The Effect of Reheat on a Micro-Gas Turbine with High Inlet Temperature

Amer TH. Alajmi[A,B], Esam F.Alajmi[B], FnyeesAlajmi[B]*
[A] Mechanical, Aerospace and Automotive Engineering Department, Coventry University,CV1 5FB,Coventry,UK
[B]Public Authority for Applied Education and Training, Kuwait City 13092, Kuwait.

Abstract

Gas turbines are among the most popular technologies for power generation today. Since fuel burns inside a turbine, hot gases are released as a result. A very high inlet temperature can damage the components inside a turbine. Hence, it is important to keep the inlet temperature bounded. On the other hand, the push for high efficiency, low-emission machines by the market has resulted in the introduction of new process for gas turbines such as reheat. In this paper, we analyse the effect of reheat on a gas turbine with high inlet temperature.

Keywords – *gas turbine, high inlet temperature, effect of reheat, thermodynamic analysis, after burner analysis*

I. INTRODUCTION

Gas turbines have been used since long for the purpose of generating electricity. They are now among the most popular technologies for generating power. Gas turbines are basically a type of internal combustion (IC) engine. It works as follows: an air-fuel mixture is burnt, which leads to the production of hot gases. The pressure of these gases helps in spinning the turbine, which, in turn, leads to the production of power. The word ‘gas’ in ‘gas turbine’ refers to the production of hot gases in a turbine, and not to the fuel itself. Gas turbines are normally run on a number of different fuel types (e.g., natural gas, synthetic fuels, and fuel oils etc.). The process of combustion is a continuous phenomenon i.e., combustion occurs continuously.

The temperature at which a gas turbine works is also called its firing temperature. The firing temperature of a turbine has a great influence on the performance efficiency of the turbine. For example, a turbine with a higher firing temperature is expected to be more efficient than a turbine with a lower firing temperature. Having said this, it is important to understand that the inlet temperature of a turbine is bounded by the magnitude of heat that can be withstood by the turbine blade which is typically made of a metal alloy. Typically the maximum inlet temperature of a gas turbine is in the range of 1200ºC - 1400ºC, but thanks to advances in the fields of thermodynamics and metallurgy, some manufacturers have been able to increase the inlet temperatures to around 1700ºC [1]. This is typically done by either coating the turbine blades with special materials or by introducing cooling systems. If these special measures are not taken, there is a risk that the metallurgical components might get damaged.

Reheat is a process with the help of which the efficiency of a gas turbine can be increased [2]. Moreover, it can also help to reduce emissions which can, otherwise, have a negative impact on the environment. Low emissions and high efficiency are the targets that almost all gas turbine manufactures aim to achieve these days. This is motivated both by the environmental impact of the emissions as well as special incentives that are typically associated with the manufacturing of low-emissions devices.

In this paper, we present an analysis of the effect of reheat on a gas turbine with a high inlet temperature.

The paper has been divided into five sections. While we have presented an overview of the working of a gas turbine in the first section, in Section 2, relevant preliminary concepts are presented. In Section 3, the methodology is detailed. Results are presented and discussed in Section 4. Finally, Section 5 presents our conclusions.

II. PRELIMINARIES

A. Thermodynamic Analysis

In this section we address the laws and equations for nozzle. All the relevant equations are also detailed in this section. Moreover, the combustion chamber is partially redesigned. The temperature outside of the turbine is taken to be 1046.27K.

Fig. 1 shows a sample gas turbine jet engine project [3] which is considered in this paper.

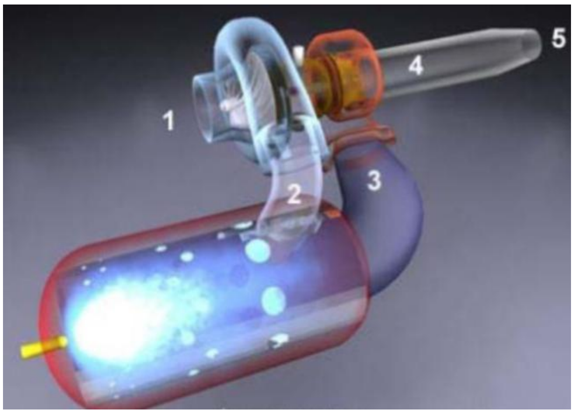


Figure 1: A Sample Mico-Gas Turbine Jet Engine Project [3] Considered In This Paper.

B. *Units of Measurement*

SI units [4] have been used in this paper. The units used for time, length, and temperature are second (s), meter (m), and kelvin (K) respectively. Similarly, the unit used for force is Newton (N) which is equal to kgm/s^2 while the unit used for energy is Newton meter (Nm) which is equal tokgm^2/s^2. A more common represented of the unit of energy is Joule (J). Lastly, Pascal (Pa), which is equal to N/m^2, is widely used as a unit of pressure. It is also the SI unit of pressure. In this work, we consider 'bar' as the unit of pressure which is equal to 100,000 Pa.

III. METHODOLOGY

A. *Thermodynamic Analysis of Nozzle Without After Burner*

The objective of thermodynamic calculation of nozzle with and without using afterburner is to compare and analyze the results with the use of injection water.

A micro-gas turbine without the use of an afterburner is shown in Figure 2.

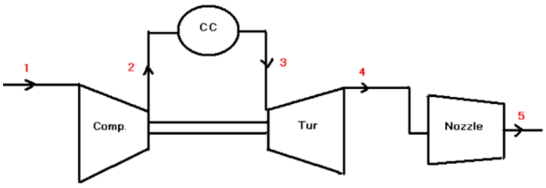
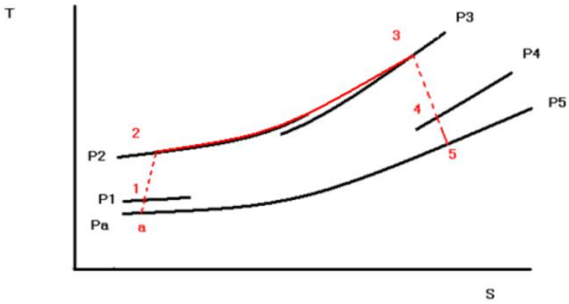


Figure 2: Micro-Gas Turbine Without Afterburner

The following values are used during the calculations: T_4 = 979.2 K, P_4 =1.99 bar, nozzle efficiency (η_j) = 0.95, ambient pressure (Pa) = 1.013 bar, fuel to air ratio (F/A) = 0.0664, total mass flow rate = 1.29kgs.

With the help of the initial data, the pressure on nozzle is calculated. Then the type of flow and the relationship between pressure differences is defined (See Fig. 3).

Figure 3: Micro gas turbine without afterburner



From the above values, the velocity of the hot gases within the nozzle is calculated i.e.
$v=\sqrt{2}\times C_p\times(T_4-T_5)$.

The constant pressure specific heat at temperature 979.2 K is C_p = 1.13 kg/(kg·k). So,
v=574.8 m/s.

The specific heat ratio at the temperature 833 K is k = 1.32, speed of sound at the exit can define by:
$C_C=\sqrt{k}\times R\times TC$

It is important to define the total temperature value which can be obtained from the equation below i.e.
$T_{04}=T_4+(v^2/2C_P)$

Where T_{04} is total temperature at point 4 and $v^2/2C_p$ is dynamic temperature that effect on the temperature during the impact of heat from the flow of gases around the bulb of thermocouple at certain speed.
T_{04} = 1125.3 K

The critical temperature of the nozzle exit can be found using the following relations:
$T_{04}/T_C=(P_4/P_C)^{k-1/k}$=1.169. Similarly, $T_C=T_{04}/1.169$=962.6 K, and $C_C=\sqrt{k}\times R\times TC$=603.8 m/s.

The Mach number M at the nozzle exit is: M = v/C = 0.95. The value of Mach number indicates that the flow gases are close to the critical value when Mach number equals 1.

The pressure ratio between the ambient pressure and the pressure at point 4 is given by P_4/P_a = 1.96 bar. The critical pressure ratio P_c can be obtained using the following relation:
$P_4/P_c=1/[1-1\eta_j((k-1)/(k+1))]^{k/k^{-1}}$=1.91.

Hence the nozzle pressure ratio is more than the critical pressure ratio and the nozzle is choking. Using the above equations, the critical pressure Pc comes out to be 1.041 bar.

The density of flow gases is defined by: $\rho = P_C/(R\times TC)$ =0.37 $kg/m3$.

The area of nozzle exit is given by: $A = m/(\rho \times C_C)$ =0.0057 m^2.

The value of the Mach number is close to the sonic Mach number (M=1). An increase in the flow, temperature and speed which will increase the value of Mach number and its relationship with the fluid velocity i.e., M <1 (Subsonic), M =1 (Sonic), M >1 (Supersonic), and M <<1 (Hypersonic)

If the Mach number of hot gases is less than 1 while using a convergent nozzle, it means that the pressure will drop at the nozzle. Thus, the speed will increase and the temperature or the density will decreases as in this case.

If the hot gas Mach number is more than 1, the above factors change completely. Where the pressure will increase, the speed will be reduced in the case of the use of a convergent nozzle. The use of convergent-divergent nozzle means will result in less pressure and the speed will increase.

The above values indicate that a preliminary finding has been reached i.e., a recommendation for the use of convergent-divergent nozzle. The hot gases Mach number is close to sonic (M ≈ 1). It should be noted that these values have been obtained without the use of afterburner.

Now, it is possible to calculate the thrust of the engine through the use of the following equation:

$thrust_{Total} = thrust_{momentum} + thrust_{pressure}$

$thrust_{momentum} = m(C_j - C_a)$

Where m is mass flow rate, C_j is jet velocity from nozzle and C_a is the vehicle velocity.

$thrust_{pressure} = (P_5 - P_1) \text{ x } A$

Where P_5 is the pressure at the nozzle exit, P_1 is the pressure at the engine inlet or ambient pressure and A is the area of the nozzle exit. Using the above relations, momentum thrust and pressure thrust values come out to be 778.9 N and 15.9 N respectively. C_a can be neglected because the speed of vehicle is zero and C_j is the gas velocity at nozzle exit. Hence, thrust $_{total}$ = 794.8 N.

From the pressure thrust value, it can be concluded that the value is relatively small because the pressure difference between the flow exit and ambient temperature is small but if the engine works at low pressure (e.g., as at high altitude), the difference between these pressures will be more and at this condition the pressure thrust value increase.

B. Thermodynamic Analysis of Nozzle with After Burner

In order to obtain the maximum temperature, the temperature of the outlet turbine is increased by 40%. This hypothesis was also used by Bathie [5]. A micro-gas turbine with an afterburner is shown in Figure 4.

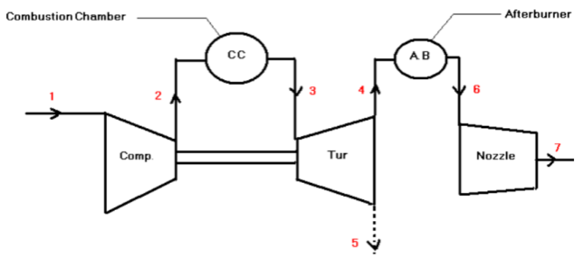


Figure 4: A Microgas Turbine With Afterburner

In this study assume that the temperature of afterburner is T_6. The convergent-divergent nozzle will be used here, i.e., T_6 = 1173 K, where T_6 is given as a total temperature.

$P_6 = P_4 = 1.99\ bar$

Total mass of flow is equal to 1.37kg/s. The velocity of gases is given by: $v = \sqrt{2\times cP\times(T_6 - T_7)}$.

The constant pressure specific heat and specific heat ratio at temperature 1173 K are 1.17kj(kg.k) and 1.32 respectively.

$T_{06} = T_6 + C^2/2CP$

$C = \sqrt{k\times R\times T_6} = 666.6 m/s.$

$T_{06} = 1362.8\ K$

$T_{06}/T_C = (P_6/P_C)^{k-1/k}$

$P_6/P_c = 1/[1 - 1\eta_j((k-1)/(k+1))]^{k/k^{-1}} = 1.91.$

$P_C = 1.041\ bar$

$T_{06}/T_C = 1.169$

$T_C = T_{06}/1.169 = 1165.7\ K$

The critical velocity at critical temperature is given by: $C_C = \sqrt{kRTC} = 664.5 m/s$. The velocity of the gases at the jet pipe is given by:

$v = \sqrt{2C(T_{06} - T_C)} = 679.1 m/s$. Hence, the Mach number of the gases flow is 1.02.

From pressure ratio P_6/P_7 and P_6/P_c the pressure ratio between (P_6/P_7) is greater than pressure ratio in (P_6/P_c) and the nozzle in this case is chocking.

$\rho = P_C/(R\times TC)$ =0.31$kg/m3$.

$A_7 = m/(\rho C_C)$ =0.0066m^2

$thrust_{momentum}$= 910.3 N

$thrust_{pressure}$= 18.4 N

$thrust_{Total}$= 928.7 N

The obtained values indicate that the hot gases entered the stage of supersonic (M ≈ 1). It is therefore expected that the nozzle must be of convergent-divergent type. The obtained values be used to detect whether an after burner has been used or not. For example, see Table 1 below.

Table 1: Thrust and Velocity Values with and Without The Use of an Afterburner.

	Without Afterburner	With afterburner
Thrust (N)	794.8	928.7
Velocity (m/s)	603.8	664.5

Table 1 shows that using an afterburner increases the velocity and the thrust by around 38% and 30% respectively.

IV. RESULTS AND DISCUSSION

A. Combustion process in the Jet Engine Nozzle.

In this section, the chemical processes which are used in the model micro jet engine are explained. Through these processes, the main objective of combustion process will be to try to find the proportion of air needed for combustion. Moreover, the proportion of the fuel needed for completing combustion is also found. It is assumed that there is a need to consider the maximum ratio of the combustion which can be applied in order to find the maximum energy that can be obtained. From these data, the possibility of water injection at the maximum ratio of combustion can be imagined. Also considering the impact on the energy produced from the combustion process with the full use of water injection, forms the basis of this study.

B. Initial Data of Combustion

In this paper, Octane C8H18 has been considered as fuel. Combustion has been performed without a change in pressure. Considering that the air is dry and that the temperature of the pipe and the temperature outside the turbine are the same (i.e. T_4 = 734.8 K. The fuel combustion processes are implemented according to the general equation of combustion:

$$CXHY+(X+Y4)[O2+7921N2] \text{----------}>XCO2+Y2H2O+792(X+Y4)N2$$

$$C8H18+(8+184)[O2+7921N2] \text{----------}>8CO2+182H2O+792(8+184)N2$$

$$C8H18+12.5O2+47N2 \text{----------}>8CO2+9H2O+47N2$$

The rate of dry air X is as follows:

$$C8H18+XD.A\text{----------}>8CO2+9H2O+XD.A-12.5O2$$

Here X is the total number of moles of dry air supplied per mole of fuel.

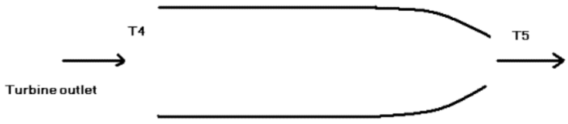


Figure 5: Turbine Outlet Duct and Nozzle

Figure 5 shows the turbine outlet duct and nozzle. In the figure, the temperature of gases emerging from the turbine is represented by T_{4a} and the temperature of the gases emerging from the nozzle is represented by T_5. In the case of the use of afterburner, the temperature of the gases emerging from the turbine T_{4a} and the temperature of afterburner T_6 and temperature out from nozzle is T_5.

For combustion at 1173K, we consider the following conditions: the fuel burns at constant pressure with dry air, the fuel is Octane C_8H_8, the air supplied at T_4 is 987.9 K, the combustion process is a complete combustion process, T_6 (temperature of afterburner) is 1173 K, CO_2 at $T_6$is −350329.7 $kj/kg{-}mol$, H_20 at T_6 is −208317.6 $kj/kg{-}mol$, $dryair$ at T_6 is 27304.1$kj/kg{-}mo$l, while $O2$ at T_6 is 98935.6$kj/kg{-}mol$.

The heat transfer according to afterburner is given by:

$$Q=Hpr+Hre$$

Where Q is the heat transfer according to afterburner process, Hpr is the enthalpy of the products and $Hre$is enthalpy of the reactants. For the complete combustion of Octane with dry air,

$$C_8H_{18}+12.5O_2\text{----------}>8CO_2+9H_2O$$

Therefore,

$$C_8H_{18}+XD.A\text{----------}>8CO_2+9H_2O+XD.A-12.5O_2$$

The above equation contains two parts: the left hand side contains the fuel and dry air. Here it should be considered that the mixture is unburned. The right hand side is the product of this combustion. It has carbon dioxide, water, and the proportion of non-air burning in addition to oxygen.

$$Hpr=27304.1*X-5914191$$

$$Hre=\Delta H_{f,8H18}+Xh_{(air,@T4=987.9)}$$

Hence, X = 208. The ratio of air to fuel combustion is given by: [$mol_{dryair}/molC_{12}H_{26}$] = 60.97. That means, to burn 1 mole of fuel, 60.97 moles from dry air is required for complete combustion.

Percentage of $Excessair=$ $[(airsupplied-airrequired)/airrequired]$i.e., Percentage of $Excessair$=241%.

The composition of the gases leaving the nozzle is shown in Table 2.

Table 2: Combustion Molecular Weight

	n_i	M_i	n_iM_i
CO_2	12	44.01	528.12
H_20	13	18.02	234.26
D. A	208	28.97	6025.7
O_2	-12.5	32.00	-400
Total	220.5		6388.08

The molecular weight of the product of the combustion leaving the nozzle is M= 28.97

$$f\sim=f/a$$

Where $f\sim$ is fuel-air ratio, and f is the fuel molecular weight of Octane which is equal to 114.2336 while $a$is molecular weight of dry air which is equal to 28.97. So,

$$f\sim=0.0189$$

From the above result, it can be concluded that for every 1 pound of dry air that enters the nozzle duct, there is 1.0189 pound of products emerging from the nozzle.

C. Combustion and Non-Combustion Air at 1173K

It is possible to find the percentage of gas burned and others none burnt gases. At the outset, the proportion entering the interaction was 53 pounds per minute which is approximately equal to 24.39 kilogram per minute. The new ratios resulting from the combustion of fuel are as follows:

24.39 kilogram per minute = 241(excess air %)

$$combustiongases=10.12\ kg/min$$

$$noncombustiongases=14.27kg/min$$

The above report shows that the total air entering the combustion is 24.39 kg/min and is divided into 13.16 kg/min from the air with burning fuel burning fully. The rest is not in the combustion and come out with the tides of the gas nozzle.

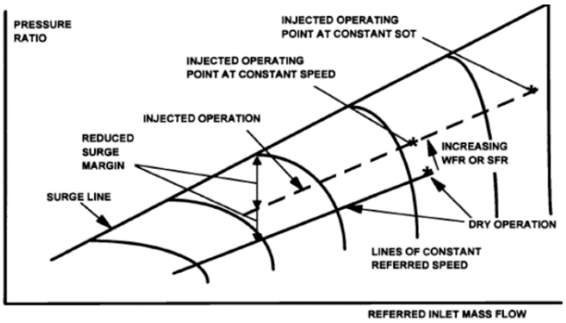


Figure 6: Water or Stream Injection into Combustor [6]

Here it must be pointed out that the rate of gas burned is low compared with non-burned gases. It is around 53%. This can reduce the thermal efficiency and it is therefore necessary to increase the temperature of the combustion design. Here, it is assumed that the temperature to be accessed is the same temperature of the combustion chamber design in the main engine. The metal surrounding combustion chamber will be affected by the temperature. It is therefore necessary to work at the design of such applications. The concept of preserving these materials through cooling is considered here. It is also considered that a large quantity of air which came from the main engine is in fact within the walls of the process of cooling metal as a part in this study. On the other hand, it is to be noted that injection of water also has helps in cooling.

D. Water Injection Into Combustion Chamber

In this section, we discuss the injection of water within the engine and look at the effect of the water injection at thrust force. Water is injected in two ways. The first is injection of water before entering the compressor and the second way is by injecting water into the combustion chamber:

- Injection of water into compressor entry helps to boost thrust and relatively small amount of water is used to lower the inlet temperature by evaporation [6].

- Injection of water into the combustion chamber helps to primarily reduce the emission and boost thrust force [6].

E. Mixing Process Analysis into Engine Main Combustion Chamber

Three fluids are mixed within the combustion chamber. These are: dry air, fuel, and water injection. The quantity of each fluid is then found and the impact of mixing of these fluids with the fluids within the combustion chamber is examined. A preliminary value helps to calculate the amount of flow and the change in the temperature of the whole mixture.

*1) **Air***

The mass flow rate of the compressor is 1.21 kg/s, the temperature is 1173 K and the gas constant Ris equal to 0.287 kj/kg·k..

*2) **Fuel***

The mass flow rate of fuel needed to reach 1173 K is given by F/A which equals 0.0664.

$$m_{fuel}=m_{air}\times F/A$$

$$m_{fuel}=0.08\ kg/s$$

The fuel type used in combustion chamber is n-octane and the gas constant of octane is R=0.073 kj/kg.k with temperature at supply fuel pipe equaling 313 K.

*3) **Water***

The water fuel ratio (WFR) is 1:2 and this value is assumed for the injection of water into combustion chamber [6]. The gas constant of water is R=0.462 kj/kg·k.

$$m_{water}=WFR\times m_{fuel}=0.04\ kg/s$$

$$m_{4\ total}=1.33\ kg/s$$

The temperature of the fluid can be obtained as follows:

$T_{total}=(m_{air}/m_{total})\times T_{air}+(m_{fuel}/m_{total})\times T_{fuel}+(m_{water}/m_{total})\times T_{water}$

$T_{total}=1095.39\ K$

The specific volume of fluid mixture can be found using:

$\upsilon_{total}=(R_{total}\times T_{total})/P=2.35\ m^3/kg.$

Now the volume flow rate can be found by using:

$V_{total}=m_{total}\times \upsilon_{total}=3.12 m^3/s$

From the above value, it can be noted that the temperature decreased from 1173 K to 1095.3 K because of water injection. This drop in temperature is due to the evaporation of water as steam which led to an increase in size and quantity which increases momentum. This momentum increases the speed of the turbine hence increases power output.

F. Effect of Water Injection on Thrust Value

In this subsection, we calculate the impact of water injection on the momentum thrust and analysis its results.

$thrust_{total}=thrust_{momentum}+thrust_{pressure}$

$thrust_{momentum}=m(Cj-Ca)$

$thrust_{pressure}=(P7-Pa)A$

$m_{total}=m_{turbineoutmixing}+m_{fuel}$

$m_{total}=1.41\ kg/s$

$thrust_{momentum}=936.9\ N$

The specific volume of gases is mixing between the gases from the turbine outlet and the specific volume from fuel injection into afterburner.

$v=(R\times T_6)/P_6=1.69\ m^3/kg$

The specific volume of gases from turbine outlet is:

$v_{turbineoutmixing}=(R\times T_4)/P_4=4.04\ m^3/kg$

$v_{total}=v+v_{turbineoutmixing}=5.73 m^3/kg$

$m_{total}=(A\times C)/v_{total}$

$A=(m_{total}\times v_{total})/C=0.012\ m^2$

$thrust_{pressure}=(P7-Pa)=33.6\ N$

$thrust_{Total}=970.5\ N$

Table 3 summarizes the thrust force between three different cases i.e., without afterburner, with afterburner, and afterburner with water injection.

Table 3: Comparison of Thrust Values for Different Cases

Case	Thrust Value
Without Afterburner	749.8 N
With Afterburner	928.7 N
Water Injection with Afterburner	970.5 N

G. Nozzle through a Duct with Varying Area

In this section we calculate the area of the entry of the gases nozzle and the area of the nozzle when gases are released at the speed of flow and Mach number. The nozzle is applied as convergent/ divergent with variable area.

The Mach number M_1 is equal 0.95 and the ratio between area inlet and throat area is given by:

$A/A* = (1/M)[2(k-1)M^2/(k+1)]^{k+1/2(k-1)}$

Or at M = 0.95, $A/A* = 1.0022$, $P/P_0 = 0.57$, and $T/T_0 = 0.88$.

$P_0 = 1.134\ bar, T_0 = 1032.2\ K$

Here A is the area of inlet of the nozzle and $A*$ is throat area. The Mach number of the exit area can be found using: $M_2^2 = ((k-1)_1^2+2)/(2kM_1^2-(k-1))$

$M_2 = 1.05$

From the of isentropic flow at $M_2 = 1.05$

$A/A* = 1.0021$, $P/P_0 = 0.515$, $T/T_0 = 0.858$

This value is close to M = 1 and the flow is supersonic and from the table of gas dynamic at k = 1.3 the ratio between area exit and throat area is given by:
$A_2/A* = 1.0021$

$A_1/A_2 = 1$

The variation between inlet and the area of exit is same because M_1 and M_2 are critical values. Also the Mach number reaches transient at M = 1.

From Figure 6, the value of P_2 and T_2 at cross section can be found by:
$P_2 = 0.584\ ba$ and $T_2 = 885.6\ K$

H. Jet Pipe Design

In this section, we calculate the design of the jet pipe chamber, which must achieve several criteria. It starts with nozzle calculation after that, we calculate the device of the after burner.

Pressure at point 6 is equivalent to 1.99 bars while temperature is equal to 1173 K. The total flow of hot gases of air and fuel through the nozzle is equivalent to 1.41 kilograms per second.

I. After Burner Sizing

In this section, we find the size required for the completion of the combustion of fuel and air. The design aims to achieve the following:

- Maximum efficiency of heat addition (add all of the available heat).
- Minimum loss in stagnation pressure.
- Small length, volume, weight.
- Safety and reliability
- Stability of flame.

Total gases that have been mixed within the combustion chamber are equal to 0.39 cubic meters per second. The volume of afterburner combustion chamber is found with the help of the volume of gas. Moreover, its diameter will be found accordingly. That is $volume = \pi \times D \times L$. Here D and L are the diameter and length of afterburner chamber. Through the above relationship, it is clear that the size of the combustion chamber is linked by its diameter if the design was a circular shape. It is also assumed that the length is 60 cm and the diameter of the pipe is given by: $D = 0.207\ m \cong 21\ cm$.

Through the preliminary measurements of the pipe which is fitted on the afterburner, it is clear that the diameter of duct pipe is about 13.33 cm. This means that there is an increase or divergence with respect to the diameter of afterburner. The high speed of the gases coming from T_4 is an obstacle to the stability of the flame combustion and therefore the design must accommodate the combustion chamber to reduce speed with low pressure drop as much as possible. The dimensions of the afterburner are summarized in Table 4.

Table 4: Dimensions of afterburner

Dimensions	Length (cm)
Pipe Length	60
Jet Pipe Diameter	13.33
Pipe Diameter	21
Exit Diameter	8.4

V. CONCLUSION

This paper presented a study of the effect of reheat on a gas turbine with high inlet temperature. The study concludes that the power generated in an engine can be used to produce the thrust that is required for transportation. But with the hypothesis of temperature within which nozzle is studied here could give an initial impression of the other part of the study, which deals with water injection at a temperature of 1173 K. But the conditions and changes in the properties of air and fuel at high temperatures is best to design at high temperature. On other hand, it is impossible to design at high temperatures also. Finally it can be concluded that each application of combustion is a special case in terms of temperature determination.

REFERENCES

[1] F. Martínez, A. Martínez, M. Velazquez, P. Diez, G. Eslava, and J. Francis, Evaluation of the gas turbine inlet temperature with relation to the excess air. Energy and Power Engineering, 3(4), 2001, 517–524.

[2] M. da Cunha Alves, H. Carneiro, J. Barbosa, L. Travieso, P. Pilidis, and K. W. Ramsden, An insight on intercooling and reheat gas turbine cycles, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 215(2), 2001, 163–171.

[3] www.salvatoreaiello.com

[4] T. D. Eatop& A. McConkey, "Applied Thermodynamics for Engineering Technologists", Longman, 4th edition.

[5] W. Bathie, "Fundamentals of gas turbines", John Willey & Sons, 2nd edition, 1996.

[6] P. P. Walsh, P. Fletcher, "Gas Turbine Performance", Blackwell, 2nd edition, 2004.