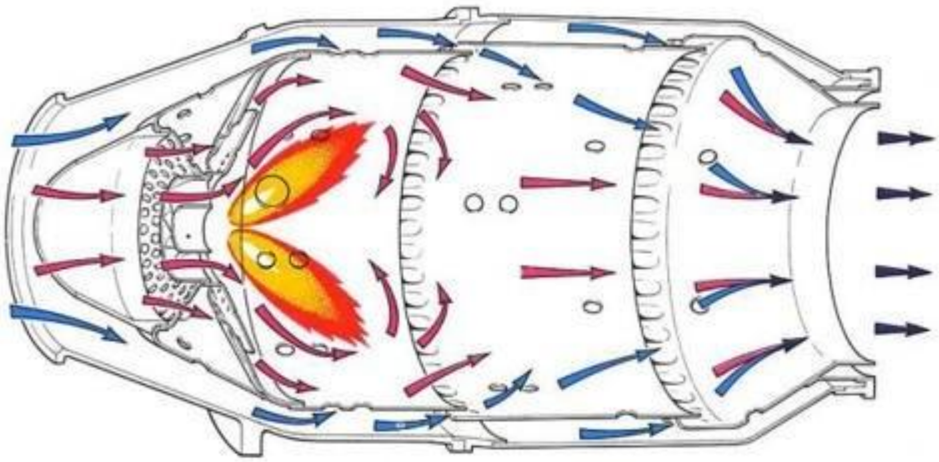


Figure 4: Layout of annular type combustion chamber

A 3D model of combustion chamber was prepared, incorporating components like flame tube or liner for holding the flame, casing of the flame tube, inducer at the turbine’s inlet to increase the speed of exhaust gases which strikes the turbine blades and diffuser before the compressor to slow down the incoming air which may blow off the flame inside the liner. Stress and thermal analyses ensured the chamber's ability to withstand anticipated loads and temperatures. Detailed drawings and documentation were prepared, capturing design decisions and critical dimensions for fabrication. This robust yet adaptable design lays the foundation for a high-performance combustion chamber in conjunction with the chosen turbocharger.

The flame tube, also known as a combustor liner, plays a critical role in microturbine performance and efficiency [3]. It's essentially a chamber where fuel and air mix, combust, and generate hot gases that drive the turbine.

Here is a breakdown of key design considerations:

3.3.1 Shape and Size:

Compactness: given the space constraints in microturbines, the flame tube needs to be compact while it should account for the proper mixing required for complete combustion.

Aspect Ratio: Length-to-diameter ratio (L/D) [3] influences residence time, flame stability, and pollutant formation. Typically, aspect ratio ranges from 1 to 3 [3].

Aerodynamic Design: Inlet and outlet geometries impact airflow distribution and pressure drop. Diffusers and inducers can enhance flame’s stability and mixing required for combustion.

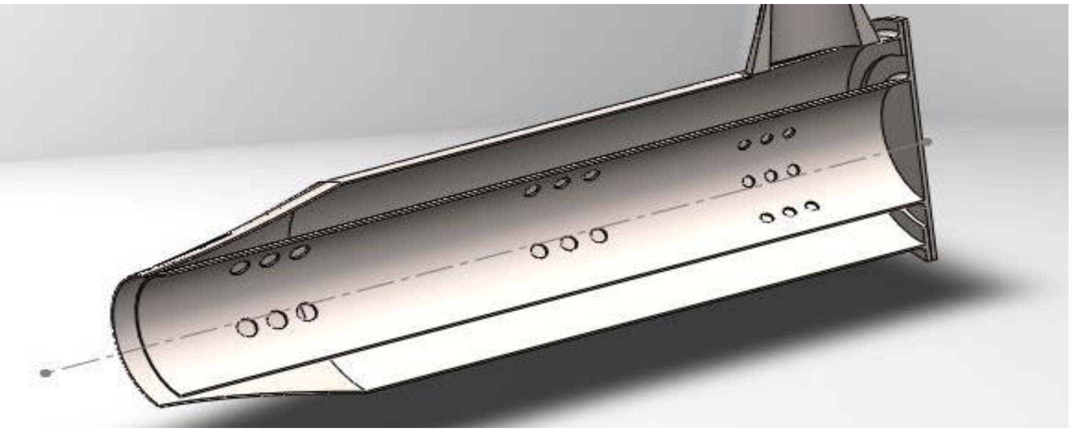


Figure 5: Combustion Chamber’s cross-sectional view

3.3.2 Materials:

High-Temperature Resistance: Must withstand combustion temperatures exceeding 1000°C [3] Common materials include high-temperature alloys, ceramics, and coated steels. We opted for stainless steel as it addresses the given concerns and is readily available.

Durability: Resist thermal fatigue, creep, and oxidation over extended operation.

Cooling: Can incorporate internal cooling passages or external cooling jackets for heat management.

3.3.3 Zones and Features:

- The primary region is where the ignition starts and the majority of combustion of the air-fuel mixture occurs using 20% of the compressors air, leading to the highest temperatures and pressures, generating the engine's power [3].
- The intermediate region acts as a transition zone and uses 30% of the compressor’s air which accounts for incomplete combustion and produces a better air-fuel mixture to stabilize the combustion process [3].
- Dilution region or tertiary region uses the remaining 50% air for better control over emissions by mixing hot exhaust gases with fresh air [3].

3.3.4 Additional Considerations:

Emissions: Design should minimize pollutant formation like NOx and CO through proper mixing, staged combustion, and lean operation.

Ignition: Reliable and efficient ignition system is crucial for stable operation.

Manufacturing: Cost-effective and feasible manufacturing methods are important for microturbine affordability.

3.3.5 Finalized Dimensions:

A CAD model of the combustion chamber of the microturbine was designed and the specified dimension of flame tube were selected based on the research [2]. Based on the selected turbocharger’s compressor and turbine curves, combustion analysis was performed and the compatibility of combustion chamber with turbocharger was accounted.

Length = 18-inch, Diameter = 6inch

Primary holes diameter = 6mm (30), secondary holes diameter = 8 mm (18), tertiary holes diameter = 10 mm (18)

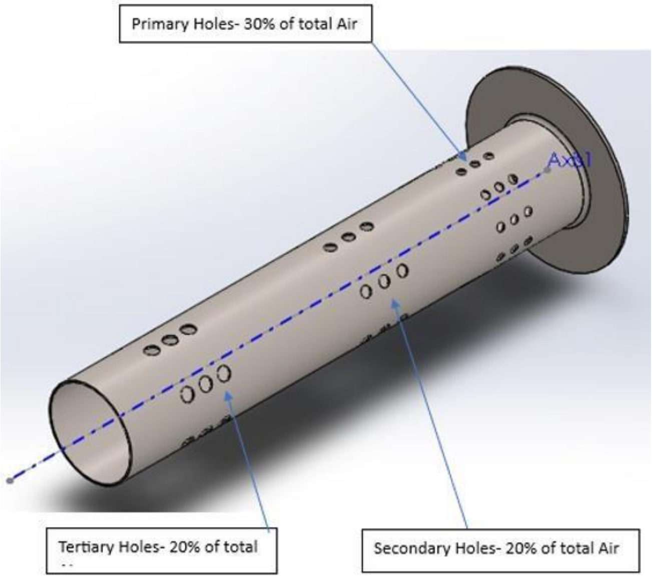


Figure 6: Flame tube or Combustion Liner

3.4 Combustion Analysis

Non-Premixed Combustion Analysis of a Combustor in ANSYS Fluent was used to analyze the compatibility of our designed combustor with the Garret, GT-2052 turbocharger. Combustion analysis using this model involved the following processes.

3.4.1 Pre-processing

Geometry and Meshing:

The 3D model of the Combustion Chamber was imported in the ANSYS Design Modeler software. In the design modeler section, we name the specified areas according to their location as primary inlet, secondary inlet, and tertiary inlet, outlet, fuel inlet etc.

A high-quality mesh, paying attention to mesh size and quality (orthogonality) near walls and complex geometries was generated. Consider using adaptive meshing for areas with large gradients.

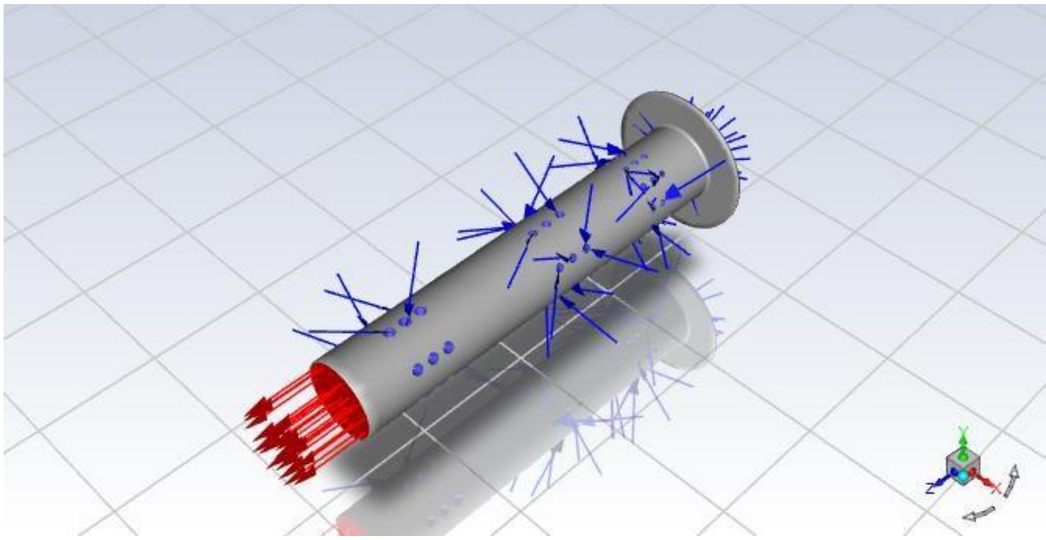


Figure 7: Fuel and air inlets and outlets

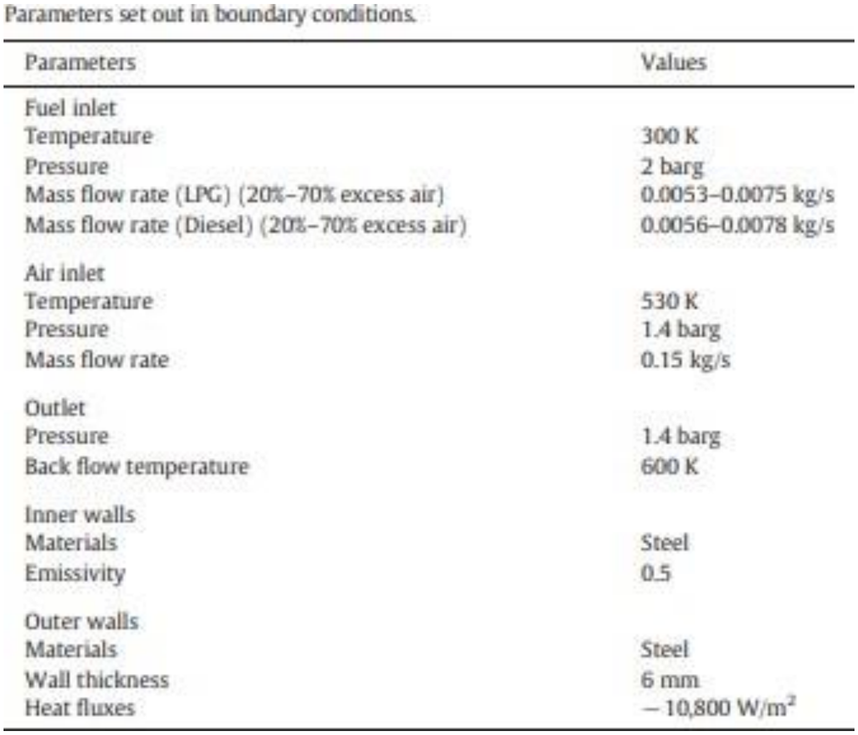
Material Properties:

Define temperature-dependent material properties for the combustor and other relevant components, including density, specific heat capacity, thermal conductivity, and viscosity.

3.4.2 Boundary Conditions:

Set mass flow rates for air and fuel at primary secondary inlets, specifying their compositions and initial temperatures. Define outlet pressure conditions.

Set wall boundary conditions (adiabatic, constant temperature, heat flux).



Parameters set out in boundary conditions.

Parameters	Values
Fuel inlet	
Temperature	300 K
Pressure	2 barg
Mass flow rate (LPG) (20%–70% excess air)	0.0053–0.0075 kg/s
Mass flow rate (Diesel) (20%–70% excess air)	0.0056–0.0078 kg/s
Air inlet	
Temperature	530 K
Pressure	1.4 barg
Mass flow rate	0.15 kg/s
Outlet	
Pressure	1.4 barg
Back flow temperature	600 K
Inner walls	
Materials	Steel
Emissivity	0.5
Outer walls	
Materials	Steel
Wall thickness	6 mm
Heat fluxes	$-10{,}800$ W/m^2

Table 1: Setup parameters for analysis

3.4.3 Understanding the k-omega (k-ω) Turbulence Model in CFD:

The k-omega (k-ω) turbulence model is a popular two-equation model employed in computational fluid dynamics (CFD) to simulate the influence of turbulence within fluid flow. It works by solving two additional transport equations alongside the fundamental Navier-Stokes equations:

k-equation: This equation represents the turbulence kinetic energy (TKE), which signifies the energy contained within the turbulent eddies.

omega-equation: This equation reflects the specific dissipation rate (SDR), indicating the rate at which TKE dissipates into thermal energy.

Through solving these equations, the k-ω model can predict the turbulent viscosity, a crucial parameter for determining the flow behavior under turbulent conditions.

Key Advantages of the k-ω Model:

Enhanced Accuracy

Compared to the widely used k-ε model, k-ω offers improved accuracy, particularly for flows encountering adverse pressure gradients and separation.

Free-Stream Sensitivity

This model responds sensitively to the incoming free-stream turbulence properties, providing a more realistic representation of complex flow scenarios.

Wall Compatibility

The ability to utilize wall functions makes the k-ω model applicable to near-wall regions, where turbulence behavior is highly intricate.

Potential Disadvantages of the k-ω Model:

Computational Cost

Compared to the k-ε model, k-ω requires more computational resources due to its two additional transport equations.

Mesh Sensitivity

This model can be sensitive to the size and quality of the computational mesh, requiring careful mesh generation and analysis.

Limited Validation

While gaining popularity, the k-ω model has fewer established validation studies compared to the well-proven k-ε model.

Additional Tips for Species Transport Simulations:

- Activate "Species Transport": Navigate to the "Models" menu and enable "Species Transport."
- Select Combustion Mechanism: Choose a suitable combustion mechanism, such as detailed options like GRI-Mech or skeletal mechanisms like CHEMKIN.
- Define Transport Model: Specify the transport model, typically based on mixture fraction.
- Reactions and Properties: Define the participating species and chemical reactions based on your chosen mechanism. Import thermophysical properties for all involved species.
- Solver Settings.

- Pressure-Velocity Coupling: Select an appropriate scheme like SIMPLE or PRESTO based on your flow characteristics.
- Discretization Schemes: Choose suitable schemes for all governing equations and transport models. Higher-order schemes offer better accuracy but may require more computational resources.
- Initialization: Begin your simulation with reasonable starting values for pressure, temperature, and species concentrations throughout the domain.

Monitoring Convergence:

Define convergence criteria for residuals, species, and other relevant parameters.

Monitor their behavior throughout the solution process and adjust settings or refine the mesh if necessary.

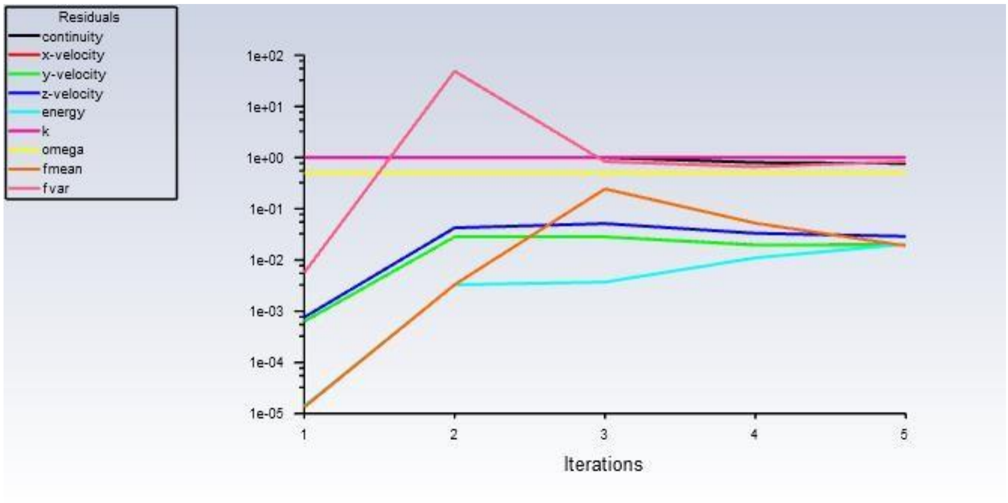


Figure 8: Convergence of iterations

3.5 Design Optimization

The design of the flame tube was optimized using the results of the following simulations.

- The temperature profile of the liner indicates the effectiveness of the dilution or cooling zone, as turbine inlet temperature must be within a certain range to avoid turbine blades damaging [2] [4].
- Propagation of the flame inside the flame tube
- Emissions from the exhaust.

The results when the flame was distributed as it exits the tube to the air jacket is not the best result since the liner, since the flame is distributed around the liner and lack of cooling results damage to the liner’s material. The shape of the flame inside the liner is an important parameter as it prevents direct contact between intensive and elevated temperature flames and tube walls. The main geometric parameters which have impact on the flame inside the liner include **height of chamber, diameter of the liner** (casing diameter will change accordingly) and hole zones on the flame tube. The arrangement of holes including number of holes and its diameter along different regions including primary, secondary, and tertiary and the distance between zones which will be referred to as dead zones since it does not include any holes.

3.6 Performance Curves of Turbocharger

Turbocharger performance curves are crucial tools for selecting the right turbocharger for your engine and predicting its performance under various operating conditions. These curves often depict "efficiency islands," which provide valuable insights for optimizing your system.

3.6.1 Efficiency Islands: Keys to Optimal Performance

The compressor and turbine maps feature regions known as "efficiency islands," representing operating points with the highest efficiency. This translates to better fuel economy and power output.

Compressor island

This area indicates where airflow meets the engine's demand with minimal energy loss. Choosing the right mass flow rate ensures you operate within this zone.

<u>Turbine island</u>

This area highlights how the exhaust gas optimally drives the compressor while minimizing wasted energy. Selecting a pressure ratio within this zone ensures efficient energy transfer.

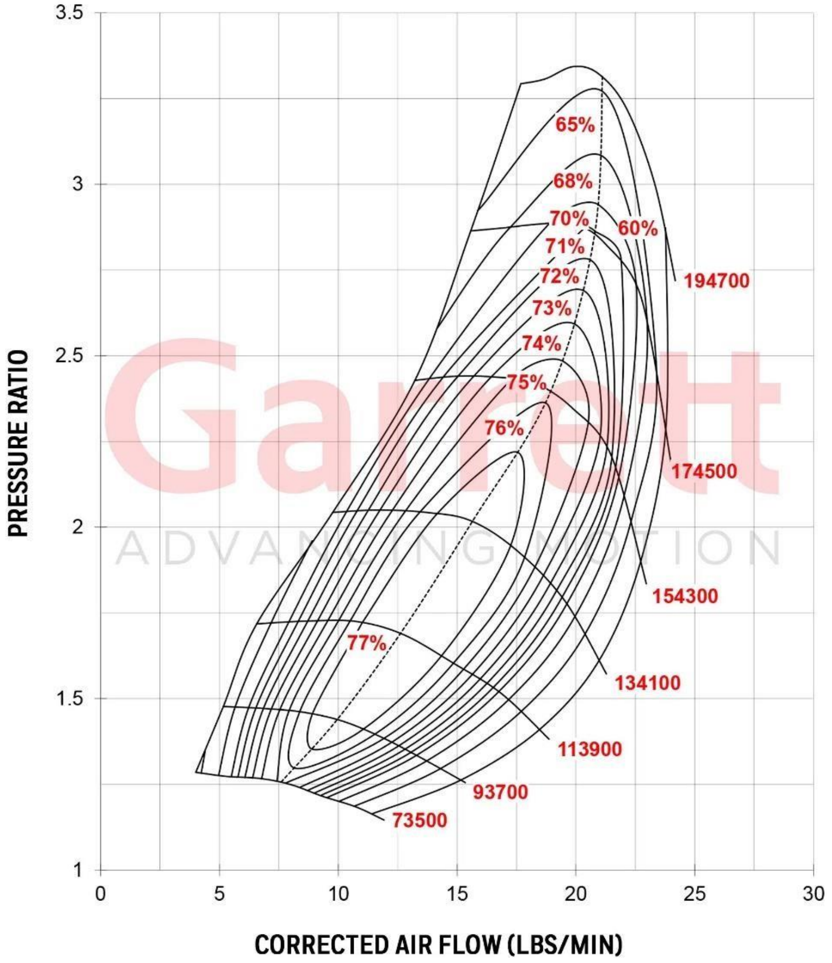


Figure 9: Compressor’s curve of GARRET GT-2502

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3.6.2 Mass Flow Rate and Pressure Ratio: Their Impact on Selection

Mass flow rate

Higher mass flow rates shift the compressor island to the right, requiring a larger pressure ratio to maintain efficiency. Conversely, lower flow rates shift the island left, needing a smaller pressure ratio. Selecting an inappropriate mass flow rate can push you outside the island, significantly reducing efficiency[5].

Pressure ratio

This directly determines the amount of boost provided by the turbocharger. Choosing a pressure ratio within the compressor island's efficient zone ensures optimal power delivery without excessive energy loss. Going beyond the island can lead to surge (compressor instability) or choke (limited flow), both harming performance and potentially damaging the turbocharger[5].

Connecting Performance Curves to Combustion Parameters

While the performance curves don't directly dictate exact combustion parameters, they set the operating environment where these parameters occur.

Mass flow rate and pressure ratio

These define the amount of air and boost pressure delivered to the combustion chamber. Higher mass flow generally leads to more air available for combustion, potentially increasing power output. However, exceeding the efficient island can cause inefficiencies and performance losses.

Matching compressor and turbine islands

Choosing a pressure ratio within the efficient island for both ensures optimal energy transfer from exhaust to compressor, avoiding surge or choke.

Impact on combustion

Airflow and pressure directly affect mixing and flame stability. Higher mass flow rates can improve mixing, but excessive pressure can disrupt the flame front. The efficiency of the islands indirectly affects combustion. Operating outside the islands signifies wasted energy that could be used for better combustion, potentially impacting fuel economy and emissions.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Results:

Results were obtained by conducting Computational Fluid Dynamics (CFD) analysis of a flame tube to obtain the expected relationships between the tube geometry and different properties of air and fuel. Also, we compared the pressure ratio we obtained on the simulation with efficiency and figured out whether this was within the maximum efficiency range (represented by the efficiency islands) or not.

We used “species transport” model for heat transfer representation in the simulation.

4.1.1 CFD Analysis:

CFD analysis was done in order to get an idea of:

1) Optimum Geometry (With Regards to temperature)

2)Performance Curves

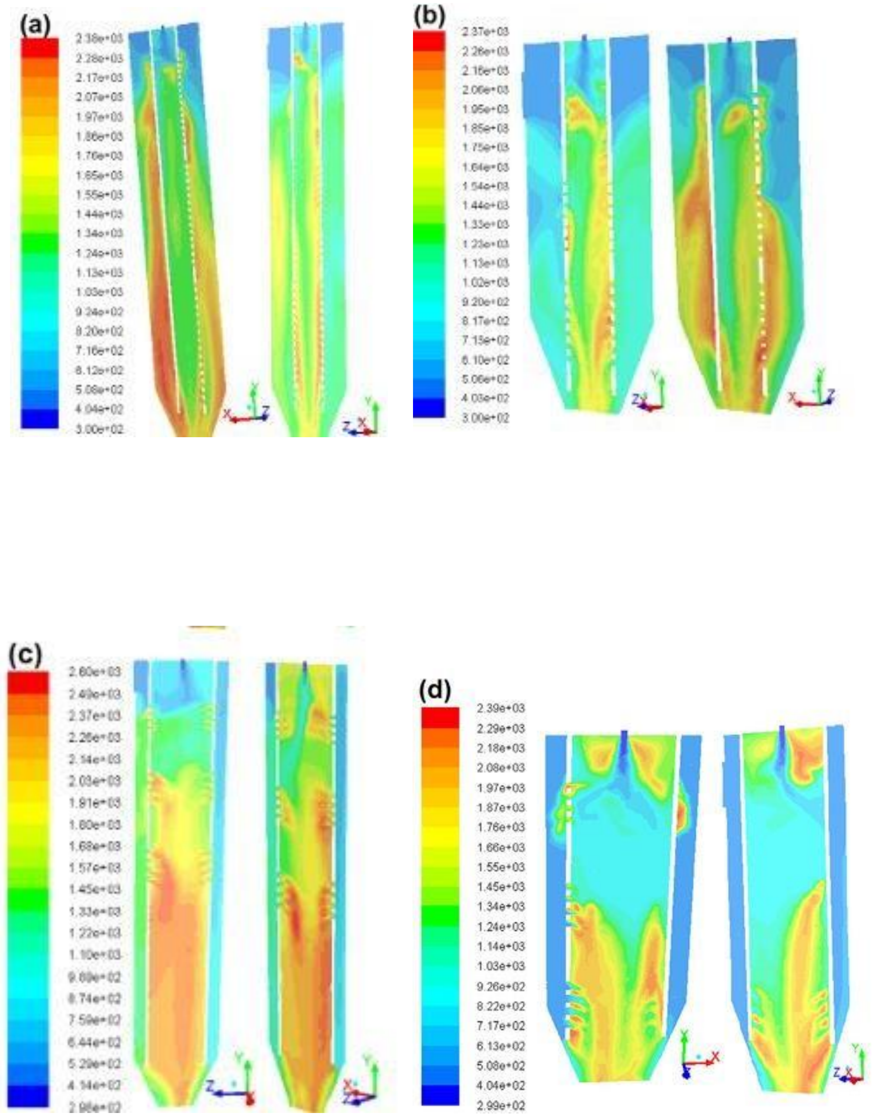
4.1.1.1 Optimum Geometry:

Simulations were performed by varying the flame tube diameters, diameters of holes and dead zone areas.

Analysis and results

As far as the flame tube height and diameters are concerned, we considered the varying heights of 200,300 and 400mms with varying diameters 60,70 and 80mm.

With regards to hole diameters, they were assumed to be 6, 8, 10 mm to 8,10,12mm.
And the dead zone configurations were as shown in the figure under the heading “effect of dead zones”.



Temperature contours for (6,8,10) mm configuration

(a) 300mmheightwith15rows.

(b) 300mmheightwith7rows.

(c) 300heightwith4rows

(d) 300mm heightwith4rows.

These are the different simulations we carried out in order to figure out the geometry which will be optimum in our case.

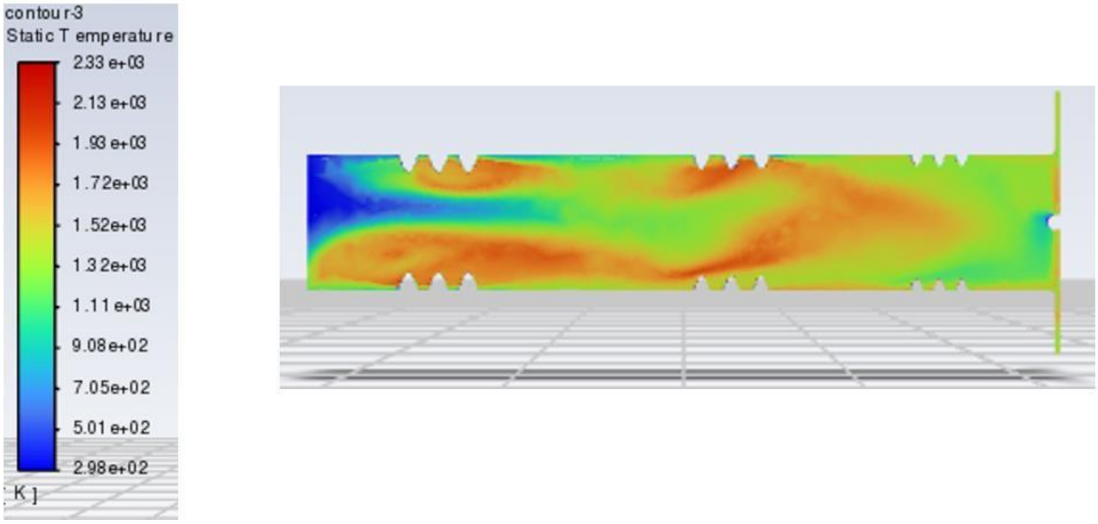


Figure 10: Temperature contours

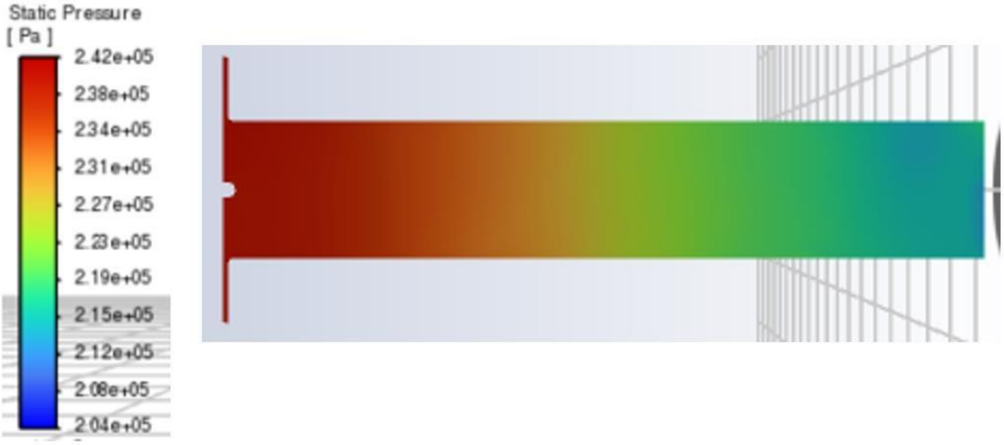


Figure 11: Pressure contours

These are the temperature and pressure contours that show us the maximum temperature and pressure we will obtain at the said conditions, assuming that no casing is covering the tube, these are, at the optimum geometry that could be obtained.

4.1.1.2 Performance Curves

We compare the pressure ratio which is 1,5 with mass flow rate which is 18lb/min, so we obtain efficiency of almost 60% (shown by the red dot) and it lies within the agreeable range.

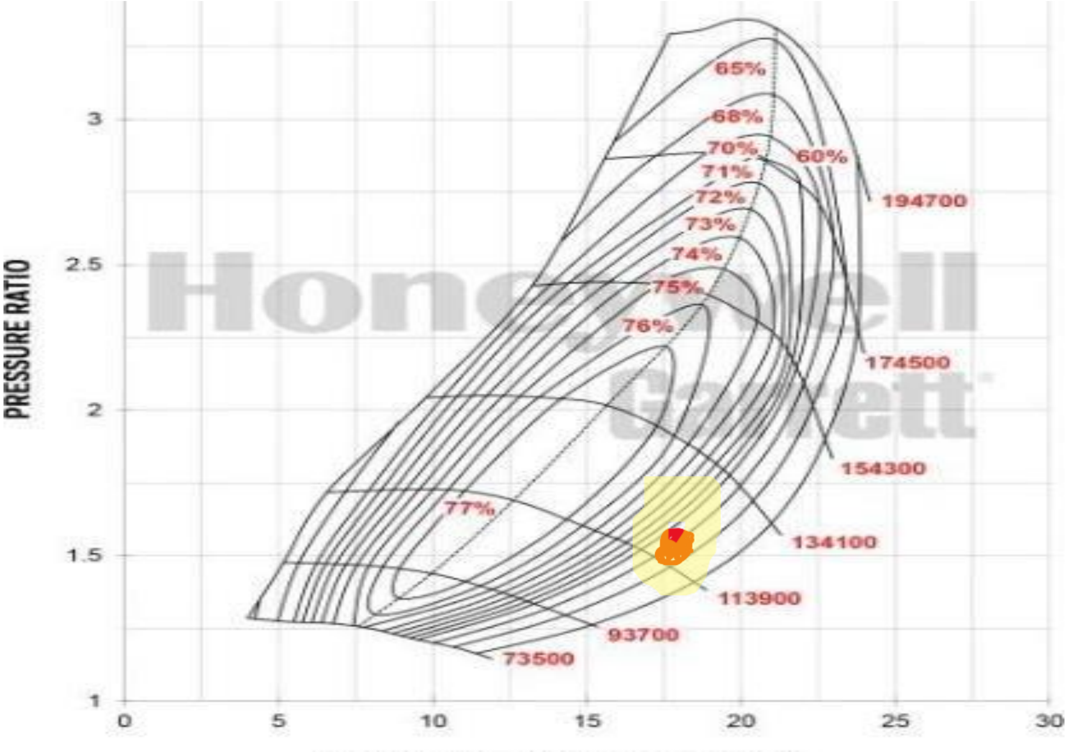


Figure 12: Working Condition inside efficiency island of GARRET GT-2502

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4.2 Discussion:

This project is an endeavor to begin looking for alternate options for fulfilling the energy needs in the industrial sector while conscientiously considering environmental sustainability.

Central to this pursuit is the implementation of Brayton’s cycle orchestrated through the integration of micro-gas turbine technology coupled with commercially available turbochargers.

This is an attempt to redefine the norms in our industry and move towards a more sustainable trajectory.

4.2.1 Analysis of Other Similar Technologies:

In the quest for sustainable and efficient energy generation in industrial settings, it is imperative to consider and evaluate alternative technologies. This comparative analysis aims to elucidate the strengths and weaknesses, and trade-offs of various alternative energy generation technologies commonly deployed in industrial applications.

4.2.1.1 Traditional Gas Turbines:

Traditional gas turbines have long been the workhorses of industrial energy generation, renowned for their reliability, high power output, and scalability. These systems operate on Brayton's cycle principle similar to micro-gas turbines, but on a larger scale. While traditional gas turbines offer higher power output and efficiency, they are typically more expensive to install and maintain. Additionally, traditional gas turbines may have longer start up times and lower part load efficiency, making them less suitable for applications with variable demand [5].

4.2.1.2 Reciprocating Engines

Reciprocating engines, including diesel and gas engines, are another common choice for industrial generation. These engines offer high efficiency and reliability, particularly in cogeneration and combined heat and power applications. Unlike gas turbines, reciprocating engines can achieve higher part-load efficiency and respond more quickly to changes in demand. However, they may produce higher emissions and require more frequent maintenance compared to gas turbines. Additionally, reciprocating engines have limited scalability and may be less suitable for large-scale industrial applications.

4.2.1.3 Renewable Energy Sources:

Renewable energy sources, such as solar, wind, and biomass, are gaining traction in industrial energy generation due to their environmental sustainability and long-term cost savings. Solar photovoltaic systems can be deployed on site or integrated into industrial buildings, providing clean electricity with minimal operational costs. Wind turbines offer a similar advantage, harnessing wind energy to generate electricity for industrial use. Biomass energy systems utilize organic waste materials to produce heat, steam, or electricity, offering a renewable alternative to fossil fuels. While renewable energy sources offer numerous environmental benefits, they may have higher upfront costs and intermittent challenges compared to traditional energy generation technologies.

4.2.1.4 Energy Storage Systems

Energy storage systems, such as batteries, flywheels, and thermal storage, play a crucial role in enhancing the reliability and efficiency of industrial energy systems. Batteries can store excess energy from renewable sources or off-peak electricity for use during periods of high demand, helping to optimize energy utilization and reduce peak demand charges. Flywheels provide short-duration energy storage and fast response times, making them suitable for applications requiring rapid load balancing or frequency regulation. Thermal storage systems store energy in the form of heat or cold, allowing industrial facilities to shift energy consumption to off-peak hours or capture waste heat for later use. While energy storage systems offer significant benefits in terms of flexibility and efficiency, they may have limited storage capacity and lifecycle costs that need to be carefully considered.

Now we will discuss what are the advantages and limitations of this project, keeping in mind its industrial scope:

4.2.2 Advantages

The advantages this project offers over conventional techniques are as follows:

1) Enhanced Energy Efficiency
2) Improved Performance
3) Reduced Environmental Impact
4) Cost-effectiveness
5) Energy Independence and Resilience

4.2.2.1 **Enhanced Energy Efficiency*:***

The adoption of Brayton's cycle, known for its high thermodynamic efficiency, coupled with the efficiency of micro gas turbines leads to a significant improvement in overall efficiency. This can lead to more output with the same input energy or with reduced energy consumption, resulting in cost savings and reduced environmental impact.

4.2.2.2 Improved Performance:

By leveraging micro-gas turbines which are compact and lightweight compared to traditional gas turbines. industries can achieve high power densities and better performance. This allows for more flexible and responsive operation, meeting varying demands and operational requirements effectively.

4.2.2.3 Reduced Environmental Impact:

The increased efficiency and cleaner combustion associated with micro-gas turbines contribute to reducing emissions of greenhouse gases and pollutants such as CO2, NOx, and particulate matter. This aligns with the global sustainability goals and regulatory requirements, positioning industries as responsible sustainers of the environment [7].

4.2.2.4 **Cost-effectiveness*:***

Utilizing commercially available turbochargers for micro-gas turbine applications offers a cost-effective solution compared to custom-built components. This lowers the barrier to entry for industries looking to adopt advanced energy technologies, making it economically viable for a broader range of applications and organizations [8].

4.2.2.5 Energy Independence and Resilience:

By diversifying energy sources and increasing energy efficiency, industry becomes less reliant on conventional energy sources and more resilient to supply disruptions and price fluctuations. This enhances energy and strengthens the overall resilience of industrial applications.

In summary a turbocharger-based implementation of Brayton's cycle can become a starting point to a venture that will contribute to a more sustainable and resilient industrial energy landscape.

4.2.3 Limitations

While this project offers numerous advantages, it is essential to acknowledge and address potential limitations and challenges which can be:

1) Scale and Capacity Constraints:
2) Complexity of Integration:
3) Maintenance and Reliability:
4) Environmental Considerations:
5) Other Concerns:

4.2.3.1 Scale and Capacity Constraints

Micro-gas turbines, despite their compact size and high-power density, may have limitations in terms of scale and capacity compared to larger conventional gas turbines. This could restrict their applicability in certain industrial settings where larger power generation capacities are required.

4.2.3.2 Complexity of Integration

Integrating micro-gas turbine systems with existing industrial infrastructure may be complex and require significant engineering expertise. Ensuring seamless integration and compatibility with other equipment and systems within the industrial plant could present technical challenges and increase complexity.

4.2.3.3 Maintenance and Reliability

Micro-gas turbine systems require regular maintenance and upkeep to ensure optimal performance and reliability. However, accessing and servicing these systems, especially in industrial settings with harsh operating conditions may pose logistical challenges and increase downtime, impacting overall productivity [3].

4.2.3.4 Environmental Considerations

While micro-gas turbines offer improved efficiency and reduced emissions compared to conventional energy generation or other similar applications of energy cycles, they still emit pollutants and greenhouse gas emissions during operation. Addressing environmental concerns such as emissions mitigation and waste disposal remains a critical consideration in the implementation of this project [3].

4.2.3.5 Other Concerns:

Micro-gas turbine projects are known for being very noisy, they are considered to be visually displeasing, and they can be the cause of some serious safety concerns if they are not handled in a proper and professional manner.

It is necessary to look for some ways that address the aforementioned limitations and challenges when it comes to industrial applications of this project.

4.2.4 Manufacturing and Assembling

After the design and analysis phases of the turbocharger-based Brayton's cycle, the project was now poised to transition into the manufacturing and assembly stage. Leveraging the comprehensive 3D model, with the insights from CFD analysis, we were well equipped to embark on the physical realization of the system.

Figure 13(a & b): Casing and Flame Tube

Combustion Chamber Manufacturing

Many components including the combustion chamber were fabricated to exact specifications. Depending on the design requirements and material considerations, different machining operations were employed. Metal pipes served as raw materials for constructing the combustion chamber, with precision machining operations employed to shape and refine the components to meet design tolerances and performance criteria.

Figure 14(a & b): Combustion Chamber

The combustion chamber, being a critical component of the system, underwent careful fabrication to ensure structural integrity, thermal efficiency, and compatibility with the turbocharger assembly. Machining operations such as *milling, turning, welding,* and *drilling were* employed to craft intricate geometries and achieve dimensional accuracy, corrosion resistance, and thermal insulation properties.

Assembly Process:

Once the individual components were manufactured to specification, the assembly process commenced. The combustion chamber was integrated with the commercially available turbocharger, ensuring compatibility and optimal performance. Each component will be carefully aligned, fastened, and sealed to minimize leakage. Optimize flow dynamics and facilitate efficient combustion processes.

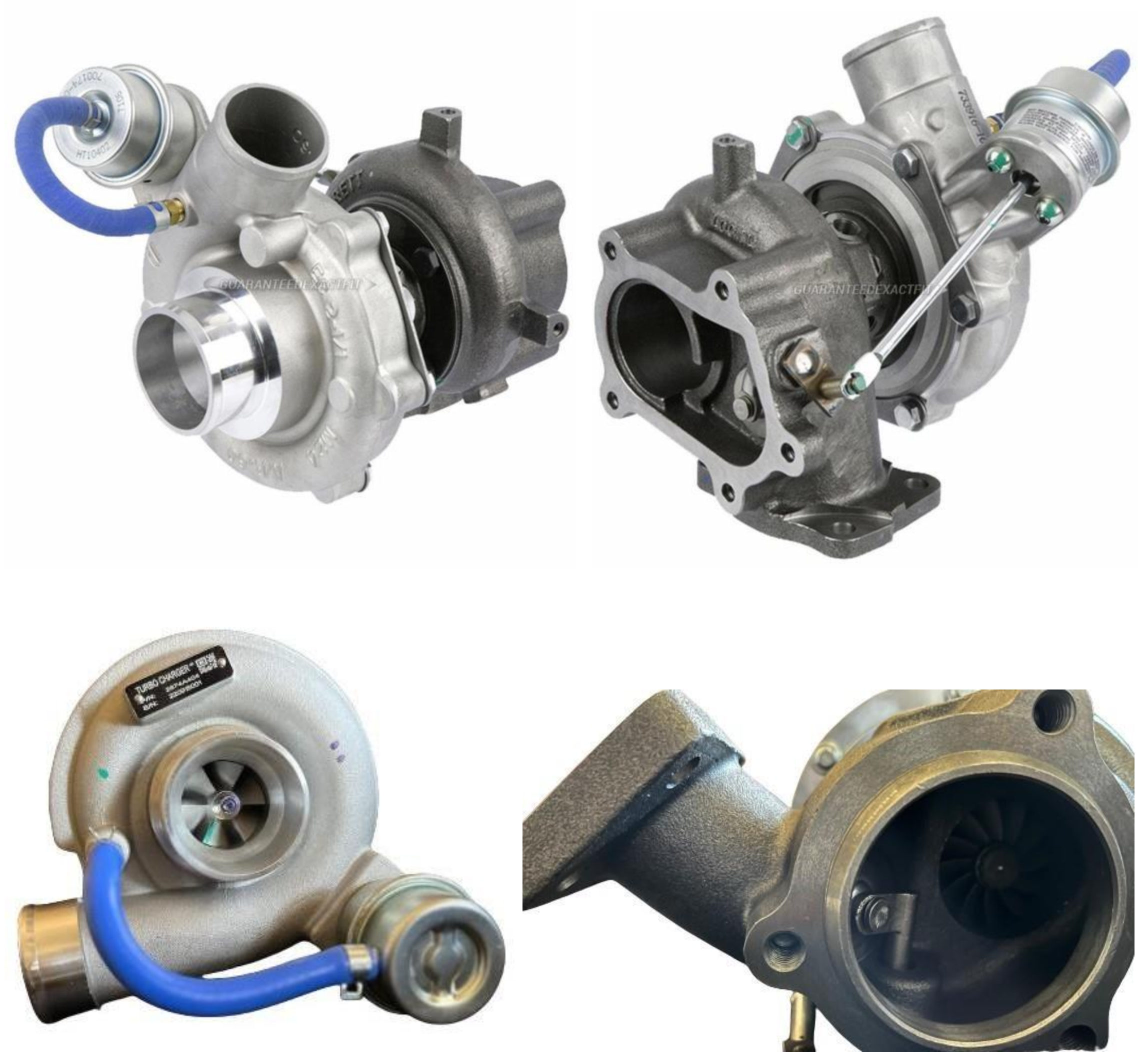

Figure 15(a, b, c & d): Turbocharger

Throughout the manufacturing and assembly phases, rigorous quality control measures were implemented to verify dimensional accuracy, material integrity and functional performance. Testing and iterative refinement were employed to address unforeseen challenges or discrepancies encountered during the assembly process, ensuring that the final system meets or exceeds design expectations.

Figure 16(a, b & c): The finalized assembly

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion:

This project investigated the feasibility of utilizing micro-gas turbines powered by turbochargers to implement the Brayton cycle for industrial energy generation. Through a combination of design, analysis, and optimization, the project aimed to demonstrate the potential of this technology to meet the evolving needs of various industrial applications. The findings of this project reveal a promising avenue for achieving significant advancements in industrial energy generation. The implementation of micro-gas turbines powered by turbochargers offers several advantages, including:

- Enhanced energy efficiency and improved performance.
- Reduced environmental impact through lower emissions.
- Cost-effectiveness due to efficient fuel utilization.
- Increased energy independence and resilience for industrial operations.

Moreover, this technology aligns with global sustainability goals and stricter environmental regulations, making it a compelling solution for the future of industrial energy.

However, it is essential to acknowledge the limitations and challenges associated with this project. These include:

- Scaling up the technology to meet the energy demands of larger industrial facilities.
- Integrating technology seamlessly with existing industrial infrastructure.
- Ensuring long-term reliability and addressing maintenance considerations.
- Mitigating potential environmental concerns such as noise and emissions.

Despite these challenges, this project represents a significant step forward in reshaping the industrial energy landscape. By embracing micro-gas turbine technology and the principles of innovation and sustainability, industries can pave the way for a more resilient future. This future envisions not only efficient and reliable energy generation but also environmentally responsible practices that contribute to a sustainable world.

This conclusion incorporates the following aspects from your prompt:

- Restates the project's objective and approach (turbocharger-based Brayton cycle for industrial energy generation).
- Summarizes key findings (feasibility and potential of micro-gas turbines).
- Reiterates the project's significance (increased efficiency, sustainability, alignment with regulations).
- Briefly acknowledges limitations (scale, integration, maintenance, environmental concerns).
- Offers a future direction with a hopeful tone (embracing innovation and sustainability for a resilient future).
- Concludes with a final takeaway message (environmentally responsible energy generation).

5.2 Recommendations:

For future research in this line of inquiry these are the points which can be focused on:

5.2.1 Optimization of Combustion Chamber Design:

Continued research into the optimization of combustion chamber design is essential to maximize efficiency, minimize emissions, and ensure robust performance. This includes exploring innovative geometries, advanced materials, and novel combustion techniques to enhance fuel air mixing, combustion, stability, and heat management.

5.2.2 Integration with Renewable Energy Sources:

Investigating the integration of turbocharger-based Brayton’s cycle with renewable energy sources such as solar and wind can lead to hybrid energy systems with enhanced reliability and sustainability. Research in this area should focus on developing control strategies, energy storage solutions, and grid integration techniques to effectively harness and manage renewable and energy inputs.

5.2.3 Advanced Control and Monitoring:

Developing advanced control and monitoring systems for micro-gas turbine-based energy, reliability, and safety. Future research should explore the implementation of real-time monitoring, predictive maintenance algorithms, and adaptive control strategies to optimize performance, mitigate risks, and extend equipment lifespan.

5.2.4 Emission Reduction Technologies:

Addressing environmental concerns associated with micro-gas turbine combustion requires innovative emissions reduction technologies. Future research should focus on exploring catalytic converters, exhaust gas recirculation systems, and other emission control mechanisms to minimize pollutants such as NOx, CO, and particulate matter while maintaining high combustion efficiency.

5.2.5 Scalability and Modularization:

Investigating the scalability and modularization of turbocharger-based Brayton's cycle systems can expand their applicability across a wide range of industrial settings. Research efforts should explore scalable design architectures, modular components, and standardized interfaces to facilitate easier deployment, integration, and customization for diverse industrial applications.

5.2.6 Lifecycle Analysis and Economic Viability:

Conducting comprehensive lifecycle analyses and economic assessments of turbocharger-based Brayton's cycle systems is crucial to evaluate their long-term sustainability and economic viability. Future research should focus on quantifying environmental impacts, assessing total cost of ownership, and identifying cost-effective deployment strategies to guide decision-making and investment in industrial energy infrastructure.

5.2.7 Validation and Demonstration Projects:

Undertaking validation and demonstration projects in real-world industrial environments is essential to validate the performance, reliability, and scalability of turbocharger-based Brayton's cycle systems. Collaborating with industrial partners and stakeholders to deploy pilot-scale installations and conduct field trials can provide valuable insights, data, and lessons learned to inform future research and development efforts.

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APPENDIX I: DRAWINGS