

# **THE STUDY OF MICRO GAS TURBINE ENGINE**

**BY**

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### **ABSTRACT**

This project aims to study engine combustion characteristics on a designed micro gas turbine from a turbocharger. The engine was built from an automobile turbocharger with a custom combustion chamber. Pressure and temperature sensors at different points of the engine allow the observation of individual thermodynamic parameters. In addition, a gas turbine analysis program will be developed to observe related thermodynamic parameters, including atmospheric absolute pressure, pressure ratio, turbine inlet temperature, compressor and turbine isentropic efficiency, and ambient temperature, that affect gas turbine engine overall performance.

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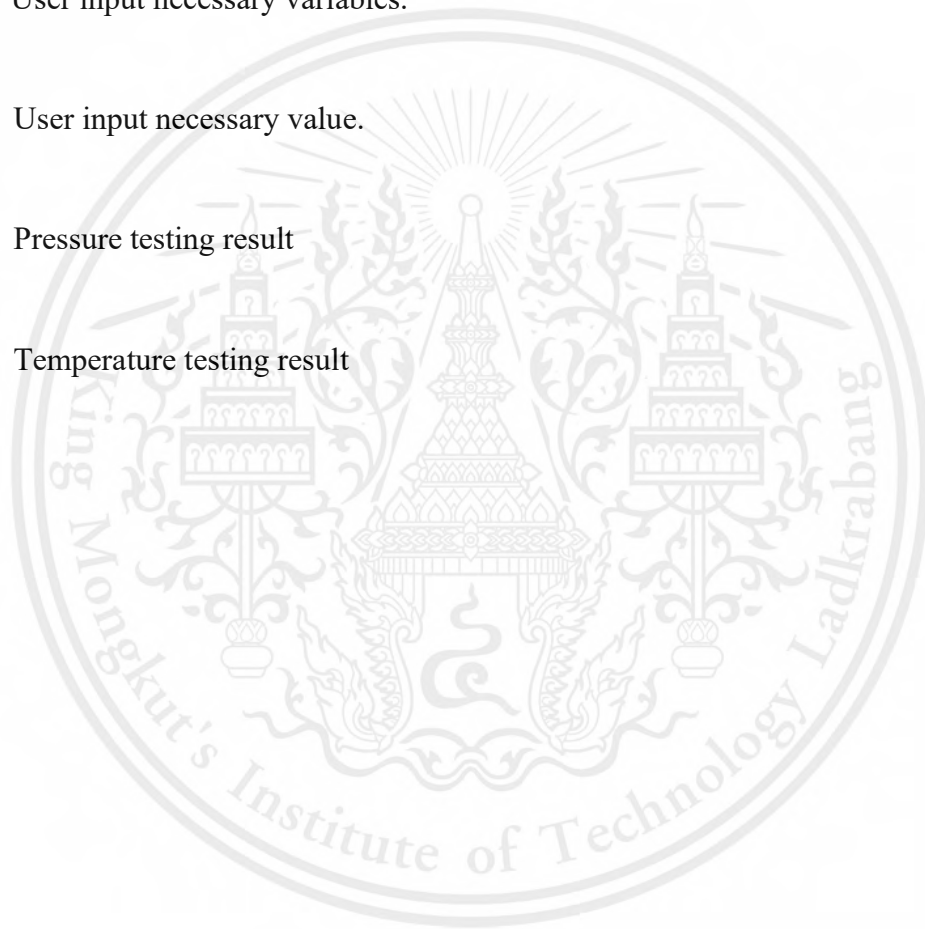
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## LIST OF SYMBOLS/ABBREVIATIONS

<b>Symbols/Abbreviations</b>	<b>Terms</b>
$P_1$	Atmospheric absolute pressure.
$R_p$	Pressure ratio.
TIT	Turbine inlet temperature.
Comisen	Compressor isentropic efficiency.
Turisen	Turbine isentropic efficiency.
$T_1$	Ambient temperature.
$P_2$	Pressure delivered by compressor.
$P_{r1}$	Relative compressor inlet pressure.
$h_1$	Specific enthalpy ambient air.
$P_{r2}$	Dimensionless pressure.
$T_{2s}$	Isentropic compressed air temperature.
$h_{2s}$	Isentropic compressed air enthalpy.
$h_{2a}$	Actual compressed air enthalpy.
$h_3$	Turbine inlet air enthalpy.
$P_{r3}$	Relative pressure at turbine inlet.
$Q_{in}$	Heat input to combustion chamber.
$P_{r4}$	Relative pressure at turbine outlet.
$h_{4s}$	Isentropic expanded air enthalpy.
$T_{4s}$	Isentropic turbine exhaust temperature.
$h_{4a}$	Actual expanded air enthalpy.
$T_{4a}$	Actual turbine exhaust temperature.
$W_C$	Work delivered by compressor.
$W_T$	Work delivered by turbine.
$\eta_{th}$	Thermal efficiency.

# CHAPTER 1

## INTRODUCTION

This chapter will discuss the background and importance, objectives, scope, expected benefits, and procedures for carrying out the key parameter that effect gas turbine overall efficiency and related thermodynamic parameters for further engine analysis program , as shown in the following section.

- 1.1 Background and importance
- 1.2 Objectives of the study
- 1.3 Scope of study
- 1.4 Expected benefits.
- 1.5 Operation procedures
- 1.6 Report outline

### **1.1 Background and importance**

Gas turbines could play a main role in future power generation, addressing issues of producing clean, efficient, and fuel-flexible electric power [1]. Gas turbines are the parts of the internal combustion engine in which burning the air-fuel mixture produces hot gases to run the turbine [2], producing power. Gas turbines are widely used for producing electricity, operating airplanes, and various industrial applications. Due to the benefit, a gas turbine engine needs a high amount of initial investment and maintenance cost due to its complex component parts [3]; however, micro gas turbine technology comes into play from a large-scale gas turbine powerplant to a smaller scale single combustion engine that can satisfy electricity energy production [4] and various applications for smaller scale project as same as conventional gas turbine engine.

This chapter introduces the Micro gas turbine, which offers several potential advantages compared to other technologies for small-scale power generation [5], including compact size, greater efficiency, lower emission, lower electricity cost, and opportunities to utilize waste fuels [6]. The micro gas turbine engine efficiency may vary significantly due to factors such as ambient temperature [7] and other related thermodynamic parameters. Studies have shown that Oyedepo and Kilanko [8] studied the thermodynamic analysis of a gas turbine power plant fitted with an evaporative cooler based in Nigeria. They concluded that power output increased

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by 5-10% and thermal efficiency by around 2-5% on decreasing the inlet air temperature by 5°C. when operating micro gas turbines, leading to operated micro gas turbines in Thailand with average climate temperature of around 30-34 °C depend on the region expected power output would be near as in Nigeria because both countries are considered high-temperature countries throughout the year, leading to engines that are designed for other countries' climate zones with engines connected to output load conditions such as the electrical power generation process, which might affect the overall engine efficiency and power production[9]. As mentioned, in gas turbine ambient air problems, some studies have shown that introducing inlet air cooling [10] with different cooling techniques can improve overall efficiency. Barakat et al. [11] investigated the application of a to-air heat exchanger (EAHE) cooling system to enhance a gas turbine power output. They noted that the EAHE inlet air cooling system helped to increase the power output by 9%, real efficiency by 4.8%, and power production by a significant amount.

However, other thermodynamic parameters may influence the efficiency and effectiveness of micro gas turbines. In this case, all related parameters affecting overall engine efficiency must be considered for an optimal operation point engine to gain expected overall efficiency and power production. Usually, the initial investment cost to make a gas turbine is considered a high-cost investment due to the high market price of engine components. That said, this research will also consider the engine parts market price as one of the main considerations.

## **1.2 Research objectives.**

1.2.1 This research aims to investigate characteristic of combustion process due to related thermodynamic parameters by using a computer coding for analysis tool to determine optimal engine operation condition of a micro gas turbine engine.

1.2.2 This research aims to study combustion process from micro gas turbine engine from turbocharger due to thermodynamic parameters including pressure and temperature for further analysis.

## **1.3 Scope of research**

1.3.1 Radial-in flow turbine blade form turbocharger automotive component.

1.3.2 Testing machine operated with no load condition.

- 1.3.3 Determine engine work output by gather related parameters including pressure and temperature.
- 1.3.4. Using liquefied petroleum gas (LPG) to be engine fuel.
- 1.3.5 Using C# computer language to develop engine analysis program.

#### 1.4 Expected benefits and application.

- 1.4.1 Prototype for micro gas turbine engine.
- 1.4.2 Gas turbine engine analysis program for further project analysis.

#### 1.5 Operational procedures

The operational procedures of this research study are shown in Table 1.

**Table 1.1** The research schedule

Task	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7
	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
1. C# fundamental learning	←→						
2. Develop engine analysis program	←→	←→					
3. Component Preparation and testing	←→	←→					
4. Testing engine set up			←→	←→			
5. Mock test with various main components				←→	←→		
6. Test and Collect data						←→	
7. Report Preparation							←→

#### 1.6 Report Outline

The rest of this report is organized as follows:

- Chapter 2 reviews the literature and thermodynamic theories for gas turbine fundamental working principle and it application.

- Chapter 3 describes the development process and methodology of an engine analysis program, in the other hand describes process of study the micro gas turbine testing machine.
- Chapter 4 discusses the data recorded, measurements, and observation. Chapter 5 closes the report, reviewing the work undertaken and draws conclusions about key parts of the work that was undertaken.

## CHAPTER 2

### REVIEW OF LITERATURE AND RELATED THEORY

This chapter discusses related field research paper ( section 2.1 ) in order to be guideline and reference for further step procedure and discuss about fundamental of how gas turbine engine work ( section 2.3 ) with related gas turbine work principle with respect thermodynamic subject due to engine working cycle ( section 2.2 ) and most importantly gas turbine main components ( section 2.4 ).

#### 2.1 Literature review

Thomas Baumgart (2001) [12] designed and built the engine. Small gas turbine using parts of the turbocharger system (Turbocharger) Model 3K-WarnerKP31 which is a turbocharger (Turbocharger) that is the smallest of today's automobiles Diameter of the impeller of the compressor Only 33 millimeters and the diameter of the turbine is only 31 millimeters. The smallest possible gas turbine engine. By using the current turbine wheel as components However, it may be too difficult to design an engine that uses an impeller of a small compressor with maximum efficiency, but it can be used as an option to become a force in the field. That's the electric current.

Chakkrin Chuayin, Thiwat Wetsaphan, Christmas Apinanthaporn; and Sinchai Chinworarat[13] (2002) designed and create the parts and assemble them into a small gas turbine engine. The design specified a driving force of approximately 60 newtons. But when actually testing the machine It was found that the driving force obtained was less than designed. This is a result of the efficiency of the fuel pump. Quality of fuel and the efficiency of the process is still not perfect

Payungsak Phiphat and Amphon Onnarat [14] (2002) designed and Build a gas turbine engine that uses a mixture of LPG + N<sub>2</sub> fuel, which will use the experimental results obtained. Applied in the agricultural industry Taking into account the thermal efficiency and Fuel efficiency was the guiding principle in the design and construction of this prototype gas turbine engine.

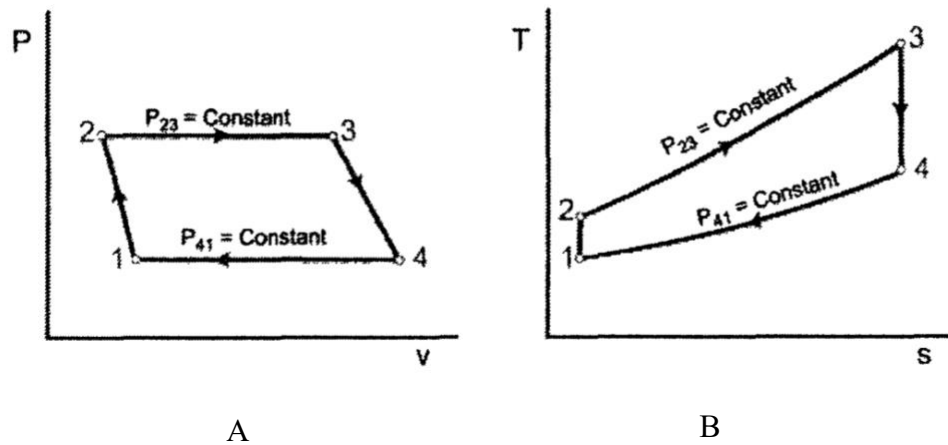
Chanan Chaisuk [15] (2007) designed and build a small gas turbine engine using Air compressor blade set and the turbine shaft from the turbocharger of the Nissan RB20 engine. Used to create a small gas turbine engine. When assembled into a gas turbine engine, it can Run the engine at idle speed and cannot accelerate the speed.

M. Fikri, M. Ridzuan, Hamidon Salleh [16] (2016) development of low-cost micro gas turbine engine, which is designed for the purposes of new electrical generation. to evaluation the performance of the developed micro gas turbine. The test rig engine basically was constructed using a Nissan 45V3 automotive turbocharger. The speed of the LP turbine can be reached up to 35000 RPM and produced 18.5kw of mechanical power performance of the developed.

M Usman Butt [17] (2019) made A low-cost micro turbojet made by using an automobile turbocharger The fuel used is liquid petroleum gas (LPG). The maximum pressure recorded in the combustion chamber was 11.5 psi and a pressure loss of about 4%. The maximum rpm (revolutions per minute) of the engine ranged to 84000.

## 2.2 Related thermodynamic theories

Gas turbine engine It is a working engine that applies the principles and theory of the Brayton cycle figure 1. The type that is suitable for use is the type that has. Combustion at constant and continuous pressure includes an air compressor (air compressor), a combustion chamber turbine set, and feeding equipment. Fuel because the shaft of the turbine (Turbine) and the air compressor (Compressor) are the same, so the shaft from the turbine is used to compress some of the air. However, most of the work will be exported to the shaft for use as desired.



**Figure 2.1** Brayton cycle A shown P-V diagram B shown T-S diagram.

From State 1 to State 2 the gas undergoes an isentropic, adiabatic compression. This process increases the temperature, pressure, and density of the gas

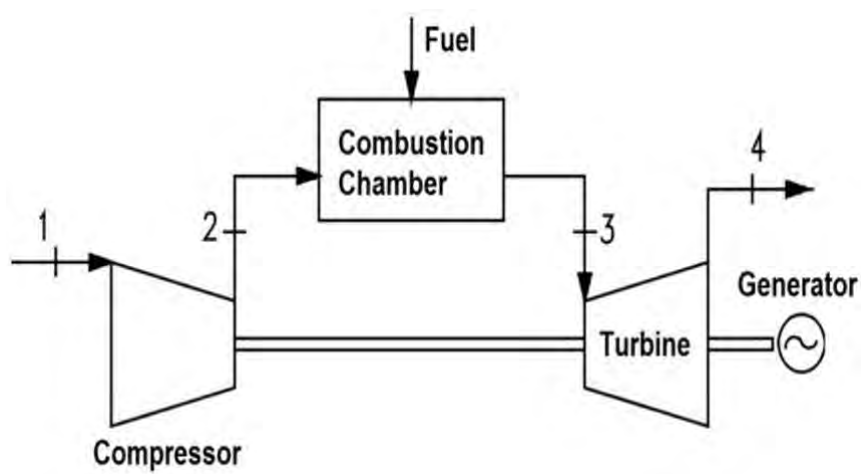
From State 2 to State 3, heat is added at constant pressure. For a gas-turbine, heat is added through a combustion process.

From State 3 to State 4 the gas passes through an adiabatic isentropic turbine which decreases the temperature and pressure of the gas

From State 4 to State 1 It is a process of delivering heat at a constant pressure design. In this process, exhaust gases that have undergone expansion are expelled into the atmosphere this phenomenon occur only in opened system in the other hand For the closed Brayton cycle, heat is removed from the gas between State 4 and State 1 via a heat exchanger.

### 2.3 Gas turbine working principle.

The gas turbine working principle in Figure 2.2 expresses that it will have pressure when air is compressed through the compressed air unit. Furthermore, with higher speeding, the speed is very high, so it must pass through a set to change speed to pressure; the speed decreased. At the same time, fuel is injected and mixed with high-pressure air. The igniter will ignite the fire and cause combustion. When the mixture is at high pressure, it will burn, and It expands violently towards the rear of the engine through the NGV booster unit and is forced into a collision with the wings of the turbine (Turbine), causing the turbine to rotate, which causes the air compressor set on the shaft to The same thing is driven to rotate as well. The rotation of the turbine is used to drive an air compressor and outputs at the same time.



**Figure 2.2** Gas turbine schematic open system diagram

## 2.4 Gas turbine main components

A gas turbine engine consists of 3 main important parts as shown.

Compressor figure 2.3: are used to compress air or increase the pressure of air entering the combustion chamber to rise or make the air mass large in a specified amount to produce. Allow the mixture to ignite to expand fully and violently when ignition occurs. The air is in the form of rotating fins mounted on a shaft, the same shaft as the turbine set.



**Figure 2.3** Compressor from automotive part

Combustion chamber Figure 2.4: Characteristics of a combustion chamber generally include a diffuser, casing, liner, and Swirler. After the compressed air leaves the air compressor, it passes through a diffuser to reduce airspeed before entering the combustion room by the casing. It is the outermost part that is covered to prevent heat. Come out to the outside, including preventing air from leaking out to the outside because it is a sensitive part. Pressure is different from the outside, which is the compressed air from an air compressor. A

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bra (Liner) will be inside, which controls air distribution in chamber , it is to Keep it hot, so it does not come out right in the casing directly because the undershirt is the part that is very close to burning. Ultimately, it is necessary to make it with heat-resistant materials.



A



B

**Figure 2.4** D.I.Y Combustion chamber A shown chamber casing B shown liner inside combustion chamber.

Turbine wheel Figure 2.5: It converts the energy generated from the expansion of hot gases, which were burned in the chamber. The gas burns and then shoots through a turbine, which changes thermal energy to kinetic energy caused by the movement of hot gas into mechanical energy in the form of rotation. Air compressors and accessories assembled or installed on the same shaft as the turbine will also be driven to rotate. As for the engine that uses power to drive the shaft, leading power is generated.



**Figure 2.5** Turbine wheel from automotive part

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## 2.5 Chapter Summary

In this chapter briefly introduce to related field literature review ( section 2.1 ) and related thermodynamic theories ( section 2.2 ) to be guidance and reference for further step procedure of the research.

# CHAPTER 3 METHODOLOGY

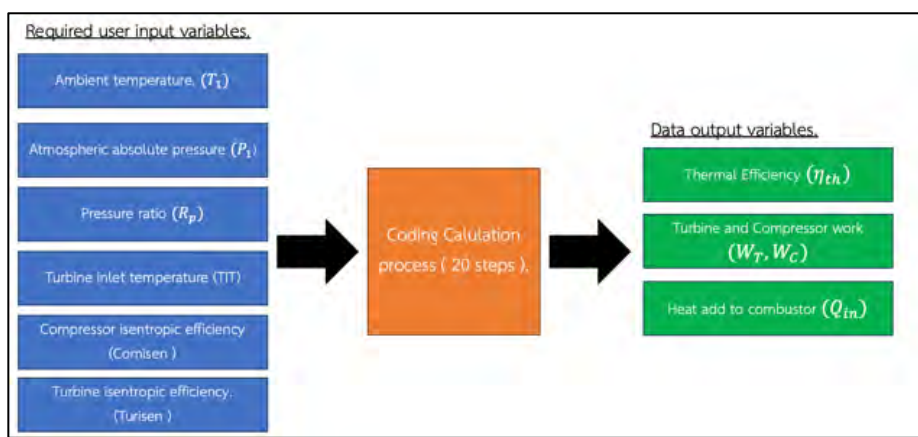
## 3.1 Introduction

In Chapter 2, we mentioned the gas turbine working cycle with the thermodynamic theory Brayton cycle. Each stage of the cycle represents a point due to the engine process, leading to the value of thermodynamic parameters, which can be considered. However, hand solutions take a long period of time due to each stage containing various calculation steps, leading to the development of a calculation program that can shorten the calculation period.

This chapter describes the development of a thermal analysis program for a gas turbine engine using related thermodynamic formulas as the basis for consideration of gas turbine engine stage by stage. The engine analysis program principle is to be an analyzing tool in terms of related thermodynamic parameters that affect overall gas turbine engine operation, such as the change in inlet temperature due to operating the gas turbine engine in various countries, the change of turbine temperature due to material heat tolerance leading to a short period of calculation time due to changing engine parts using the engine analysis program. Another part of this chapter will gather raw data from the testing machine of a micro gas turbine engine using automotive parts, including a compressor and turbine set with a DIY combustion chamber, to study thermodynamic parameters, including pressure and temperature for engine characteristics in the topic of how related parameter change over time and there utilize.

## 3.2 Engine analysis program

In this section will be only mentioned engine analysis program, the program itself is consider as calculation program aims to shorten calculation period of gas turbine engine efficiency and other components work output using thermodynamic theories and related equation to be base consideration. Coding flow chart express in figure 3.1.



**Figure 3.1** Coding flow chart

According to Figure 3.1 coding flow chart, the program will require the user to input necessary values due to the engine working principle, including ambient temperature, atmospheric absolute pressure, pressure ratio between the inlet and outlet of both components, including compressor and turbine, turbine inlet temperature, both compressor and turbine isentropic efficiency. The coding calculation process follows, including thermodynamic theories and equations. This section will be expressed in (section 3.2.1). The program will include thermal efficiency, turbine and compressor work, and heat added to the combustor for further engine analysis.

### 3.2.1 Coding calculation program procedure.

As mentioned in section 3.2 the coding calculation process express in twenty step procedure using thermodynamic theories and equation [18] to be base reference for further analysis. The coding calculation step procedure expresses as following.

Step 1: Store user input for all user input variable.

In first sept user required to input necessary value needed for further calculation coding process. Needed necessary value express in table 3.1.

**Table 3.1:** User input necessary variables

$P_1$	Atmospheric absolute pressure.
$R_p$	Pressure ratio.
TIT	Turbine inlet temperature.
Comisen	Compressor isentropic efficiency.
Turisen	Turbine isentropic efficiency.
$T_1$	Ambient temperature.

Step 2: Store all look up table array.

In second step due to coding calculation most of the reference value according from A-17: Ideal gas properties of air figure 3.2, leading to needed to import all the value from A-17 table in coding process.

TABLE A-17 Ideal-gas properties of air										
T K	h kJ/kg	P <sub>r</sub>	u kJ/kg	v <sub>r</sub>	s <sup>o</sup> kJ/kg · K	T K	h kJ/kg	P <sub>r</sub>	u kJ/kg	s <sup>o</sup> kJ/kg · K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.44	457.78	92.84
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76
300	300.19	1.3850	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53
310	310.24	1.5546	221.25	572.3	1.73498	730	745.62	33.72	536.07	62.13
315	315.27	1.6442	224.85	549.8	1.75106	740	756.44	35.50	544.02	59.82
320	320.29	1.7375	228.42	528.6	1.76690	750	767.29	37.35	551.99	57.63
325	325.31	1.8345	232.02	508.4	1.78249	760	778.18	39.27	560.01	55.54
330	330.34	1.9352	235.61	489.4	1.79783	770	789.03	43.35	567.12	51.64
340	340.42	2.149	242.82	454.1	1.82790	800	821.95	47.75	592.30	48.08
350	350.49	2.379	250.02	422.2	1.85708	820	843.98	52.59	608.59	44.84
360	360.58	2.626	257.24	393.4	1.88543	840	866.08	57.60	624.95	41.85
370	370.67	2.892	264.46	367.2	1.91313	860	888.27	63.09	641.40	39.12
380	380.77	3.176	271.69	343.4	1.94001	880	910.56	68.98	657.95	36.61
390	390.88	3.481	278.93	321.5	1.96633	900	932.93	75.29	674.58	34.31
400	400.98	3.806	286.16	301.6	1.99194	920	955.38	82.05	691.28	32.18
410	411.12	4.153	293.43	283.3	2.01699	940	977.92	89.28	708.08	30.22
420	421.26	4.522	300.69	266.6	2.04142	960	1000.55	97.00	725.02	28.40
430	431.43	4.915	307.99	251.1	2.06533	980	1023.25	105.2	741.98	26.73
440	441.61	5.332	315.30	236.8	2.08870	1000	1046.04	114.0	758.94	25.17
450	451.80	5.775	322.62	223.6	2.11161	1020	1068.89	123.4	776.10	23.72
460	462.02	6.245	329.97	211.4	2.13407	1040	1091.85	133.3	793.36	22.39
470	472.24	6.742	337.32	200.1	2.15604	1060	1114.86	143.9	810.62	21.14
480	482.49	7.268	344.70	189.5	2.17760	1080	1137.89	155.2	827.88	19.98
490	492.74	7.824	352.08	179.7	2.19876	1100	1161.07	167.1	845.33	18.896
500	503.02	8.411	359.49	170.6	2.21952	1120	1184.28	179.7	862.79	17.886
510	513.32	9.031	366.92	162.1	2.23993	1140	1207.57	193.1	880.35	16.946
520	523.63	9.684	374.35	154.1	2.25997	1160	1230.92	207.2	897.91	16.064
530	533.98	10.37	381.84	146.7	2.27967	1180	1254.34	222.2	915.57	15.241
540	544.35	11.10	389.34	139.7	2.29906	1200	1277.79	238.0	933.33	14.470
550	555.74	11.86	396.85	133.1	2.31809	1220	1301.31	254.7	951.09	13.747
560	565.17	12.66	404.42	127.0	2.33685	1240	1324.93	272.3	968.95	13.069
570	575.59	13.50	411.97	121.2	2.35531					3.21751

Figure 3.2 : A-17: Ideal gas properties of air, Thermodynamics: An Engineering Approach (SI UNITS) (9 th, ISE) [18].

Step 3: Compute compressor delivered pressure ( $P_2$ ).

According from user input variable pressure ratio and atmospheric absolute pressure can determined the pressure delivered by compressor using equation 1. And store value for further calculation.

$$P_2 = R_p * P_1 \quad (1)$$

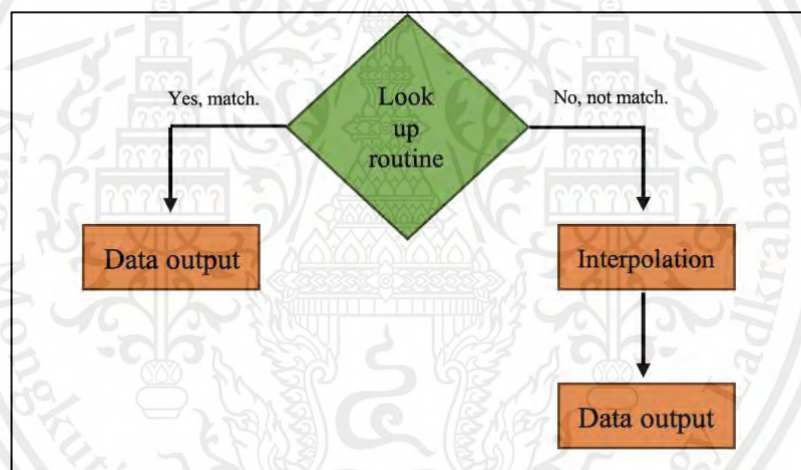
Where  $P_2$  and  $P_1$  represent atmospheric absolute pressure, the pressure delivered by compressor respectively and  $R_p$  is pressure ratio between compressor inlet with respect outlet.

Step 4: Determine  $P_{r1}$  from ambient temperature.

According from user input variable ambient temperature ( K ) leading to determine relative compressor inlet pressure (  $P_{r1}$  ) from interpolation formula equation 2, look up routine figure 8 reference values form A-17: Ideal gas properties of air table figure 7.

$$y = y_1 + (x - x_1) \frac{(y_2 - y_1)}{(x_2 - x_1)} \quad (2)$$

Where y and x represent linear interpolation value, independent variable respectively and  $x_1, y_1, x_2, y_2$  represent value function at points.



**Figure 3.3** : A-17 interpolation look up routine.

According from figure 3.3 after user input value the program will operate between two routes. The first route that user input data match value in A-17 figure 3.3 table leading to output variables as same as value in A-17 table, on the other hand second route when user input data variables do not include in A-17 table program will begin interpolation look up routine using equation 2 for calculate data output value.

Step 5: Determine specific enthalpy ambient air (  $h_1$  ) from ambient temperature.

According from user input variable ambient temperature ( K ) leading to determine Specific Enthalpy ambient air (  $h_1$  ) from interpolation formula, look up routine reference values form A-17: Ideal gas properties of air .

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Step 6: Determine dimensionless pressure  $P_{r2}$  .

To determine dimensionless pressure (  $P_{r2}$  ) needed two necessary values to compute using equation 3 relation between relative pressure and pressure ratio.

$$R_p = \frac{P_{r1}}{P_{r2}} \quad (3)$$

Where  $R_p$  represent pressure ratio between compressor inlet and outlet pressure due to phenomena happened while compressor operated isentropic compression is occur leading to equation 3  $P_{r1}$  is numerator and dimensionless pressure ( $P_{r2}$ ) is denominator.

Step 7: Determine isentropic compressed air temperature (  $T_{2s}$  ) from dimensionless pressure.

According to dimensionless pressure (  $P_{r2}$  ) from step 6 leading to determine isentropic compressed air temperature (  $T_{2s}$  ) from A-17 interpolation look up routine.

Step 8: Determine isentropic compressed air enthalpy (  $h_{2s}$  ) from isentropic compressed air temperature.

According to isentropic compressed air temperature (  $T_{2s}$  ) from step 7 leading to determine isentropic compressed air enthalpy (  $h_{2s}$  ) from A-17 interpolation look up routine.

Step 9: Determine actual compressed air enthalpy (  $h_{2a}$  ) .

To determine actual compressed air enthalpy needed three necessary values to compute using equation 4 relation between enthalpy and compressor isentropic efficiency.

$$h_{2a} = \left( \frac{h_{2s} - h_1}{Comisen} \right) + h_1 \quad (4)$$

Where  $h_{2a}$  ,  $h_{2s}$  represent actual compressed air enthalpy and isentropic compressed air enthalpy respectively.  $h_1$  ,  $Comisen$  represent specific enthalpy ambient air and  $Comisen$  represent compressor isentropic efficiency from user input variables.

Step 10: Determine turbine inlet air enthalpy (  $h_3$  ) .

According from first step user input variables turbine inlet temperature ( TIT ) can be utilize due to A-17 interpolation look up routine leading to output data turbine inlet air enthalpy (  $h_3$  ).

Step 11: Determine relative pressure at turbine inlet (  $P_{r3}$  ).

According from first step user input variables turbine inlet temperature ( TIT ) can be utilize due to A-17 interpolation look up routine leading to output data relative pressure at turbine inlet (  $P_{r3}$  ).

Step 12: Determine heat input to combustion chamber (  $Q_{in}$  ).

Heat input to combustion chamber can determine by enthalpy relation between turbine inlet air enthalpy and actual compressed air enthalpy equation 5.

$$Q_{in} = h_3 - h_{2a} \quad (5)$$

Where  $Q_{in}$  represent heat input to combustion chamber and both enthalpy values represent turbine inlet air enthalpy, actual compressed air enthalpy respectively.

Step 13: Determine relative pressure at turbine outlet (  $P_{r4}$  ).

To determine relative pressure at turbine outlet needed two necessary values to compute using equation 6 relation between relative pressure and pressure ratio.

$$R_p = \frac{P_{r4}}{P_{r3}} \quad (6)$$

Where  $R_p$  represent pressure ratio between turbine inlet and outlet pressure due to phenomena happened while turbine operated isentropic expansion is occur leading to equation 3 relative pressure at turbine outlet (  $P_{r4}$  ) is numerator and relative pressure at turbine inlet (  $P_{r3}$  ) is denominator.

Step 14: Determine isentropic expanded air enthalpy (  $h_{4s}$  ).

According to dimensionless pressure (  $P_{r4}$  ) from step 13 leading to determine isentropic expanded air enthalpy (  $h_{s4}$  ) from A-17 interpolation look up routine.

Step 15: Determine isentropic turbine exhaust temperature (  $T_{4s}$  ).

According to dimensionless pressure ( $P_{r4}$ ) from step 13 leading to determine isentropic turbine exhaust temperature ( $T_{4s}$ ) from A-17 interpolation look up routine.

Step 16: Determine actual expanded air enthalpy ( $h_{4a}$ ).

Actual expanded air enthalpy can be determine using relation between enthalpy values and first step user input turbine isentropic efficiency equation 7.

$$h_{4a} = h_3 - (h_3 - h_{4s}) \times \text{Turisen} \quad (7)$$

Where  $h_{4a}$ ,  $h_{4s}$  represent actual and isentropic expanded air enthalpy with an turbine inlet air enthalpy ( $h_3$ ) and first step user input variable turbine isentropic efficiency ( $\text{Turisen}$ ).

Step 17: Determine actual turbine exhaust temperature ( $T_{4a}$ ).

According to actual expanded air enthalpy ( $h_{4a}$ ), from step 16 leading to determine actual turbine exhaust temperature ( $T_{4a}$ ) from A-17 interpolation look up routine.

Step 18: Determine work delivered by compressor ( $W_C$ ).

To determine work delivered by compressor needed two necessary values specific enthalpy ambient air and actual compressed air enthalpy using relation between enthalpy values equation 8.

$$W_C = h_{2a} - h_1 \quad (8)$$

Where  $W_C$  represent work delivered by compressor both enthalpy values  $h_{2a}$ ,  $h_1$  represent actual compressed air enthalpy and specific enthalpy ambient air.

Step 19: Determine work delivered by turbine ( $W_T$ ).

To determine work delivered by turbine needed two necessary values turbine inlet air enthalpy and actual expanded air enthalpy using relation between enthalpy values equation 9.

$$W_T = h_3 - h_{4a} \quad (9)$$

Where  $W_T$  represent work delivered by turbine both enthalpy values  $h_{4a}$ ,  $h_3$  represent actual expanded air enthalpy and turbine inlet air enthalpy.

Step 20: Determine thermal efficiency ( $\eta_{th}$ ).

To determine thermal efficiency needed three necessary values between work delivered by compressor and work delivered by turbine relation with heat input to combustion chamber equation 10.

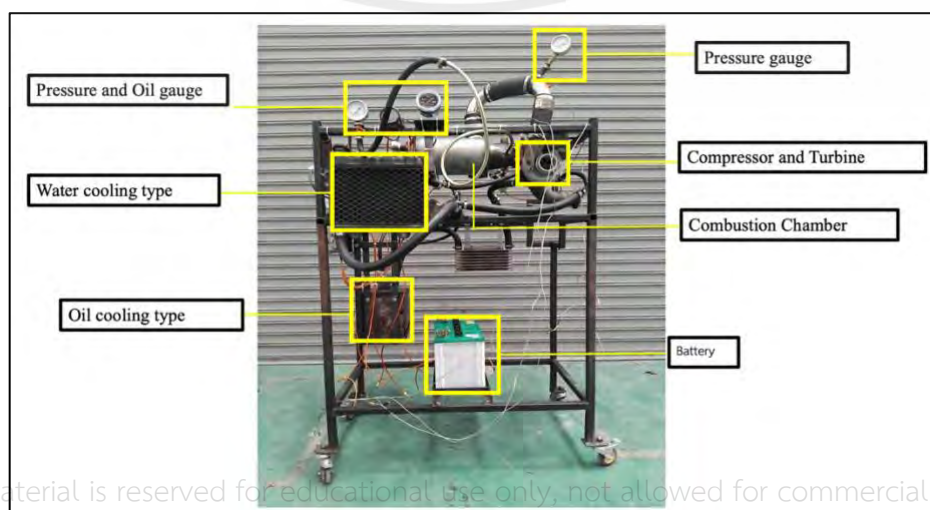
$$\eta_{th} = \left( \frac{W_T - W_C}{Q_{in}} \right) \times 100 \quad (10)$$

Where  $\eta_{th}$  represent thermal efficiency both  $W_T$ ,  $W_C$  represent work delivered by turbine and compressor respectively,  $Q_{in}$  value represent heat input to the combustion chamber.

Lastly coding output will express more in detail in chapter 4 experimental details.

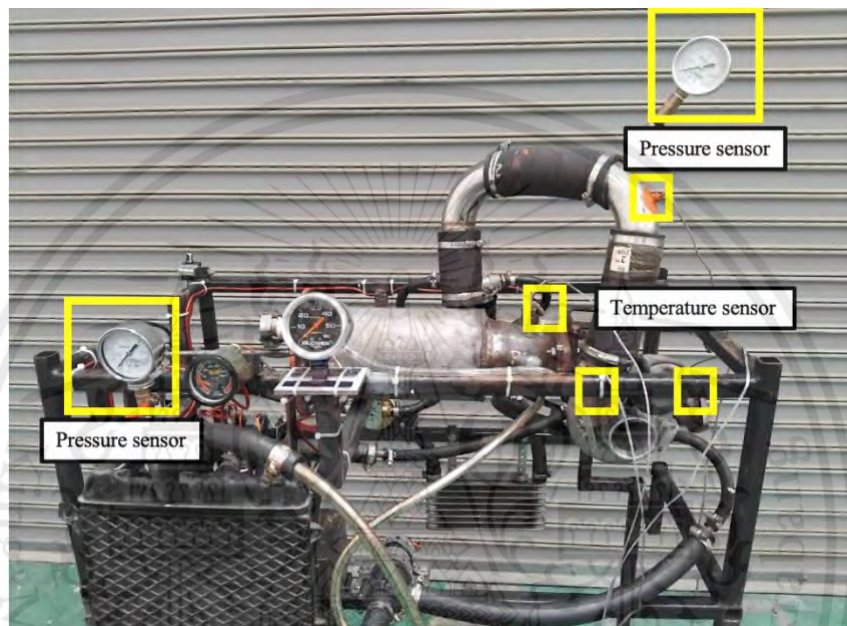
### 3.3 Study of micro gas turbine engine.

This section will gather data from the testing machine, a micro gas turbine engine Figure 9 converted from an automotive turbocharger part; the reason for choosing an automotive turbocharger part and converting it to a gas turbine engine is that the turbocharger also shares main components ( section 2.4 ) in order to make a gas turbine engine most importantly the turbocharger is an easy to access part in the automotive market also market price significantly low when compared with actual compressor and turbine made for actual gas turbine due to this research is cost-effective as much as possible therefore, automotive turbocharger part is justified.



**Figure 3.4** : Micro gas turbine form turbocharger

According to Figure 9, the main engine components are pointed to a yellow box, including a D.I.Y. combustion chamber connected with a turbocharger set representing compressor and turbine with two types of cooling: water cooling for turbine housing and oil cooling for bearings and all electronics devices supplied by a 24 V battery. This testing engine uses L.P.G. as fuel. With a thermocouple temperature sensor and pressure sensor using a gauge meter for observation, figure 10 connects the main engine while operating to observe output data for further analysis.



**Figure 3.5 :** Pressure and temperature sensor

According to Figure 3.5, the pressure sensor is indicated as large yellow boxes. The temperature sensor is indicated as smaller yellow boxes, and the pressure sensor uses a gauge meter to represent the measurement device to observe pressure at stages 2 and 3 while operating the engine. On the other hand, for the temperature sensor, a thermocouple sensor plug-in is used at every engine stage, and data is forwarded out to the data logger ( MEMORY HiLOGGER LR8431-20 ) Figure 3.6 for observation. Lastly, another measurement detail can determine the air flow rate throughout the engine by using the velocity meter Figure 3.7 for further data analysis.



**Figure 3.6 :** data logger ( MEMORY HiLOGGER LR8431-20 )



**Figure 3.7 :** velocity meter

## CHAPTER 4

### EXPERIMENTAL RESULT

#### 4.1 Introduction

Chapter 3 mentioned two methodologies, including developing an engine analysis program and studying micro gas turbines from automotive turbochargers. This chapter will mention the engine analysis program output data details and output data gathered from micro gas turbines from automotive turbocharger parts. The first results of the engine analysis program are summarized in the section, and the second result from the study of micro gas turbines from the automotive is summarized in the section.

#### 4.2 Engine analysis program summary

Engine analysis program is designed for gas turbine engines that connect to load output, meaning in order to observe output data mentioned in chapter 3 ( section 3.2 ), one of the most crucial output parameters, thermal efficiency, can be observed under load conditions however, for no load condition, gas turbine engine mainly focus on work delivered by both compressor and turbine for further work utilize also beneficial form engine analysis program. The output data of the engine analysis program will be expressed as follows: heat addition from the combustor, work delivered by the turbine and compressor, and thermal efficiency, respectively.

##### 4.2.1 Heat addition

In this section will show the result output data parameter heat addition from the combustion chamber. Figure 4.1 can be determined by equation 5 (section 3.2.1 ); the heat addition process happened from stage 2 to stage 3 while engine operating heat is added at constant pressure to the gas to prepare for the expansion process in the further engine stage.

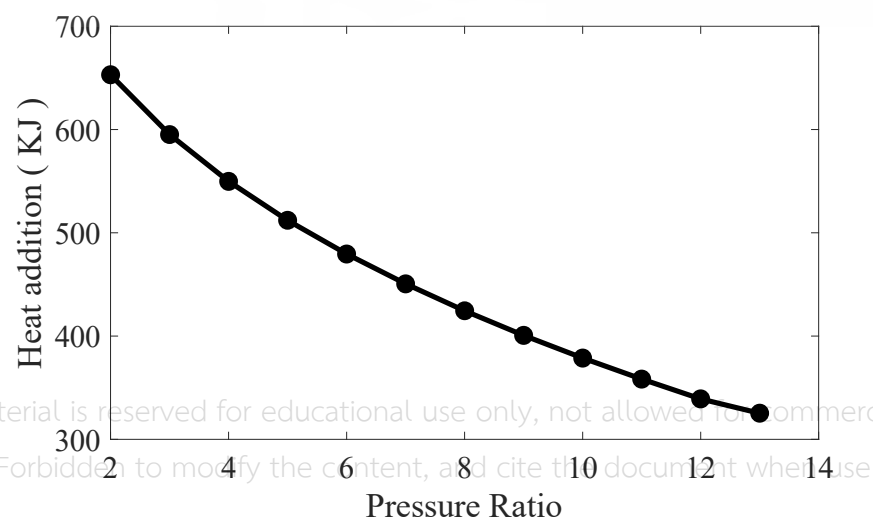


Figure 4.1 : Heat addition to combustion chamber

To output heat addition from combustor data according from chapter 3( section 3.2.1 ) initial user input variables table 4.1 to be user input variable for first step for demonstration.

**Table 4.1:** initial user input values

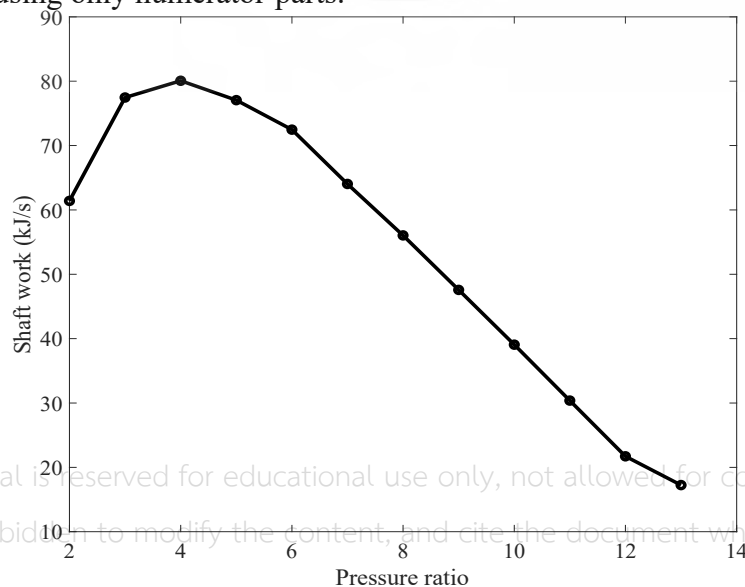
Atmospheric absolute pressure ( $P_1$ )	101,235 Pa
Pressure ratio ( $R_p$ )	1-13
Turbine inlet temperature ( TIT )	1273.15 K
Compressor isentropic efficiency (Comisen)	0.8
Turbine isentropic efficiency (Turisen)	0.8
Ambient temperature ( $T_1$ )	308.15 K

Where pressure ratio operated between 1 to 13 reasons behind is increasing pressure ratio due to the overall trend reversal occur. Turbine inlet temperature number related with heat durability of turbine material and both compressor and turbine isentropic efficiency base on thermodynamic textbook [10].

Figure 4.1 shows a strong downtrend, which is shown as a graphical result. This downtrend occurs because, according to the Brayton cycle, the heat addition stage happens in stages 2 to 3. The higher the pressure ratio, the less room for heat to generate, and therefore, the higher the pressure ratio, the less necessary heat is delivered to the system, leading to a strong downtrend.

#### 4.2.2 Net shaft work

In this section will show result output data network ( work delivered by turbine subtract by work use by compressor ) or net shaft work figure 4.2 can determined by equation 20 (section 3.2.1 ) using only numerator parts.



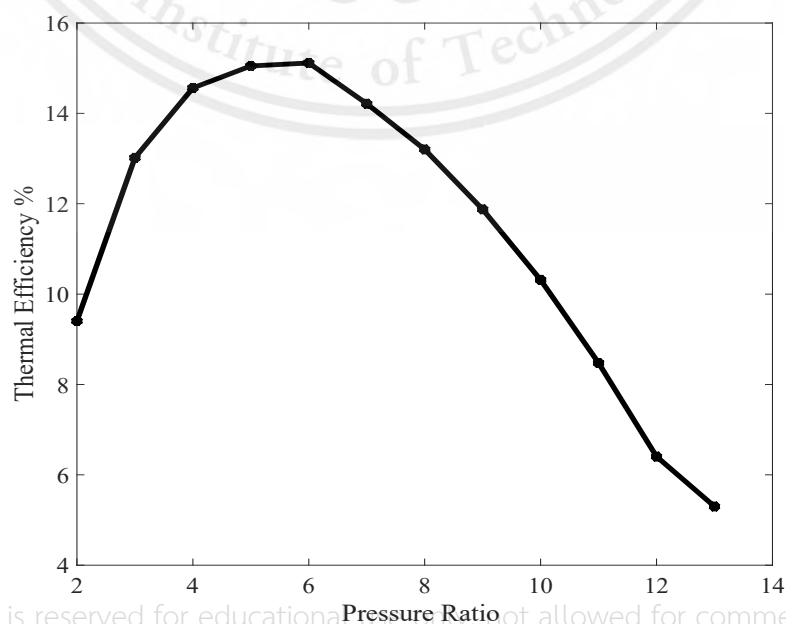
**Figure 4.2 :** Net shaft work.

To output work delivered by turbine and compressor from combustor data according from first step ( section 3.2.1 ) initial user input variables table 4.1 to be user input variable for first step for demonstration.

According to Figure 4.2, the trend x-axis represents the pressure ratio, with the y-axis representing the net shaft work the overall trend line shows an optimal peak of net work done by the compressor and turbine with an approximate pressure ratio of around 4; after the point, the trend is reversed from this information, the engine analysis program can determine the actual optimal point of net shaft work leading to consideration to be the optimal point for an engine to operate however optimal engine point is due to various related internal and external parameters the engine analysis program is a tool for consideration process.

### 4.2.3 Thermal efficiency

This section will show the result output data parameter thermal efficiency. Figure 4.3 can be determined by equation 20 (section 3.2.1 ). Thermal efficiency results can occur only when the engine is connected to external load conditions; thermal efficiency value is the relation between the heat addition process and net work done by both turbine and compressor. Thermal efficiency plays the leading role in how the system will justify profits or else due to the net work done by both compressor and turbine is the mechanical work that the operator will receive; on the other hand, heat addition to the combustion chamber from a combustor is where operator needed to be supplied work to the system. If the more significant operator receives more justified profit, the project will be.



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Figure 4.3 : Thermal efficiency

To output thermal efficiency data according from first step ( section 3.2.1 ) initial user input variables table 4.1 to be user input variable for first step for demonstration

According to Figure 4.3, the trend x-axis represents the pressure ratio, while the y-axis represents thermal efficiency. The overall trend line increases at the peak value, known as the engine operation optimal point; however, the engine does not need to operate at optimal due to other external factors. After peaking at the optimal point, the trend line is reversed. The trend line reversal occurs by increasing the pressure ratio, leading to a lesser heat addition gap process. This phenomenon significantly affects thermal efficiency drop.

#### 4.2.4 Effect of turbine inlet temperatures

The main consideration of the engine analysis program is shortening the calculation time, this scenario according from the testing machine micro gas turbine from automotive turbocharger parts nowadays there are various choice to choose for turbocharger, the engine analysis program can determine various of best optimal point due to the change of components Figure 4.4.

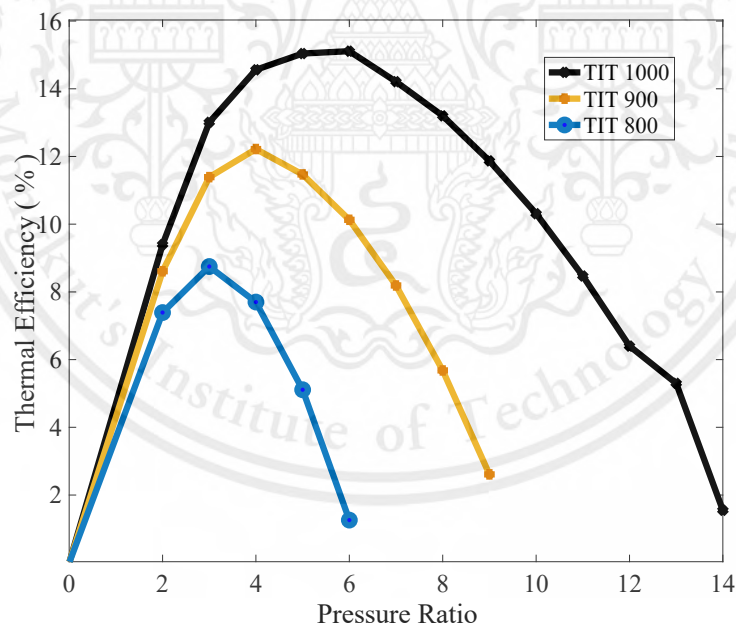


Figure 4.4 : Comparison among turbocharger sets

To output thermal efficiency data according from first step ( section 3.2.1 ) initial user input variables table 4.1 to be user input variable for first step for demonstration in additionally the comparison with 3 turbocharge sets with specific turbine inlet temperature of each part. Result shown each performance curve due to their components with various best engine operation optimal point to be consideration.

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Figure 4.4 shows the variations of thermal efficiency with compression ratio at constant TIT. It can be seen that efficiency increases with compression pressure ratio up to certain value and then becomes almost constant for a fixed turbine inlet temperature. In some cases, a decrease in efficiency is also observed.

### 4.3 Study of micro gas turbine engine summary

In chapter 3 mentioned measurement method to observe related thermodynamic parameter including pressure table 4.2 and temperature table 4.3 express as following.

**Table 4.2:** Pressure testing result

$P_1$	$P_2$	$P_3$	$P_4$
1 atm	1.5 bar	1.4 bar	1 atm

According to Table 4.2, testing pressure data was gathered for pressure sensors at stages 2 and 3. On the other hand, pressure at stages 1 and 4 are considered as pressure for ambient entering the compressor inlet, but pressure at stage 4 leads out to the environment due to the testing machine being under no-load condition; therefore, pressure at stage 4 value is most likely approximate around 1 atm. From stage 2 to stage 3, the pressure from the compressor leads through the combustion chamber and before entering the turbine inlet; the reason behind this significant pressure drops, most likely from the combustion process in the chamber or related internal parameters, might also affect this pressure drop.

**Table 4.3:** Temperature testing result

$T_1$	$T_2$	$T_3$	$T_4$
37 °C	49 °C	1000 °C	383 °C

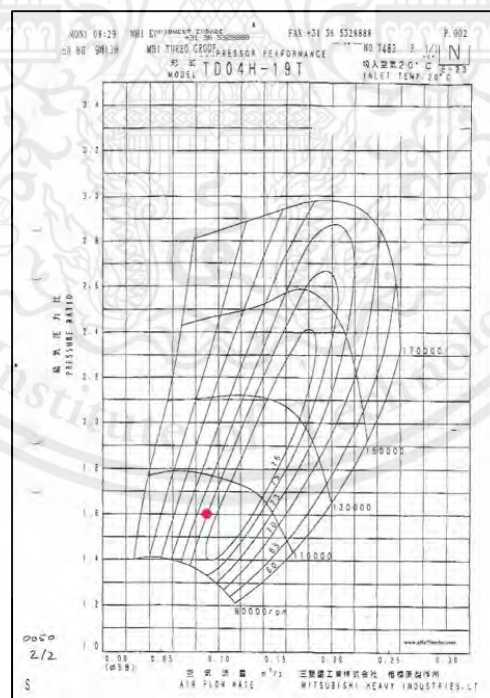
According to Table 4.3, testing temperature data is gathered from temperature sensors throughout the engine stage. At stage 1, the ambient temperature depends on the climate zone that the engine is in; in this case, Thailand, the temperature at first is approximately around 37 °C As the data in the table from stage 1 to stage the temperature increases the significant amount due to compression process resulting temperature increasing however from stage 2 to stage can

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spot a vast increasing gap from 49 °C to 1000 °C due to the compressed gas goes through heat addition process in the combustion chamber leading hot gas ready for the following step procedure before entering the turbine noted that hot gas from combustion chamber needed to add heat at the calculated amount due to if too much proportion. After the heat addition process for the combustion chamber, hot gas is ready to enter the turbine in order to go through an expansion process from the turbine leading to the turbine wheel turning, to produce machinal energy to drive the shaft for power production and other utilize under load conditions, in additional no load conditions as the testing machine is under no load condition meaning output power mostly likely came out as kinetic energy or in the form of hot gas both of the terms can be utilized such as for kinetic most commonly used to drive a machine in the other hand hot gas or hot air can be utilized by using as boiler heating source to drive another steam turbine engine, etc.

From table 4.2 testing pressure data with a measurement device velocity meter figure 3.7 , the data from both sources are enough to determine engine best optimal point to operate by using compressor performance map figure 4.4 for analysis process.



**Figure 4.5** : Compressor performance map

According from testing engine result can obtain compressor operating point represent by red dot in Figure 4.5 at Pressure ratio from compressor pressure approximate around 1.5 and air volume flow rate from velocity meter is approximate around  $0.08 \text{ m}^3/\text{s}$ .

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## CHAPTER 5

### CONCLUSION

This chapter will discuss the summary of the experimental results and suggestions for improving the engine analysis program and the study of micro gas turbine, which is shown in the following topics.

- 5.1 Summary of engine analysis program results
- 5.2 Suggestions for engine analysis program
- 5.3 Summary of study micro gas turbine from turbocharger results
- 5.4 Suggestions for study micro gas turbine from turbocharger

#### **5.1 Summary of engine analysis program results**

This section will summarize the results of the engine analysis program. One of the main reasons to develop this engine analysis program using C# computer language to be base consideration, according to the coding flow chart ( section 3.2 ) figure 3.1, the calculation step procedure contains twenty steps of calculation by the hand leading to determining the result take a long period to compute each step by hand one by one. Therefore, the program was developed with six necessary user input variables required by the program. The rest of the step lets the computer compute the result. This engine analysis program includes heat addition to the combustion chamber, whether for combustor or other heat addition to system method, the network delivered by turbine and compressor, and, most importantly, thermal efficiency. The engine analysis program can show precise results based on thermodynamic equations and related theories. The program can determine the engine operation point to the best possible engine operation point to be a reference for the design of a gas turbine engine that should be operated at that point. From this point of view, the engine analysis program can be used as a reverse engineering tool to determine the solution to any problem related to thermodynamic and gas turbine engine equations, etc. The engine's best optimal point to operate can be expressed in various including the amount proportion of heat addition process to keep the country of the process leading to lesser heat cost another condition is determine net work done by turbine and compressor that in best optimal point that engine should produce to gain benefit and profit from the engine. Leading to the most important parameter, thermal efficiency, if the

operator can control the main affect parameter of thermal efficiency, including heat added to the combustion chamber and net work done by both turbine and compressor, that the best possible thermal efficiency that the engine should be doing.

## 5.2 Suggestions for engine analysis program

This section will mention room for improvement in developing an engine analysis program. Firstly, the program itself is designed for only gas turbines that are connected to external load conditions in order to observe thermal efficiency and other related parameters connected to load is non-negotiated; however, for no-load condition gas turbine engines instead of most of the work used to drive usually no load condition the power output in form kinetic energy hot gas or air, therefore not only kinetic energy can be further utilized also hot gas due to yet engine analysis program does not provide any this form of thermal analysis.

## 5.3 Summary of study micro gas turbine from turbocharger results

This section will summarize the result of the study of a micro gas turbine from automotive turbocharger parts under no load condition; therefore, thermal efficiency is not included due to not being connected with external load, leading to the work output for no-load condition categories as kinetic energy and in the form of thermal energy to the environment whether not utilize or not. According to Table 4.2, testing pressure data gathered for pressure sensor at stages 2 and 3 with results 1.5 bar and 1.4 bar, respectively the significant pressure drop occur by air pass through liner hole, depend on number and size of linear holes in the chamber. In the other hand pressure at stage 1 and 4 consider as pressure for ambient enter the compressor inlet and leaving to environment respectively most likely approximate around 1 atm for both stages. According to Table 4.3, testing temperature data is gathered from temperature sensors throughout the engine stage. At stage 1, the ambient temperature depends on the climate zone of the engine; in this case, Thailand, the temperature at first is around 37 °C. In the data in the table from stage 1 to stage, the temperature increases significantly amount due to the compression process, resulting in the temperature increasing however, from stage 2 to stage can spot a vast increasing gap from 49 °C to 1000 °C due to the compressed gas going through a heat addition process in the combustion chamber, leading hot gas ready for the following step procedure before entering the turbine noted that hot gas from combustion chamber needed to add heat at calculated amount due to if too much proportion of heat added

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highly affect the turbine parts due to material heat tolerance. After the heat addition process for the combustion chamber, hot gas is ready to enter the turbine in order to go through an expansion process from the turbine leading to the turbine wheel turning, to produce machinal energy to drive the shaft for power production and other utilize under load conditions, in additional no load conditions as the testing machine is under no load condition meaning output power mostly likely came out as kinetic energy or in the form of hot gas both of the terms can be utilized such as for kinetic most commonly used to drive a machine in the other hand hot gas or hot air can be utilized by using as boiler heating source to drive another steam turbine engine, etc. From Table 4.2 testing pressure data with a measurement device velocity meter, the data from both sources are enough to determine the engine's operating point using the compressor performance map Figure 4.4 for the analysis process. From testing engine results, we can obtain the compressor operating point at the Pressure ratio from compressor pressure of approximately 1.5, and the air volume flow rate from the velocity meter is approximately  $0.08 \text{ m}^3/\text{s}$ . Equation 8 ( section 3.2.1 ) determines the kinetic work because the engine operated under no load condition, which leads to work delivered by the turbine is most likely equal to work delivered by the compressor.

#### **5.4 Suggestions for study micro gas turbine from turbocharger**

In this section, we will mention room for improvement in the development of a micro gas turbine from an automotive turbocharger. The engine operates under no load, but if connected to an external source, the experiment will be able to observe the thermal efficiency parameter, leading to the possibility that if the micro gas turbine from an automotive turbocharger testing machine operates under load condition, it will be able to use the engine analysis program for further analysis.

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## APPENDIX A

### CODING STEP PROCEDURE

```

private static void Main(string[] args)
{
    double propi = 0;
    double propo = 0;

    // Pressure Variables
    double PA = 101.325;
    double RP = 0;
    double PC = 0;
    double PPPP = 101.325;

    // Temperature Variables
    double TIN = 308.15; // ****Please Input Ti
    double TSS = 0;
    double TTTTS = 0;
    double TTTTA = 0;

    // Entropy Variables
    double HF = 0;
    double HHS = 0;
    double HHA = 0;
    double HHH = 0;
    double HHHHS = 0;
    double HHHHA = 0;

    // PR Variables
    double PRF = 0;
    double PRR = 0;
    double PRRR = 0;
    double PRRRR = 0;

    //Other Variables
    double COMISEN = 0.8;
    double TIT = 1000;
    double QIN = 0;
    double TURISEN = 0.8;
    double COMWORK = 0;
    double TURWORK = 0;
    double THERMEFF = 0;

    // *For user input variables
    //TIN
    //RP
    //PA
    //TURISEN
    //COMISEN

// A-17 table

```

```
// A-17 table

double[] T = { 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, 500, 510, 520, 530, 540, 550, 560, 570, 580, 590, 600, 610, 620, 630, 640, 650, 660, 670, 680, 690, 700, 710, 720, 730, 740, 750, 760, 770, 780, 790, 800, 810, 820, 830, 840, 850, 860, 870, 880, 890, 900, 910, 920, 930, 940, 950, 960, 970, 980, 990, 1000, 1010, 1020, 1030, 1040, 1050, 1060, 1070, 1080, 1090, 1100, 1110, 1120, 1130, 1140, 1150, 1160, 1170, 1180, 1190 };
double[] H = { 199.97, 209.97, 219.97, 230.02, 240.02, 250.05, 260.08, 270.11, 280.14, 290.17, 300.20, 310.23, 320.26, 330.29, 340.32, 350.35, 360.38, 370.41, 380.44, 390.47, 400.50, 410.53, 420.56, 430.59, 440.62, 450.65, 460.68, 470.71, 480.74, 490.77, 500.80, 510.83, 520.86, 530.89, 540.92, 550.95, 560.98, 571.01, 581.04, 591.07, 601.10, 611.13, 621.16, 631.19, 641.22, 651.25, 661.28, 671.31, 681.34, 691.37, 701.40, 711.43, 721.46, 731.49, 741.52, 751.55, 761.58, 771.61, 781.64, 791.67, 801.70, 811.73, 821.76, 831.79, 841.82, 851.85, 861.88, 871.91, 881.94, 891.97, 901.99, 911.99, 921.99, 931.99, 941.99, 951.99, 961.99, 971.99, 981.99, 991.99, 1001.99, 1011.99, 1021.99, 1031.99, 1041.99, 1051.99, 1061.99, 1071.99, 1081.99, 1091.99, 1101.99, 1111.99, 1121.99, 1131.99, 1141.99, 1151.99, 1161.99, 1171.99, 1181.99, 1191.99 };
double[] PR = { 0.3363, 0.3987, 0.4690, 0.5477, 0.6355, 0.7329, 0.8400, 0.9580, 1.0870, 1.2280, 1.3820, 1.5500, 1.7330, 1.9320, 2.1480, 2.3820, 2.6350, 2.9080, 3.2020, 3.5180, 3.8580, 4.2240, 4.6180, 5.0420, 5.4880, 5.9580, 6.4540, 6.9780, 7.5320, 8.1180, 8.7280, 9.3640, 10.0280, 10.7220, 11.4480, 12.2080, 13.0040, 13.8380, 14.7120, 15.6280, 16.5780, 17.5640, 18.5880, 19.6520, 20.7580, 21.9080, 23.1040, 24.3480, 25.6320, 26.9580, 28.3280, 29.7440, 31.2080, 32.7200, 34.2800, 35.8800, 37.5200, 39.2000, 40.9200, 42.6800, 44.4800, 46.3200, 48.2000, 50.1200, 52.0800, 54.0800, 56.1200, 58.2000, 60.3200, 62.4800, 64.6800, 66.9200, 69.2000, 71.5200, 73.8800, 76.2800, 78.7200, 81.2000, 83.7200, 86.2800, 88.8800, 91.5200, 94.2000, 96.9200, 99.6800, 102.4800, 105.3200, 108.2000, 111.1200, 114.0800, 117.0800, 120.1200, 123.2000, 126.3200, 129.4800, 132.6800, 135.9200, 139.2000, 142.5200, 145.8800, 149.2800, 152.7200, 156.2000, 159.7200, 163.2800, 166.8800, 170.5200, 174.2000, 177.9200, 181.6800, 185.4800, 189.3200, 193.2000, 197.1200, 201.0800, 205.0800, 209.1200, 213.2000, 217.3200, 221.4800, 225.6800, 229.9200, 234.2000, 238.5200, 242.8800, 247.2800, 251.7200, 256.2000, 260.7200, 265.2800, 269.8800, 274.5200, 279.2000, 283.9200, 288.6800, 293.4800, 298.3200, 303.2000, 308.1200, 313.0800, 318.0800, 323.1200, 328.2000, 333.3200, 338.4800, 343.6800, 348.9200, 354.2000, 359.5200, 364.8800, 370.2800, 375.7200, 381.2000, 386.7200, 392.2800, 397.8800, 403.5200, 409.2000, 414.9200, 420.6800, 426.5200, 432.4000, 438.3200, 444.2800, 450.2800, 456.3200, 462.4000, 468.5200, 474.6800, 480.8800, 487.1200, 493.4000, 499.7200, 506.0800, 512.4800, 518.9200, 525.4000, 531.9200, 538.4800, 545.0800, 551.7200, 558.4000, 565.1200, 571.8800, 578.6800, 585.5200, 592.4000, 599.3200, 606.2800, 613.2800, 620.3200, 627.4000, 634.5200, 641.6800, 648.8800, 656.1200, 663.4000, 670.7200, 678.0800, 685.4800, 692.9200, 700.4000, 707.9200, 715.4800, 723.0800, 730.7200, 738.4000, 746.1200, 753.8800, 761.6800, 769.5200, 777.4000, 785.3200, 793.2800, 801.2800, 809.3200, 817.4000, 825.5200, 833.6800, 841.8800, 850.1200, 858.4000, 866.7200, 875.0800, 883.4800, 891.9200, 900.4000, 908.9200, 917.4800, 926.0800, 934.7200, 943.4000, 952.1200, 960.8800, 969.6800, 978.5200, 987.4000, 996.3200, 1005.2800, 1014.2800, 1023.3200, 1032.4000, 1041.5200, 1050.6800, 1059.8800, 1069.1200, 1078.4000, 1087.7200, 1097.0800, 1106.4800, 1115.9200, 1125.4000, 1134.9200, 1144.4800, 1154.0800, 1163.7200, 1173.4000, 1183.1200, 1192.8800 };
double[] U = { 142.56, 149.69, 156.82, 164.00, 171.13, 178.28, 185.46, 192.67, 199.91, 207.18, 214.48, 221.81, 229.17, 236.56, 243.98, 251.43, 258.91, 266.42, 273.96, 281.53, 289.13, 296.76, 304.42, 312.11, 319.83, 327.58, 335.36, 343.17, 351.01, 358.88, 366.78, 374.71, 382.67, 390.66, 398.68, 406.73, 414.81, 422.92, 431.06, 439.23, 447.43, 455.66, 463.92, 472.21, 480.53, 488.88, 497.26, 505.67, 514.11, 522.58, 531.08, 539.61, 548.17, 556.76, 565.38, 574.03, 582.71, 591.42, 600.16, 608.93, 617.73, 626.56, 635.42, 644.31, 653.23, 662.18, 671.16, 680.17, 689.21, 698.28, 707.38, 716.51, 725.67, 734.86, 744.08, 753.33, 762.61, 771.92, 781.26, 790.63, 799.93, 809.26, 818.62, 828.01, 837.43, 846.88, 856.36, 865.87, 875.41, 884.98, 894.58, 904.21, 913.87, 923.56, 933.28, 943.03, 952.81, 962.62, 972.46, 982.33, 992.23, 1002.16, 1012.12, 1022.11, 1032.13, 1042.18, 1052.26, 1062.37, 1072.51, 1082.68, 1092.88, 1103.11, 1113.37, 1123.66, 1133.98, 1144.33, 1154.71, 1165.12, 1175.56, 1186.03, 1196.53, 1207.06, 1217.62, 1228.21, 1238.83, 1249.48, 1260.16, 1270.88, 1281.63, 1292.41, 1303.22, 1314.06, 1324.93, 1335.83, 1346.76, 1357.72, 1368.71, 1379.73, 1390.78, 1401.86, 1412.97, 1424.11, 1435.28, 1446.48, 1457.71, 1468.97, 1480.26, 1491.58, 1502.93, 1514.31, 1525.72, 1537.16, 1548.63, 1560.13, 1571.66, 1583.22, 1594.81, 1606.43, 1618.08, 1629.76, 1641.47, 1653.21, 1664.98, 1676.78, 1688.61, 1700.47, 1712.36, 1724.28, 1736.23, 1748.21, 1760.22, 1772.26, 1784.33, 1796.43, 1808.56, 1820.72, 1832.91, 1845.13, 1857.38, 1869.66, 1881.97, 1894.31, 1906.68, 1919.08, 1931.51, 1943.97, 1956.46, 1968.98, 1981.53, 1994.11, 2006.72, 2019.36, 2032.03, 2044.73, 2057.46, 2070.22, 2083.01, 2095.83, 2108.68, 2121.56, 2134.47, 2147.41, 2160.38, 2173.38, 2186.41, 2199.47, 2212.56, 2225.68, 2238.83, 2252.01, 2265.22, 2278.46, 2291.73, 2305.03, 2318.36, 2331.72, 2345.11, 2358.53, 2371.98, 2385.46, 2398.97, 2412.51, 2426.08, 2439.68, 2453.31, 2466.97, 2480.66, 2494.38, 2508.13, 2521.91, 2535.72, 2549.56, 2563.43, 2577.33, 2591.26, 2605.21, 2619.19, 2633.2, 2647.24, 2661.31, 2675.41, 2689.53, 2703.68, 2717.86, 2732.07, 2746.31, 2760.58, 2774.88, 2789.21, 2803.57, 2817.96, 2832.38, 2846.83, 2861.31, 2875.82, 2890.36, 2904.93, 2919.53, 2934.16, 2948.82, 2963.51, 2978.23, 2992.98, 3007.76, 3022.57, 3037.41, 3052.28, 3067.18, 3082.11, 3097.07, 3112.06, 3127.08, 3142.13, 3157.21, 3172.32, 3187.46, 3202.63, 3217.83, 3233.06, 3248.32, 3263.61, 3278.93, 3294.28, 3309.66, 3325.07, 3340.51, 3355.98, 3371.48, 3387.01, 3402.57, 3418.16, 3433.78, 3449.43, 3465.11, 3480.82, 3496.56, 3512.33, 3528.13, 3543.96, 3559.82, 3575.71, 3591.63, 3607.58, 3623.56, 3639.57, 3655.61, 3671.68, 3687.78, 3703.91, 3720.07, 3736.26, 3752.48, 3768.73, 3785.01, 3801.32, 3817.66, 3834.03, 3850.43, 3866.86, 3883.32, 3899.81, 3916.33, 3932.88, 3949.46, 3966.07, 3982.71, 3999.38, 4016.08, 4032.81, 4049.57, 4066.36, 4083.18, 4100.03, 4116.91, 4133.82, 4150.76, 4167.73, 4184.73, 4201.76, 4218.82, 4235.91, 4253.03, 4270.18, 4287.36, 4304.57, 4321.81, 4339.08, 4356.38, 4373.71, 4391.07, 4408.46, 4425.88, 4443.33, 4460.81, 4478.32, 4495.86, 4513.43, 4531.03, 4548.66, 4566.32, 4584.01, 4601.73, 4619.48, 4637.26, 4655.07, 4672.91, 4690.78, 4708.68, 4726.61, 4744.57, 4762.56, 4780.58, 4798.63, 4816.71, 4834.82, 4852.96, 4871.13, 4889.33, 4907.56, 4925.82, 4944.11, 4962.43, 4980.78, 4999.16, 5017.57, 5036.01, 5054.48, 5072.98, 5091.51, 5110.07, 5128.66, 5147.28, 5165.93, 5184.61, 5203.32, 5222.06, 5240.83, 5259.63, 5278.46, 5297.32, 5316.21, 5335.13, 5354.08, 5373.06, 5392.07, 5411.11, 5430.18, 5449.28, 5468.41, 5487.57, 5506.76, 5525.98, 5545.23, 5564.51, 5583.82, 5603.16, 5622.53, 5641.93, 5661.36, 5680.82, 5700.31, 5719.83, 5739.38, 5758.96, 5778.57, 5798.21, 5817.88, 5837.58, 5857.31, 5877.07, 5896.86, 5916.68, 5936.53, 5956.41, 5976.32, 5996.26, 6016.23, 6036.23, 6056.26, 6076.32, 6096.41, 6116.53, 6136.68, 6156.86, 6177.07, 6197.31, 6217.58, 6237.88, 6258.21, 6278.57, 6298.96, 6319.38, 6339.83, 6360.31, 6380.82, 6401.36, 6421.93, 6442.53, 6463.16, 6483.82, 6504.51, 6525.23, 6545.98, 6566.76, 6587.57, 6608.41, 6629.28, 6650.18, 6671.11, 6692.07, 6713.06, 6734.08, 6755.13, 6776.21, 6797.32, 6818.46, 6839.63, 6860.83, 6882.06, 6903.32, 6924.61, 6945.93, 6967.28, 6988.66, 7010.07, 7031.51, 7052.98, 7074.48, 7096.01, 7117.57, 7139.16, 7160.78, 7182.43, 7204.11, 7225.82, 7247.56, 7269.33, 7291.13, 7312.96, 7334.82, 7356.71, 7378.63, 7400.58, 7422.56, 7444.57, 7466.61, 7488.68, 7510.78, 7532.91, 7555.07, 7577.26, 7599.48, 7621.73, 7644.01, 7666.32, 7688.66, 7711.03, 7733.43, 7755.86, 7778.32, 7800.81, 7823.33, 7845.88, 7868.46, 7891.07, 7913.71, 7936.38, 7959.08, 7981.81, 8004.57, 8027.36, 8050.18, 8073.03, 8095.91, 8118.82, 8141.76, 8164.73, 8187.73, 8210.76, 8233.82, 8256.91, 8280.03, 8303.18, 8326.36, 8349.57, 8372.81, 8396.08, 8419.38, 8442.71, 8466.07, 8489.46, 8512.88, 8536.33, 8559.81, 8583.32, 8606.86, 8630.43, 8654.03, 8677.66, 8701.32, 8725.01, 8748.73, 8772.48, 8796.26, 8820.07, 8843.91, 8867.78, 8891.68, 8915.61, 8939.57, 8963.56, 8987.58, 9011.63, 9035.71, 9059.82, 9083.96, 9108.13, 9132.33, 9156.56, 9180.82, 9205.11, 9229.43, 9253.78, 9278.16, 9302.57, 9327.01, 9351.48, 9375.98, 9400.51, 9425.07, 9449.66, 9474.28, 9498.93, 9523.61, 9548.32, 9573.06, 9597.83, 9622.63, 9647.46, 9672.32, 9697.21, 9722.13, 9747.08, 9772.06, 9797.07, 9822.11, 9847.18, 9872.28, 9897.41, 9922.57, 9947.76, 9972.98, 10000.00 };
double[] S = { 1.29559, 1.34444, 1.39105, 1.43557, 1.47824, 1.51917, 1.55837, 1.59589, 1.63173, 1.6659, 1.6994, 1.73123, 1.76141, 1.78994, 1.81682, 1.84205, 1.86563, 1.88756, 1.90784, 1.92647, 1.94345, 1.95878, 1.97246, 1.98449, 1.99487, 2.0036, 2.01068, 2.01605, 2.02071, 2.02466, 2.0279, 2.03043, 2.03215, 2.03306, 2.03316, 2.03245, 2.03093, 2.0286, 2.02546, 2.02151, 2.01676, 2.01121, 2.00487, 1.99774, 1.98982, 1.98111, 1.97161, 1.96132, 1.95024, 1.93837, 1.92571, 1.91226, 1.89802, 1.88299, 1.86717, 1.85056, 1.83326, 1.81527, 1.79659, 1.77722, 1.75716, 1.73641, 1.71497, 1.69284, 1.67002, 1.64651, 1.62231, 1.59742, 1.57184, 1.54557, 1.51861, 1.49106, 1.46292, 1.43419, 1.40487, 1.37496, 1.34446, 1.31336, 1.28166, 1.24936, 1.21646, 1.18296, 1.14886, 1.11416, 1.07886, 1.04296, 1.00646, 0.96936, 0.93166, 0.89336, 0.85446, 0.81496, 0.77486, 0.73416, 0.69286, 0.65096, 0.60846, 0.56536, 0.52166, 0.47736, 0.43246, 0.38696, 0.34086, 0.29416, 0.24686, 0.19996, 0.15246, 0.10436, 0.05566, 0.00636, -0.04344, -0.09354, -0.14304, -0.19194, -0.24024, -0.28794, -0.33504, -0.38154, -0.42744, -0.47274, -0.51744, -0.56154, -0.60504, -0.64794, -0.69024, -0.73194, -0.77304, -0.81354, -0.85344, -0.89274, -0.93144, -0.96954, -1.00704, -1.04394, -1.08024, -1.11594, -1.15104, -1.18554, -1.21944, -1.25274, -1.28544, -1.31754, -1.34904, -1.38, -1.4104, -1.4403, -1.4697, -1.4986, -1.527, -1.5549, -1.5823, -1.6092, -1.6356, -1.6615, -1.6869, -1.7118, -1.7362, -1.7601, -1.7835, -1.8064, -1.8288, -1.8507, -1.8721, -1.893, -1.9134, -1.9333, -1.9527, -1.9716, -1.9901, -2.0081, -2.0256, -2.0426, -2.0591, -2.0751, -2.0906, -2.1056, -2.1201, -2.1341, -2.1476, -2.1606, -2.1731, -2.1851, -2.1966, -2.2076, -2.2181, -2.2281, -2.2376, -2.2466, -2.2551, -2.2631, -2.2706, -2.2776, -2.2841, -2.2901, -2.2956, -2.3011, -2.3061, -2.3106, -2.3151, -2.3191, -2.3226, -2.3261, -2.3291, -2.3321, -2.3351, -2.3381, -2.3411, -2.3441, -2.3471, -2.3501, -2.3531, -2.3561, -2.3591, -2.3621, -2.3651, -2.3681, -2.3711, -2.3741, -2.3771, -2.3801, -2.3831, -2.3861, -2.3891, -2.3921, -2.3951, -2.3981, -2.4011, -2.4041, -2.4071, -2.4101, -2.4131, -2.4161, -2.4191, -2.4221, -2.4251, -2.4281, -2.4311, -2.4341, -2.4371, -2.4401, -2.4431, -2.4461, -2.4491, -2.4521, -2.4551, -2.4581, -2.4611, -2.4641, -2.4671, -2.4701, -2.4731, -2.4761, -2.4791, -2.4821, -2.4851, -2.4881, -2.4911, -2.4941, -2.4971, -2.5001, -2.5031, -2.5061, -2.5091, -2.5121, -2.5151, -2.5181, -2.5211, -2.5241, -2.5271, -2.5301, -2.5331, -2.5361, -2.5391, -2.5421, -2.5451, -2.5481, -2.5511, -2.5541, -2.5571, -2.5601, -2.5631, -2.5661, -2.5691, -2.5721, -2.5751, -2.5781, -2.5811, -2.5841, -2.5871, -2.5901, -2.5931, -2.5961, -2.5991, -2.6021, -2.6051, -2.6081, -2.6111, -2.6141, -2.6171, -2.6201, -2.6231, -2.6261, -2.6291, -2.6321, -2.6351, -2.6381, -2.6411, -2.6441, -2.6471, -2.6501, -2.6531, -2.6561, -2.6591, -2.6621, -2.6651, -2.6681, -2.6711, -2.6741, -2.6771, -2.6801, -2.6831, -2.6861, -2.6891, -2.6921, -2.6951, -2.6981, -2.7011, -2.7041, -2.7071, -2.7101, -2.7131, -2.7161, -2.7191, -2.7221, -2.7251, -2.7281, -2.7311, -2.7341, -2.7371, -2.7401, -2.7431, -2.7461, -2.7491, -2.7521, -2.7551, -2.7581, -2.7611, -2.7641, -2.7671, -2.7701, -2.7731, -2.7761, -2.7791, -2.7821, -2.7851, -2.7881, -2.7911, -2.7941, -2.7971, -2.8001, -2.8031, -2.8061, -2.80
```

```
// step 5 T1 look up for H1 (H1 = HF)
```

```
    for (int i=0; i<119; i++)
```

```
    {
        dummyi[i] = T[i];
```

```
    }
```

```
    for (int i=0; i<119; i++)
```

```
    {
        dummyo[i] = H[i];
```

```
    }
```

```
    propi = TIN;
```

```
    ;
```

```
    for (int i = 0; i < 119; i++)
```

```
    {
```

```
// Step 6 Compute PR2
```

```
    PRR = RP * PRF; // P2 = RP * P1
```

```
    //Console.WriteLine("PR2 = {0} kPa ",PRR );
```

```
//Step 7 PR2 look up for T2S
```

```
    for (int i=0; i<119; i++)
```

```
    {
```

```
        dummyi[i] = PR[i];
```

```
    }
```

```
    for (int i=0; i<119; i++)
```

```
    {
```

```
        dummyo[i] = T[i];
```

```
    }
```

```
// Step8 T2S look up for H2S

    for (int i=0; i<119; i++)
    {
        dummyi[i] = T[i];
    }
    for (int i=0; i<119; i++)
    {
        dummyo[i] = H[i];
    }

    propi = TSS;
    ;

    for (int i = 0; i < 119; i++)
    {

        if (dummyi[i] > propi)
```

```
//Step 9 compute H2A form COMISEN, H2S, and H1

    //Console.WriteLine("Enter COMISEN"); // Assign COMISEN
    //COMISEN = Convert.ToDouble(Console.ReadLine());

    HHA = ((HHS - HF)/COMISEN) + HF;
    //Console.WriteLine("H2A value = {0} ",HHA );

//Step 10 TIT look up for H3

    //Console.WriteLine("Enter Turbine inlet temperature");
    //TIT = Convert.ToDouble(Console.ReadLine());

    for (int i=0; i<119; i++)
    {
        dummyi[i] = T[i];
    }
    for (int i=0; i<119; i++)
    {
        dummyo[i] = H[i];
```

```
//Step 11 TIT look up for PR3

for (int i=0; i<119; i++)
{
    dummyi[i] = T[i];
}

for (int i=0; i<119; i++)
{
    dummyo[i] = PR[i];
}

propi = TIT;
Console.WriteLine( "TIT value = {0}",TIT);
Console.ReadKey();

;

for (int i = 0; i < 119; i++)
{
    if (dummyi[i] > propi)

```

```
// Step 12 compute QIN

QIN = (HHH - HHA);

Console.WriteLine( "QIN value = {0}",QIN);
Console.ReadKey();

//Step 13 Compute PR4

PRRRR = ( PPPP / PC ) * PRRR;

//Console.WriteLine( "PR4 value = {0}",PRRRR);
//Console.ReadKey();

//Step 14 PR4 look up for H4S

for (int i=0; i<119; i++)
{
    dummyi[i] = PR[i];
}

for (int i=0; i<119; i++)
{

```

```
//Step 15 PR4 look for T4S
```

```

for (int i=0; i<119; i++)
{
dummyi[i] = PR[i];

}
for (int i=0; i<119; i++)
{
dummyo[i] = T[i];

}

propi = PRRRR;
;
for (int i = 0; i < 119; i++)
{
if (dummyi[i] > propi)

```

```
// Step 16 compute H4A from H3, TURISEN, H4S
```

```

//Console.WriteLine("Enter Turbine Isentropic"); // Assign TUR
//TURISEN = Convert.ToDouble(Console.ReadLine());

HHHHA = HHH - (TURISEN * (HHH - HHHHS));

Console.WriteLine( "H4A value = {0}",HHHHA);
Console.ReadKey();

```

```
//Step 17 H4A look up for T4A
```

```

for (int i=0; i<119; i++)
{
dummyi[i] = H[i];

}
for (int i=0; i<119; i++)
{
dummyo[i] = T[i];

```

```
// Step 18 Compute compressor work

COMWORK = (HHA - HF);
Console.WriteLine( "Work done by compressor value = {0}",COMWORK);
Console.ReadKey();

// Step 19 Compute turbine work

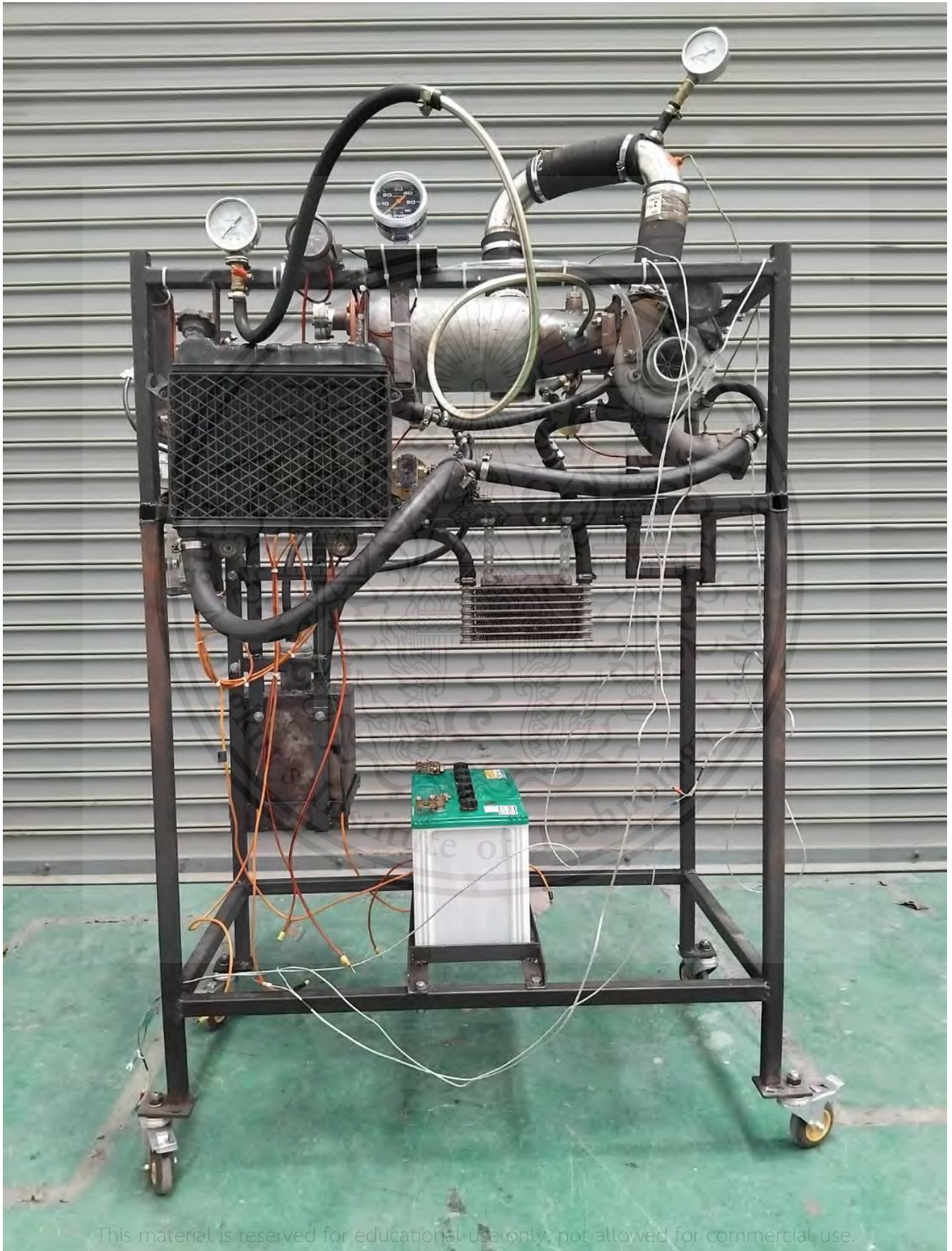
TURWORK = (HHH - HHHHA);
Console.WriteLine( "Work done by turbine value = {0}",TURWORK);
Console.ReadKey();

//Step 20 Compute thermal efficiency

THERMEFF = ( (TURWORK - COMWORK) / QIN ) * 100;
Console.WriteLine( "Thermal efficiency = {0}",THERMEFF);
Console.ReadKey();

}
}
```

## APPENDIX B MIRCO GAS TURBINE



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