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TURBINE OUTPUT IMPROVEMENT BY LOWERING THE AMBIENT TEMPERATURE AND ELIMINATION OF HUMIDITY

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Abstract: Areas that experience high temperatures during hot seasons suffer significant losses in production capacity and gas turbine efficiency. When the air temperature increases, the flow rate of the air mass decreases, and thus this leads to a decrease in the energy produced by gas turbines. In this regard, atmospheric air can be cooled using evaporative or absorption chillers. Emphasis was placed in this project on the effect of air temperature on the performance of the North Benghazi power plant. The results showed that the higher the air temperature, the lower the flow mass and the capacity of the turbine shaft. In addition, an increase in the air temperature leads to a decrease in the thermal efficiency. It was also evident from our study that any increase in the percentage of steam in the surrounding atmosphere at the expense of dry air for the same volume of the mixture of dry air and water vapor together leads to a decrease in the weight of the total mass of the volume of this mixture and accordingly reduces the capacity of the turbine shaft and vice versa.

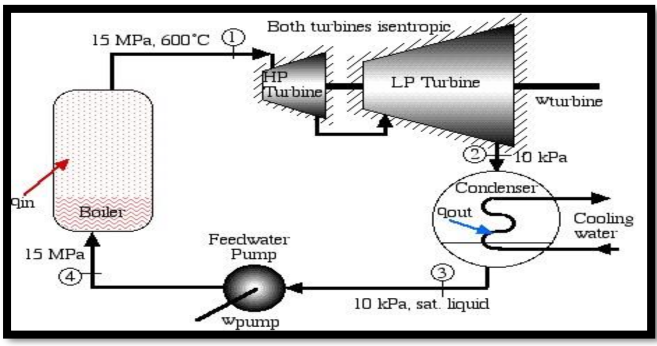
Keywords: Power Plant, Turbine Efficiency, Lowering the Ambient Temperature and Humidity Eliminations.

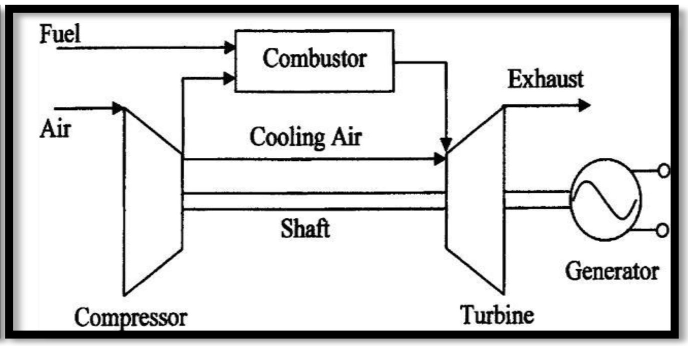
1. INTRODUCTION

Currently, extending the energy supply, design optimization and increasing the efficiency are the main goals and targets of the industries and their plans. Due to the increase of human population, a continuously increasing amount of electricity needed to be generated. There are various technologies for power generation in the world, such as wind energy, water energy, steam turbines (ST) and gas turbines (GT). The costs of the fuels are increasing continuously in the entire world. Consequently, increasing efficiency and cost optimization of power plants are attractive subjects for engineers. Some part of the world's power is generated in thermal power plants by using steam and gas turbines.

Gas turbine power plants operating in hot climate condition suffer a decrease in output power and efficiency during the hot summer months. The typical combustion turbine on a hot summer day, for instance, produces up to 20% less power than on a cold winter day. As a result, a number of cooling techniques and technologies have evolved over the years to maximize turbine output. Inlet air-cooling system is a popular choice worldwide to reduce the power loss especially at times of peak demand in the summer. Cooling the turbine inlet air back to the ISO condition can restore the

Figure 1 Steam turbine cycle Figure 2 Gas turbine cycle





design point performance. [1] Ameri, and Hejazi stated in their study paper that for each 1ºC increase in ambient temperature, the power output will decrease by 0.74%. Performance and economic enhancement of cogeneration gas turbines through compressor inlet air cooling has been described by Lucia et. al [2] who showed that gas turbine air cooling systems serve to raise performance to peak power levels during the hot months when high atmospheric temperatures cause reductions in net power output. This work describes the technical and economic advantages of providing a compressor inlet air cooling system to increase the gas turbine's power rating and reduce its heat rate. Reason for the performance drop is that the hot air entering the turbine is less dense than cool air, so the flow mass through the machine is reduced. One way to avoid the performance degradation is by installing an inlet air-cooling system. Nasser and El-Kalay [3] and Boonnasa et. al [4] proposed the use of absorption chillers powered by the waste heat of the exhaust gases to cool the compressor inlet air.

The aim of this project to study the effect of ambient temperature and humidity on the performance of the north Benghazi power plant.

2. The Benghazi North Power Plant

2.1 General description:

The Benghazi North Combined Cycle Power Plant (**BCCPP**) is located north of Benghazi, in northern part of Libya state. The Benghazi north power plant is the main power source in the eastern wing of the general electricity network of the Libyan state.

Figure 3. Benghazi combined cycle power plant

The first stage was constructed by Siemens manufacturing company in 1971, which consisted of six Steam Turbine units, four units of 40 MW and two units of 30 MW.

In view of the increasing demand for electric power, the general electricity company **(GECOL)** contracted with **ABB** (Swiss-Swedish multinational company) to install three gas turbine units' type "GT13 E1" with a total capacity of 450 MW, in 1995 these units Alstom company (multinational connected to the public network for electricity, where these units operate by fuel gas and light oil in simple cycle system.

In 2001, company), was contracted to set up an additional gas unit module GT13E2. It was installed in 2002 and entered on the general electricity grid with a capacity of 160 MW. all the gas units that were created are operated in a simple cycle system with the possibility of a combined cycle.

2.2 Plant Operation:

The GTs are designed for base load, part load and peak load operations. Presently the units are mainly operated at base load in consideration of the load demand from the grid.

Table 1 Base, part and peak load operations

	units	Min.	Design	Max.
Ambient temperature	[ºC]	5	37	50
Ambient pressure	[bar]	1.012		
Rel. humidity range	[%]	0 – 100		

2.3 Peak Load Operation:

The maximum set point for turbine inlet temperature is limited to 1100ºC for gas and 1070°C for oil operation.

2.4 Exhaust Temperature:

During start up the rise of the exhaust, temperature should be observed. The peak value depends on the thermal condition of the turbine prior to the startup (cold start/hot start) and the ambient condition (especially ambient temperature). The peak temperature is expected to be in the speed range of 1850 rpm and 2250 rpm and is limited] during start up to 450ºC.

3. Results and Discussions

3.1 Formulas derivation and calculations

3.1.1 Steady state flow energy equation (S.S.F.E.E) and its derivatives:

Each component of the gas turbine engine operates in a steady manner. For a steady flow process and retuning to steady state flow energy equation applying it for turbine ideal cycle (remembering that turbine and compressor are assumed to operate adiabatically and reversibly (isentropically), that the heat addition is one of zero work, and the kinetin and potential energy assumed to be neglected, the result equation were : Alobaid et. al [5] Petruzzi et. al [6]

$$h1 + \frac{V1}{2} + gz1 + W = h2 + \frac{V2}{2} + gz2 + q \quad 2 \quad 2 \quad (1)$$

Since, $W = q + (h2 - h1) + \frac{(V2-V1)2}{2} + (Z2g - Z1g)$

$W = h2 - h1 = Cp\ (T2 - T1)$ (2)

Taking in consideration that the mass flow is constant (all units of the work and energy of heat will be in (*kJ /kg*) and the total energy input to the system is equal to the total energy output.

Equations of gas turbine net work:

From Temperature-entropy diagram for basic gas turbine engine with friction:

$Wcomp = h2' - h1 = Cp_a\ (2' - T1)$ *Compressor work* (3)

$Wturb = h3' - h4' = Cp_g\ (T3' - T4')$ *Turbine work* (4)

$Wnet = Wturb - Wcomp = Cp\ (T3' - T4') - Cp\ (T2' - T1)$ *Net Work* (5)

Equations of gas turbine heat addition and efficiency:

$Q_{in} = h3' - h2' = Cp_g\ (3' - h2')$ *Heat addition* (6)

$$\eta_{th} = \frac{w_{net}}{Q_{in}} = \frac{Cp_g\ (T3'-T4') - Cp_a\ (T2'-T1)}{Cp_g\ (T3'-T2')} \quad \textit{Thermal efficiency}\ (7)$$

Equation for power output:

Since the flow is constant, by neglecting the flow mass in the (S.S.F.E.E) and its extracted equations, so the resulting units will be in (*KJ/Kg*). Take the mass flow in consideration and multiply it by the network the result will be the power output.

$P_{output} = W_{net*\dot{m}}$ *Power output* (8)

Equations for isentropic efficiency:

Isentropic efficiency is a parameter to measure the degree of degradation of energy in steady-flow devices. It involves the comparison between the actual performance of a device and the performance that would be achieved under idealized circumstances for the same inlet and exit state.

$\eta_{C} = \frac{(T2-T1)}{T2'-T1)}$ Compressor isentropic efficiency (9)

$\eta_{T} = \frac{(T3'-T4')}{T3'-T4)}$ Turbine isentropic efficiency (10)

This work focuses on the effect of density and mass flow on the turbine power output,

The values used in the following calculation have been taken from a unit of gas turbine located in north Benghazi power plant station. The values also taken intentionally at low and high ambient temperatures in different seasons.

The effect of temperatures on the density and mass flow according to produced power was obvious insuring that the decrease in the ambient temperature leads to increase in mass flow consequently the power output, and that the increase in the ambient temperature leads to decrease in mass flow consequently the power output.

3.2 Data and calculations:

Data of **ISO** conditions in this calculation is real and actual and has been taken from the operation volume of the manufacturer that submitted to the client (north Benghazi station supervisors and technicians on the site). Even though, the data of temperatures applied for other calculation is also actual and have been taken from the logbook, which records the daily analogue and digital readings concerning the gas turbine unit. The ambient temperature of our calculation was at standard reference conditions for gas turbines (ISO 3977) whereas T1 = 15°*C* (59°F) and ambient pressure = 101.3 kPa (14.7 psia)

T1 k	T3 (TIT) k	$\dot{m}_{air}$ kg/s	$\dot{m}_{gas}$ kg/s	Cp_{gas}	γ_{gas}	η_C %	Cp_{air}	γ_{air}	η_T %	P_2/P_1 bar
288	**1343**	**528.6**	**9.8**	**1.005**	**1.3**	**0.86**	**1.11**	**1.4**	**0.86**	**14**

3.2.1 Actual compressor temperature calculations:

From given T1 and pressure ratio (*P2/P1*), T_2 can be calculated isentropically:

$T2 = T1\ (\frac{P2}{P1})^{\gamma-1/\gamma}$ $T2 = 288 * (14)^{0.286} = 612\ k_{\circ}$

From Equation (9), calculate the actual temperature T2' using compressor isentropic efficiency:

$T2' = \frac{(T2-T1+\eta_C*T1)}{\eta_C} = \frac{(612-288+0.86*288)}{0.86} = 664.7k_{\circ}$

3.2.2 Actual turbine outlet temperature calculations:

As dealing with the process isentropically and referring to Figure (2), also as mentioned that no pressure drop during the heat addition process and that the pressure leaving the turbine is equal to the pressure entering the compressor, then consider $P_2=P_3$ and $P_1=P_4$.

From given T3' and pressure ratio $(P_3/P_4) = (P_2/P_1)$. T_4 can be calculated isentropically:

$T4 = \frac{T3'}{(\frac{P2}{P1})^{\gamma-1/\gamma}}$ $\circ$ $T4 = \frac{1343\ k^{\circ}}{(14)^{0.25}} = 694.6\ k$

From Equation (4.10), the actual temperature T4' using turbine isentropic efficiency:
$T4' = T3' - \eta_T * (T3' - T4)$ $\qquad$ $T4' = 1343 - (0.86) * (1343 - 694.6) = 785\ k°$
Since, T1 = 288k°, T2' = 664.7k°, T3' = 1343k°, T4' = 785 k°
Referring to the equations above:
$Wcomp = h2' - h1 = Cp_a\ (2' - T1) = 1.005 * (664.7 - 288\ ) = 378.6\ kj/kg$
$Wturb = h3' - h4' = Cp_g\ (T3' - T4') = 1.11 * (1343 - 785) = 619\ kj/kg$
$Wnet = Wturb - Wcomp = Cp_g\ (T3' - T4') - Cp_a\ (T2' - T1) = 619 - 378.6 = 241\ kj/kg$
$P_{output} = W_{net} * \dot{m}\ 241 * 528\ .6 = 127{,}393\ Kw = 127\ Mw$
Applying same steps of calculations with different data, getting the results in the table 2 below including our previous calculation:

Table 2 Resulting works, flow mass and power output at different air inlet temperatures

T1 (°C)	T3′ (°C)	T4′ (°C)	W (i/p) (kj/kg)	W(o/p) (kj/kg)	W_{net} (kj/kg)	$\dot{m}$ **a** (kg/s)	P (o/p) (MW)
5	1059	506	366	614	247	544	134
15	1070	512	379	619	241	529	127
37	1100	530	408	633	225	488	110
50	1110	536	425	638	213	401	85

3.2.3 Thermal efficiency:

From Equation (4.8) at T1 = 15° C thermal efficiency of the turbine =

$$\eta_{th} = \frac{w_{net}}{Q_{in}} = \frac{Cp\ (T3' - T4') - Cp\ (T2' - T1\ )}{Cp\ (\ T3' - T2')} = \frac{241}{1.11\ (\ 1343 - 664.7\ )} = 32\%$$

Applying same calculations with the other ambient temperatures, getting the results in the table 3 below:

Table 3 Resulting thermal efficiencies at different air inlet temperatures

Ambient temperature (T_1 °C)	**Thermal efficiency (ηth)**
5	33.2
15	32
37	30.8
50	30

Table 4 Ambient temperature effects on power output in different types of gas turbines

Ambient Temperature	**Plant power output in Mwatts at varying Ambient Temperature**					
	GE 7FA.05		**SiemensT SGT6-5000F**		**Wartsila**	
	Compined cycle	**Simple sycle**	**Compined cycle**	**Simple sycle**	**Compined cycle**	**Simple sycle**
10°C	312	214	269	204	305	276
15°C	306	209	289	198	304	276
20°C	300	205	280	191	303	276
25°C	292	200	270	185	301	276
30°C	282	194	259	178	300	276
35°C	271	188	248	172	292	269

Notice from the information in the table (2) above that as the ambient temperature decreases, the mass flow and the turbine power shaft increases and these results goes with the relation between the density and the temperature, which have Inverse relation:

$\rho = \frac{P}{RT}$ And $\rho = \frac{m}{v}$ $\quad \therefore \frac{P}{RT} \alpha \frac{m}{v}$ $\quad \therefore T\alpha \left(\frac{1}{m}\right)$

The cooler, denser air increases output and efficiency In terms of gas turbine efficiency, the effect of air density is well known: denser intake air increases mass flow rate, which consequently results in improved turbine output and efficiency. Air density is inversely proportional to temperature, meaning that rising temperatures decrease air density and therefore reduce gas turbine efficiency and power. Inlet-air cooling, especially in warm and hot environments, is commonly used to compensate for the efficiency loss caused by high air temperature. Even a small reduction in air temperature can lead to a significant increase in power output. A 1°C reduction in air temperature can increase output by up to 0.5%. From the previous calculations, we get to a certain result that as mass flow the compressors receive from the air intake system as much mechanical power we gain in the shaft.

3.3 The effect of humidity on air density and mass flow rate

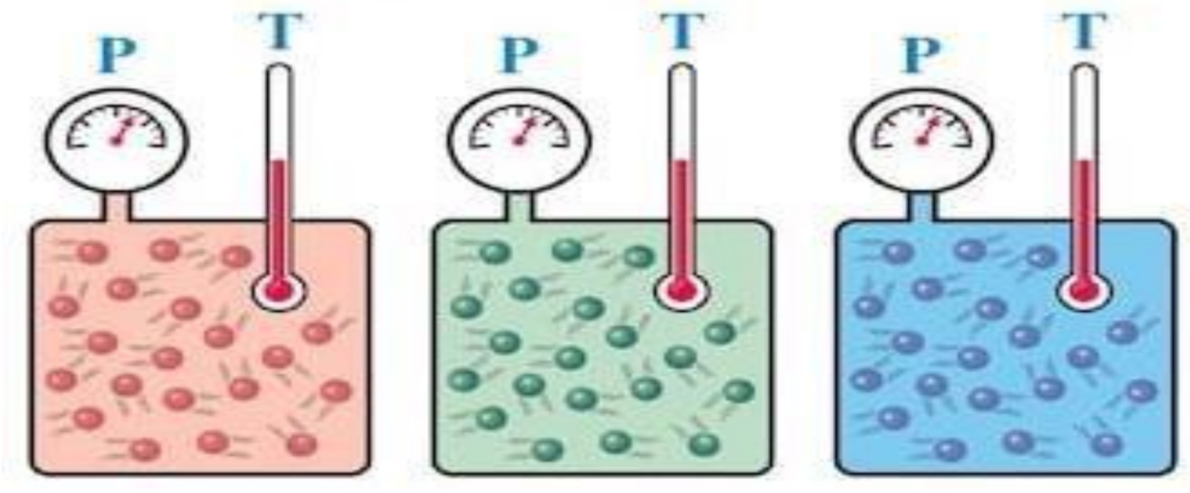
3.3.1 General effect of humidity on the power plants:

Gas turbines are air-breathing machines whose power output is dependent on the air mass through the compressor. Ambient temperature, altitude and humidity all affect the density of air. On hot days, when air is less dense, power output falls off. Hot and humid air is less dense than dry, cooler air and the density is thinner at high altitudes. As the density of air decreases, more power is required to compress the same mass of air. This reduces the output of the gas turbine and decreases efficiency.

Gas turbine manufacturers specify performance at standard conditions called ISO ratings**.** The three standard conditions specified in the ratings are Ambient Temperature 15^{o}C, Relative Humidity 60%, and Ambient Pressure at Sea Level. Gas turbine efficiency deteriorates by 1% for every 10 degree rise in temperature above ISO conditions. This translates into a power output reduction of 5 to 10 per cent.

How air density decrease with the increase of humidity.

Avogadro’s Law states that equal volumes of gases, at the same temperature and pressure, contain the same number of molecules.



(H2+O) + 20 (N2+O2) = 20 ((H2+O/2 + N2+O2 /2))

Figure 4. Distribution of molecules

Dry atmosphere comprises about 78% nitrogen (N2) and 21% oxygen (O2). The molecular weights of a nitrogen molecule and an oxygen molecule are 28 and 32 respectively. See the figure 5 below.

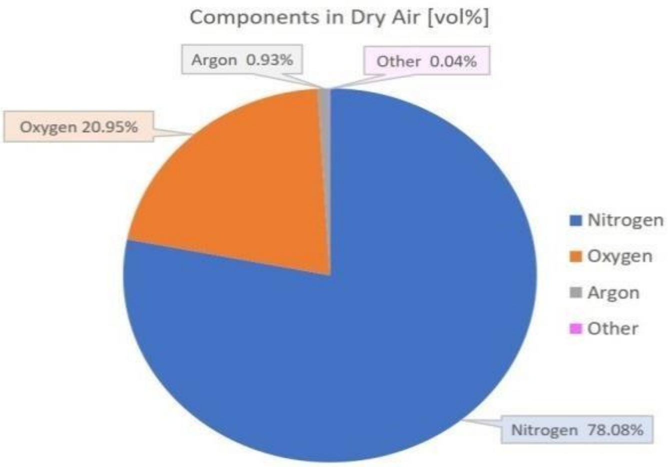


Figure 5 Components in dry air

Water vapor, on the other hand, has a molecular weight of 18. If you replace oxygen and nitrogen with water vapor, the total mass of a cubic meter of air must go down. Density is mass / volume. Thus, a decrease in mass reduces density. Adding water vapor to air (i.e., increasing humidity) decreases air density and therefore decreases mass.

Table (5) shows atomic mass for the element concerning (mole/g)

Element name	Atomic mass
Hydrogen	1
Nitrogen	14
Oxygen	16

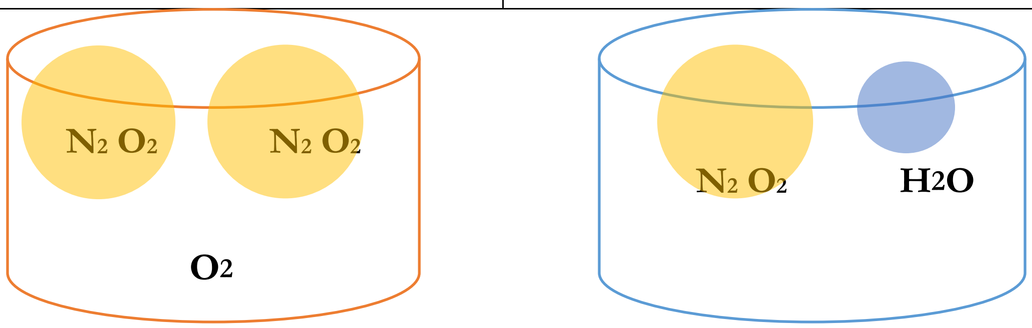


Figure 6 Dry air molecules Figure 7 Moist air molecules

*Note that the molecule of H_2O takes the place of molecules of air components.

3.3.2 Calculation the difference in weight between dry and moist air:

In this simple calculation, we deal with two cases, one case having two molecules of dry air, the other case having one molecule for each dry air and water (moist air). As a result, the moist air has heavier mass than the dry air.

Table 6 Molecule weight in (g) for dry and moist air

Air	The molecule	Atomic mass (molecule weight in g)	The Property
Dry	(N2 + O2)+ (N2+O2)	(14*2+16*2)+(14*2+16*2)= 120 g	Heavier
Moist	(N2+O2)+(H2 O)	(14*2+16*2)+(1*2+16) = 78 g	Lighter

3.3.3 Calculation of vapor ratio against dry air ratio:

Table 7 Vapor ratio against dry air ratio

Total of moles	Molecular mass of dry air in a mole N2 + O2	Number of dry air moles	Molecular mass of vapor in a mole H2O	Number of vapor moles	Total of Molecular mass in moist air
5	28+32 = 60	4	2+16= 18	1	60*4+18*1=258
5	28+32 = 60	3	2+16= 18	2	60*3+18*2=216
5	28+32 = 60	2	2+16= 18	3	60*2+18*3=174
5	28+32 = 60	1	2+16= 18	4	60*1+18*4=132

Looking at the result values in the table 7 we notice that as the ratio of the vapor increases over the ratio of the dry air as the molecular mass decreases and versa vesa. In conclusion we come to a definite result that the moist air or humidity has its negative effect on the weight of mass flow and consequently on the turbine power shaft. The vapor also increases with the increase of the temperature and the relative humidity as shown in the figure 8.

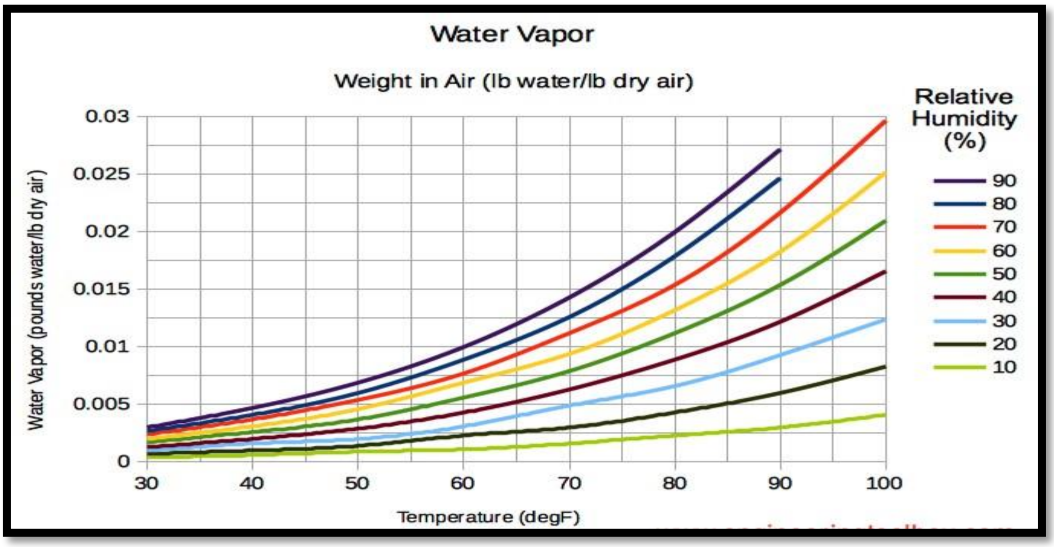


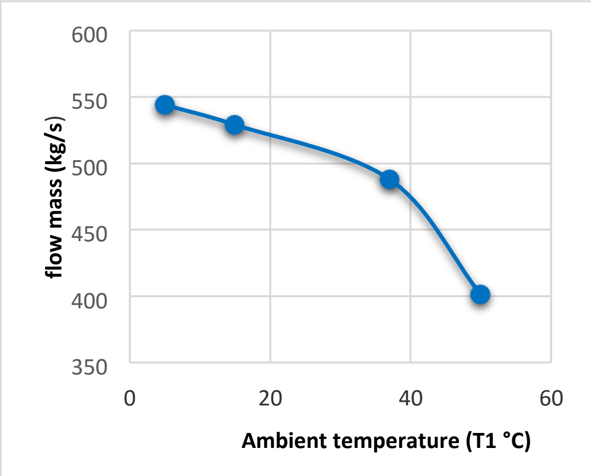
Figure (8) Eeffects of ambient temperature and relative humidity on the water vapor

4. Results and Discusion

4.1 Flow mass, ambient temperature, efficiency and power output:

From calculations that made in this chapter and from the tables 2 above, the final result is in the Figure 9 which represents the behavior of the ambient temperature and the mass flow in a chart and confirms that there is inverse relationship between the two parameters, that is to say as the ambient temperature decreases, the mass flow entering the turbine inlet increases.

In addition, ambient temperature has inverse relationship with the power output and this what the Figure 10 illustrates below.



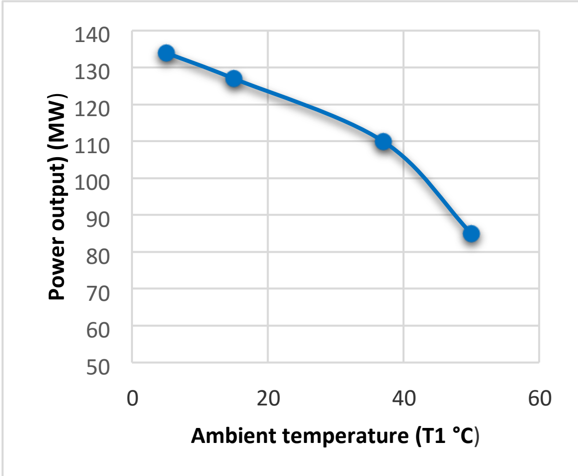
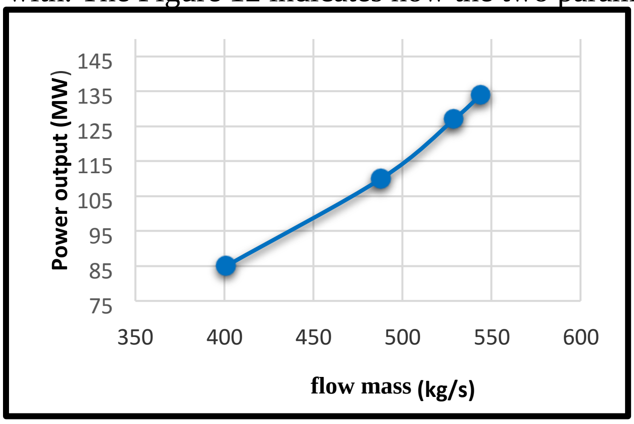


Figure 9 Ambient temperature and flow Figure 10 Ambient temperature and power output mass relationship

The Figure 11 shows how the power output behave against the varieties of the flow mass value and it is clearly upon the chart, that the two parameters have inverse relationship, on other words , increasing the flow mass means increasing in the power turbine shaft and this is the core of our study case.

Besides, referring to table 3 the calculations have been made from the formulas and the data available to know the relationship between the varieties of ambient temperatures and the thermal efficiency accompanied with. The Figure 12 indicates how the two parameters behave.



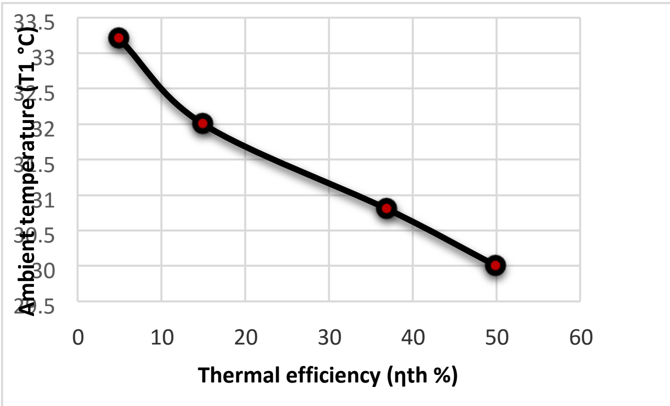
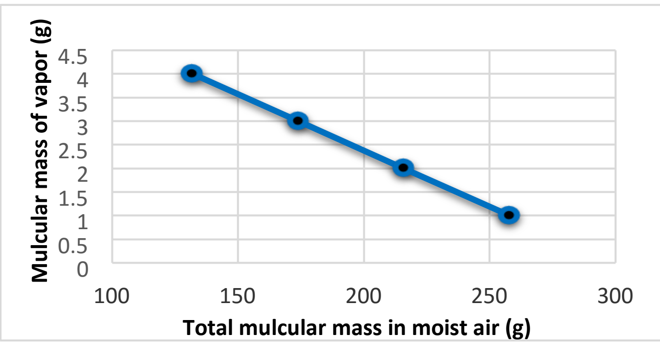


Figure 11 Flow mass and power Figure 12 Ambient temperature and output relationship thermal efficiency relationship

4.2 Humidity and power output:

In this study, taking in consideration the effect of humidity and how it change the weight of the mass when the vapor unify with the dry air forming moist air, Figure 13 and 14 shown that the increasing of the vapor ratio over the dry air causes the decrease in the mass and versa vesa.



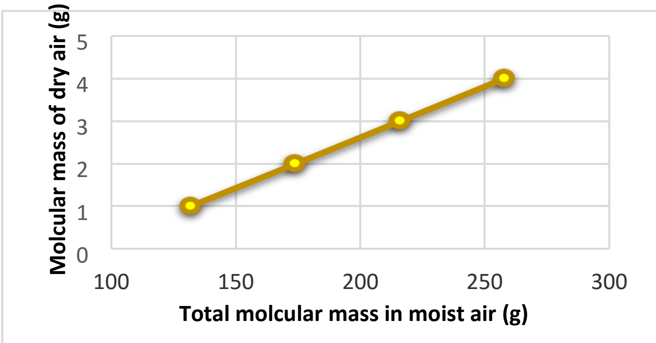


Figure 13 Vapor molecular mass and Figure 14 Dry molecular mass and total total molecular mass in moist air relationship molecular mass in moist air relationship

5. Conclusions

- The changes in ambient temperature have obvious effects on the values on turbine power output because of the relationship between the temperature and air density, air density and air mass, consequently air mass and work in power shaft
- Results that are recorded in the table 2 in chapter four shows that as the ambient temperature increases, the flow mass and turbine power shaft decrease. On the other hand, the figure 12 in chapter four shows the direct relationship between the flow mass and turbine power output.
- Lowering ambient temperature has also influence on thermal efficiency as it is illustrated in the table 3 and figure 13 in chapter four, that is increasing in ambient temperature means decreasing in thermal efficacy.
- The figures show that any increase of the vapor at the expense of dry air in the same mixture volume, will decrease the weight of the total mass in that volume accordingly decrease the power.

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