Eng. & Tech. Journal ,Vol.28, No.2, 2010

The Influence of Water Injection on Two - Shaft Gas Turbine Performance with Regeneration

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Received on: 20/4/2009
Accepted on: 5/11/2009

Abstract

A two-shaft gas turbine type GT-85-2-H has been modified and converted into a research unit. The main modifications consist of incorporating regeneration system and water spray system in the inlet air duct of the GT-85-2-H gas turbine. The influence of regeneration and water injection in the air intake on gas turbine performance has been studied. The results show that regeneration improves the thermal efficiency by about 56% due to reduction in the fuel consumption, and reduces the power output due to back pressure losses that occur because of the regenerative system by about 20.67%.The brake specific fuel consumption is reduced by about 59%.

Water injection strongly affects the power output. Water injection tends to increase the brake power output by about 47%.The thermal efficiency is also increased by about 30%.The specific fuel consumption is reduced by about 29%.

Keywords: Gas turbine, Water injection, Regeneration.

تأثير حقن الماء على أداء محرك توربيني ثنائي المحور مع أعادة التوليد

الخلاصة

تم تحوير محرك توربيني ثنائي المحور من نوع GT-85-2-H وتحويله إلى وحدة بحثية. التحويرات الرئيسية تضمنت اضافة منظومة اعادة التوليد ومنظومة تذرية المياه في مدخل ضاغط الهواء لمحرك GT-85-2-H التوربيني. كما تم دراسة تأثيرات إعادة التوليد وحقن الماء على أداء التوربين الغازي. اظهرت النتائج أن أعادة التوليد يحسن الكفاءة الحرارية بحوالي 56% بسبب الانخفاض الحاصل في استهلاك الوقود ويقلل القدرة الخارجة بسبب خسائر الضغط الرجعي الحاصلة بسبب منظومة اعادة التوليد وبحوالي 20.67% كما تم تقليل استهلاك الوقود النوعي وبحوالي 59%. حقن الماء يؤثر وبصورة كبيرة على القدرة الخارجة حيث يميل إلى زيادة القدرة الخارجة وبحوالي 47%. الكفاءة الحرارية ازدادت أيضاً وبحوالي 30% كما تم تقليل استهلاك الوقود النوعي وبحوالي 29%.

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https://doi.org/10.30684/etj.28.2.17
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Introduction

Although the simple Brayton cycle gives reasonable efficiencies, it nonetheless does not take into account some of the complications of real power plant. Beside increasing T_3 (turbine inlet temperature), the modifications on the simple cycle which can be carried out, are as in the following processes :

1- Regeneration.
2- Compressor intercooling.
3- Turbine reheating.
4- Water or steam injection.

Regeneration

Regeneration is an internal exchange of heat within the cycle as shown in Figure 1. The heat energy of the hot gases flowing from the turbine raising the air temperature just before entering the combustion chamber and increases its enthalpy.

Water Injection

Water injection is a method by which the power output of a gas-turbine cycle is materially increased and the efficiency is only marginally increased [1].

In some aircraft propulsion units and some stationary units, water is injected into the compressor and evaporates as the air temperature rises through the compression process. The heat of vaporization, thus, reduces the compressed air temperature and reduces the compressor work. The cycle efficiency, too, is seen to increase [2].

The aims of present research are:

1- Improving the thermal efficiency by regeneration.
2- Using water injection as a means of increasing the power output materially and increasing the efficiency marginally.

Experimential Work

The test of engine chosen for this rig is a two -shaft gas turbine (Gilkes - Rollab "tutor" gas turbine GT-85-2-H).The compression process of the cycle carried out on the GT-85-2-H by a single stage centrifugal compressor operating at a speed up to 90000 r.p.m with a pressure ratio of 2:1 could be achieved [3]. The discharge from the compressor is fed to the combustion chamber where the combustion process takes place with nominal operating air/fuel ratio of approximately 70:1 [3]. The combustion products, at temperature up to about 720 °C are fed to the first turbine and then to the second turbine which is called power turbine. The outlet from the power turbine is then exhausted to the atmosphere. Figure 2 shows schematically the components layout and the measurements locations that are available on the GT-85-2-H.

The present gas turbine model (GT-85) is designed and constructed for a straightforward experimental performance studies. Therefore, it is not suitable for the study with regeneration and water injection processes. Consequently, some modifications are carried out on GT-85 , as shown in Figure 3.

Regeneration System

A double pipe heat exchanger is chosen to act as a regenerator in this study. Regeneration arrangement consists of the following parts:-

1. Two elbows; the first is attached to the exhaust pipe of the power turbine and directs the flow to the connecting pipe; the second is attached to the connecting pipe and directs the flow to the inlet pipe of the double pipe. Each elbow is 10 cm inner diameter and curved with 90°. They are made from carbon steel.
2. Connecting pipe connects the two elbows. It is of 18 cm length and 10 cm inner diameter. Each end is

welded to its own elbow. This connecting pipe is made of carbon steel.

3. Flange that is welded to the second elbow and the inlet pipe to the double pipe.
4. An inlet pipe with 10 cm inner diameter and 20 cm length attached to the bottom of the double pipe.
5. Double pipe, which consists of large, pipe with 16 cm inner diameter and covers the air tube pipe. The air tube is originally installed and it is modified with this pipe. The air tube is tapered pipe with the top diameter of 4.4 cm and the bottom is 5.6 cm. The large pipe was fitted to the air tube by clamps. The long of the double pipe is 50 cm.
6. Exhaust pipe of 10 cm diameter and 30 cm length welded to the top of the double pipe.

The whole parts of the regenerator are covered with insulation to prevent heat dissipation. The hot gases flow in the annular space between the air tube and the large pipe. Also, two thermocouples are installed to measure the inlet and exhaust hot gases temperature. Their sensors are inserted in the large pipe of the double pipe. Its indicator is ranged between 0-1000 °C. The test rig manufacturer has installed a temperature gauge to at the end of air tube to measure the temperature of the delivered air from the compressor .Another one is inserted in the joint connecting the compressor outlet pipe and the air tube to measure T_2. The old one has been used to measure the temperature of the air after heating (T_{22}).

Water spray system

The second modification on the gas turbine system is the incorporation of water spray system as shown in Figure 3.The process of water spraying adapted throughout this study is based on mixing a blast of pressurized air with a stream of water.

Equipments used to Generate Water Spray

Water requires to be broken up into small droplets so as it can effectively evaporate before entering the first turbine .Atomization of the water is most commonly carried out by mixing the water with high pressure air [4]. The following equipments are used to generate water spray:-

1. A reciprocating compressor for air supply with pressure up to (7 bar) to water spray device (aerograph).
2. Water spray device (aerograph).
3. Two butterfly valve for quick closing /opening of water supply to the aerograph.
4. A (200cc) glass water container with (50, 50,100) cc divisions and stop watch to be used as a flow-meter.
5. High-pressure rubber tube for air supply from the compressor to the aerograph.

Effects Of Regeneration

Fuel Mass Flow Rate

Due to air preheating in the regenerative cycle, fuel requirements are expected to be less than that of normal cycle. Since heat will be transferred to the compressed air by the amount of:-

$$Q=\dot{m}_a \, cp_a \, (T_{22}-T_2) \quad ....(1)\ [5]$$

This heat gain will lower the quantity of fuel, which should be burned. Curves of normal and regeneration tend to be divergent for higher speeds as shown in Fig. 4. This is believed to be due to heat accumulation in the test rig and inefficient ventilation during the continuous operation that will raise the overall temperature of the components. The maximum reduction occur is (13.1%) relative to the normal cycle and the minimum is (8.01%) .

Brake Power Output of Power Turbine

Brake power output of power turbine versus fuel mass flow rate and turbine inlet temperature is shown in Figure 5.

Because of back pressure losses occurred due to regeneration system, brake power output has been minimized. Also the reduction happened in the overall mass flow rate of burned gases affect the value of the brake power output. The maximum reduction occurs is (20.67%) relative to the normal cycle and the minimum is (5.3%).

Thermal Efficiency

Fuel requirements have been lowered in the regeneration cycle, minimizing the heat supplied to the cycle, for a given value of gas generator speed. Also the compressor work has been lowered, raising the net power value.

Since[6]

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_c \qquad \text{.........(2)}$$

So, thermal efficiency has been improved, since[6]

$$h_{th} = \frac{\dot{W}_t - \dot{W}_c}{C.V * \dot{m}_f} \qquad \text{..........(3)}$$

which is clearly shown in Figure 6.This improvement increases with the progress of the operation of the test rig, since heat accumulations will contribute in minimizing the fuel mass flow rate and consequently the thermal efficiency. The maximum improvement occur is (56.41%) relative to the normal cycle and the minimum is (19.91%) .

Heat Gain

The heat transferred to the compressed gases versus the fuel flow rate is shown in Figure 7. The curves indicate an inflection point since heat transfer is a function of the temperature difference. The temperature difference decreases in the higher compression ratios, where the higher the compression ratio, the higher is the temperature of the air entering the regenerator. The maximum value of heat gain is [4215.475 (W)] at [0.00124365 (kg/s) fuel mass flow rate] and [1 .404 pressure ratio].

Effects Of Regeneration And Water Injection

Power Input to Compressor

The cooling process to air due to water injection in the inlet duct affects the compressor power strongly, since the power input to compressor is strongly dependent on the temperature difference, where[5]

$$\dot{W}c = \dot{m}_a\, cp\,(T_2 - T_1) \qquad \text{......................(4)}$$

The temperature difference is minimized when the compressor outlet temperature is lowered and even the inlet temperature. This is because of the nature of the pressure curves on T-S diagram, where they become convergent at lower entropy. To prove that, let us consider Gibbs equation [5]:

$$T\,ds = du + p d\upsilon \qquad \text{.......... (5)}$$

Using enthalpy definition

$$h = u + p\,\upsilon \qquad \text{............. (6)}$$

Differentiating both sides of equ.(6) yields:

$$dh = du + p d\upsilon + \upsilon\, dp \qquad \text{...................... (7)}$$

Substituting equ. (5) into equ. (7)yields:

$$Tds = dh - \upsilon\, dp \qquad \text{............. (8)}$$

So re-arranging equ. (8):

$$dp = \frac{cpdT}{u} - \frac{Tds}{u} \qquad \text{……… (9)}$$

Equation (9) indicates that for a negative sign for (dT) and (ds). the result is a negative value of dp (since dT is multiplied by (cp)). Figure 8 shows the minimization in the compressor power. The maximum reduction is (15.39%) relative to the regeneration cycle and the minimum is (8.61%). But the maximum reduction is (42.15%) relative to the normal cycle and the minimum is (19.03%).

Brake Power Output of Power Turbine

Water injection improves the expansion ratio, so the brake power of power turbine will be improved too. Figure 9 shows the brake power of power turbine versus fuel flow rate. They indicate an increase in the brake power of power turbine. This increase in power of a power turbine plant with water injection is, in part the result of increased mass- flow rate of air and water vapor with out a corresponding increase in compressor work.

Figure 12 shows the Brake power of power turbine versus the ratio of injected water mass flow rate to fuel mass flow rate with different gas generator speeds. The maximum increase is (46.75%) relative to the regeneration cycle and the minimum is (7.9%). But the maximum increase is (23.15%) relative to the normal cycle and the minimum is (15.78%).

Thermal Efficiency

The relationship of the thermal efficiency in case of regeneration cycle is expressed by [6]:

$$h_{th.reg} = 1 - \left(\frac{T_1}{T_3}\right)\left(r_p\right)^{(k-1)/k} \qquad \text{…….(10)}$$

This formula indicates an increase in thermal efficiency with a decrease in turbine inlet temperature. But Figure 10 indicates a reduction in the thermal efficiency. This is belong mainly to the reduction occur in the turbine inlet temperature is greater than the reduction occur in the compressor inlet temperature as stated before. But thermal efficiency is still higher than that of normal cycle because of the efficient burning process and the increase of the brake power of power turbine. The maximum reduction is (33.06%) relative to the regeneration cycle and the minimum is (14.1%). But relative to the normal, the maximum increase is (29.89%) cycle and the minimum is (23.44%).

Heat Gain

Figure 11 shows the heat transferred to the compressed air versus fuel flow rate. Since water injection cools the compressor air, the temperature difference will be larger than that of regeneration cycle. So, larger value of heat gain is expected rather than that of regeneration cycle. The maximum increase is (11.63%) relative to the regeneration cycle and the minimum is (6.62%).

Conclusions

1- Regeneration and water injection systems can be achieved in a simple two-shaft gas turbine (GT-85-2-H) to improve the performance. The studied cases are: -

Normal testing, testing with regeneration and testing with regeneration and water injection in the intake duct of the compressor.

2- Regeneration affects the performance of the system cycle as follows:

I- Regeneration reduces the fuel

consumption and compressor work, consequently a good improvement to the thermal efficiency have been achieved. An improvement of (56.41%) for the thermal efficiency relative to the normal cycle has been reached.

II- Regeneration causes reduction in the brake power output due to pressure losses. The maximum reduction occurs was (20.67%) relative to the normal cycle.

3- Water injection strongly affects the performance parameters of the two-shaft gas turbine cycle and as follows: -

(I) The brake power output has been increased up to (46.75%) relative to the regeneration cycle and up to (23.15%) relative to the normal cycle.

(II) The thermal efficiency is lowered from that of the regeneration cycle by 33.06%. But thermal efficiency is still higher than that of normal cycle by (29.89%).

NOMENCLATURE

Symbol	**Definition**	**Unit**
c	specific heat	J/kgK
h	enthalpy	kgJ/kg
m	mass flow-rate	kg/s
p	pressure	N/m^2
T	temperature	K
u	internal energy	Jk/kg
v	volumetric flow-rate	m^3/s
w	work	J

Subscript

1	compressor inlet
2	compressor outlet
22	outlet from heat exchanger
3	combustion chamber outlet/1st turbine inlet
a	ambient; air
f	fuel

Greek letter

γ	specific heats ratio
η	efficiency

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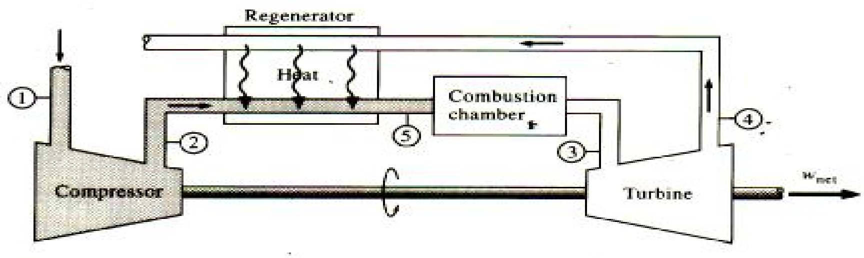

Figure (1) Flow of a gas-turbine cycle with regeneration

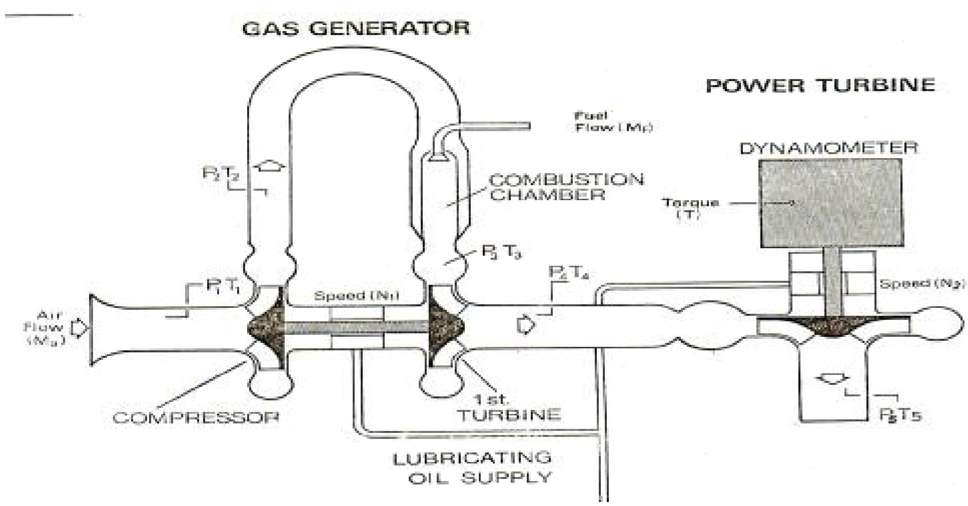

Figure (2) Schematic arrangement for gas turbine before modifications

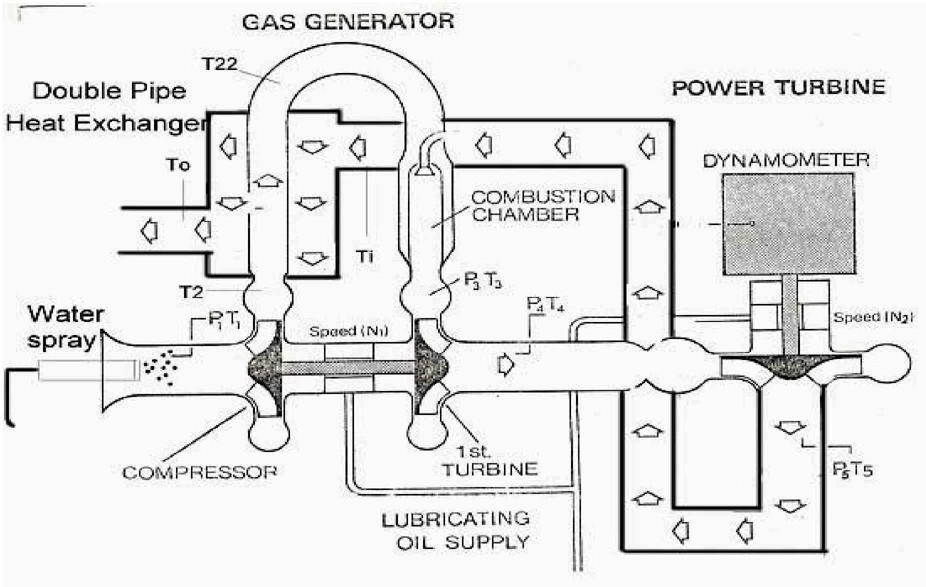

Figure (3) Schematic arrangement for gas turbine after modifications.

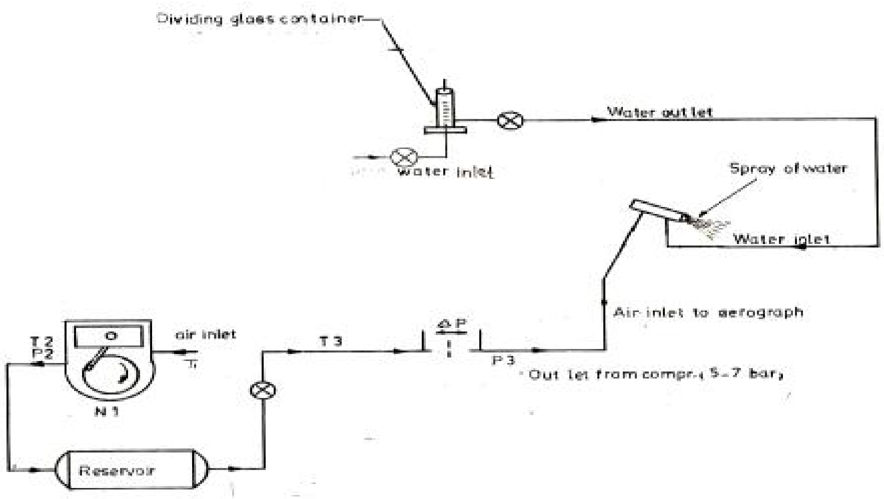

Figure (3a) Schematics arrangement of water spray system

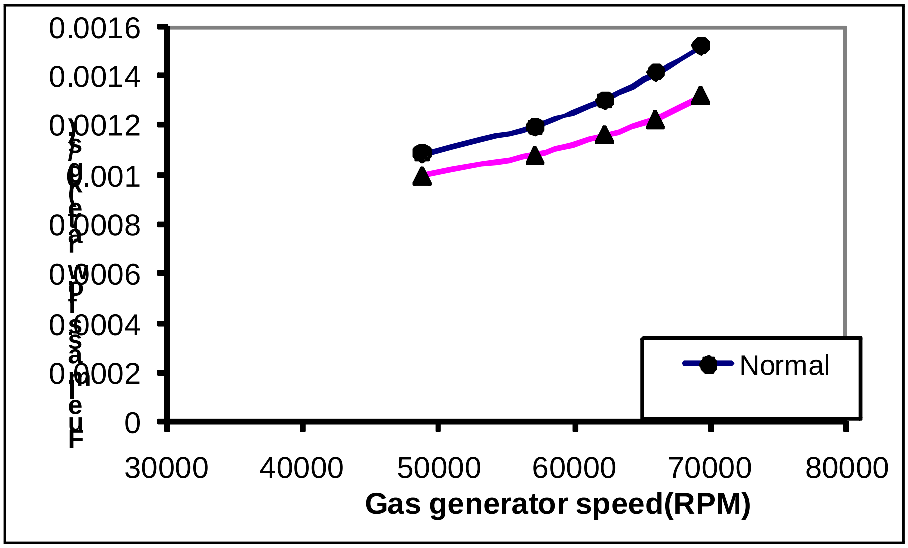

Figure (4) Fuel mass flow rates vs. gas generator speed

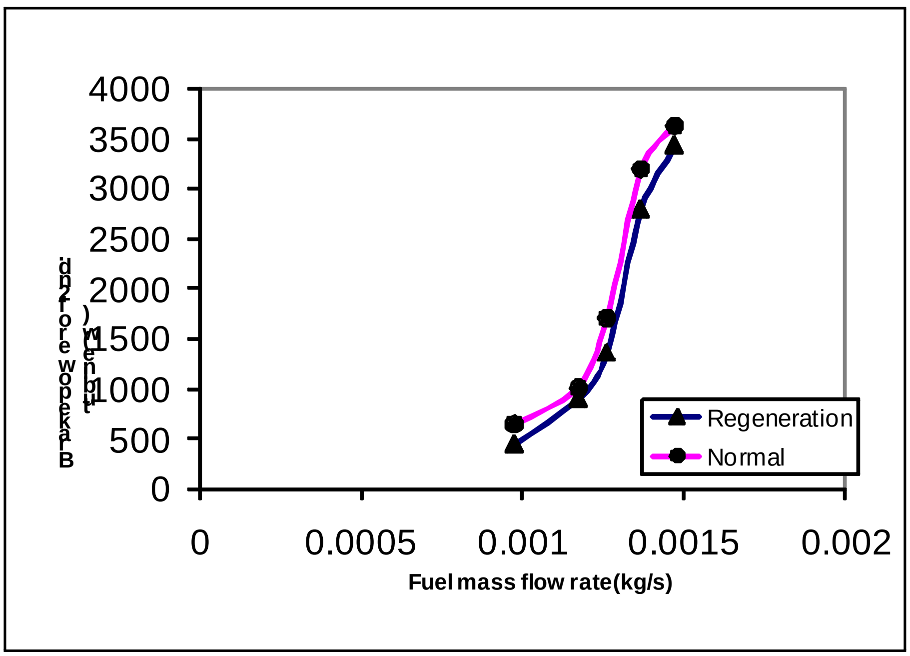

Figure (5) Brake power of power turbine vs. Fuel Flow rate

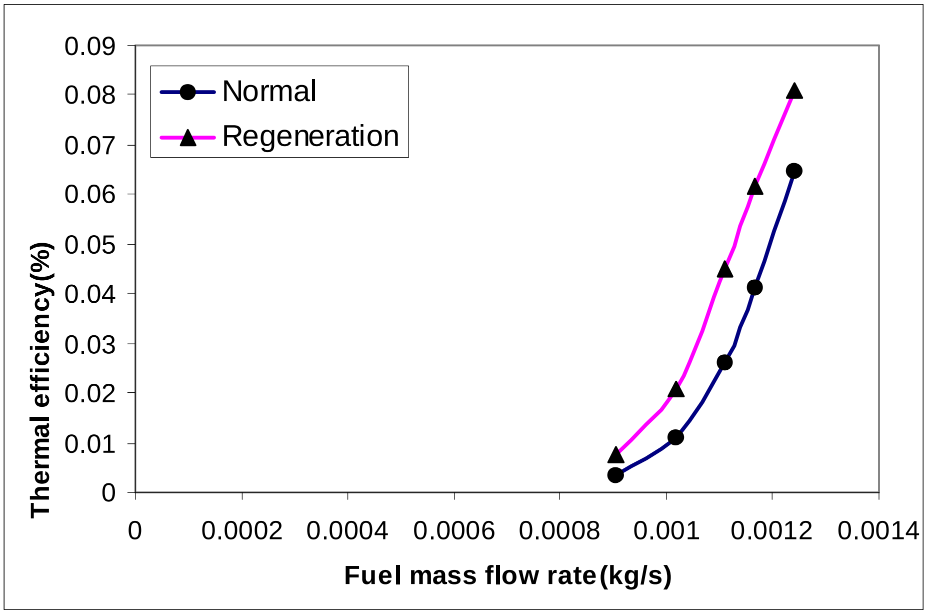

Figure (6) Thermal efficiency vs. Fuel Flow rate

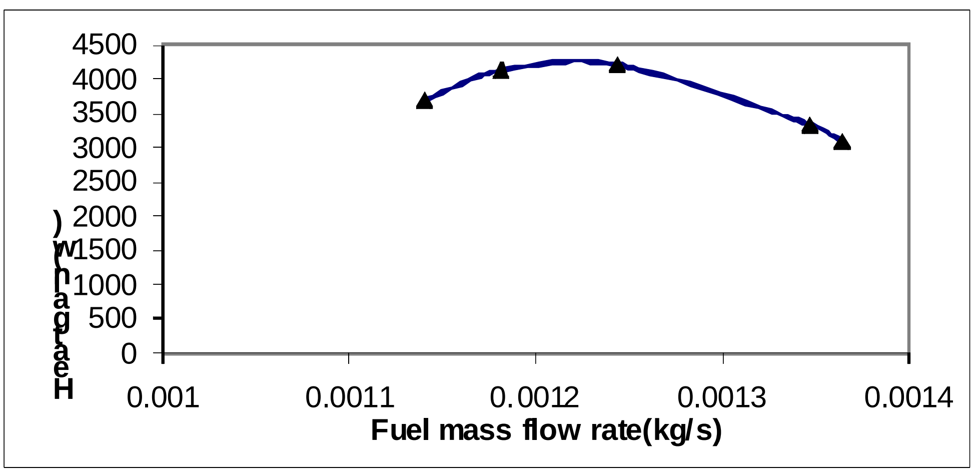

Figure (7) Heat transferred to the compressed air vs. Fuel Flow rate In case of regeneration.

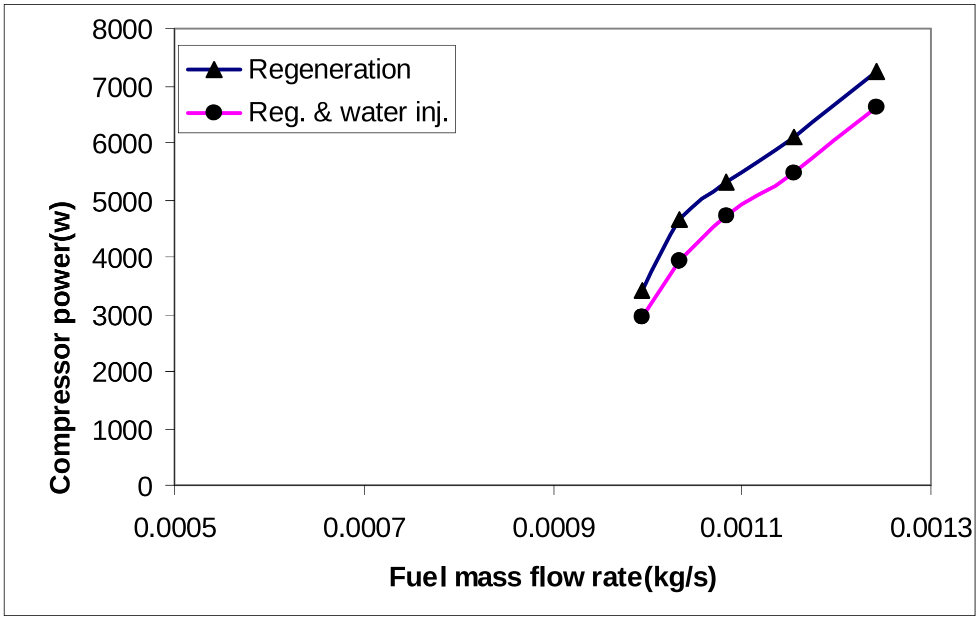

Figure (8) power input to compressor vs. fuel mass flow rate

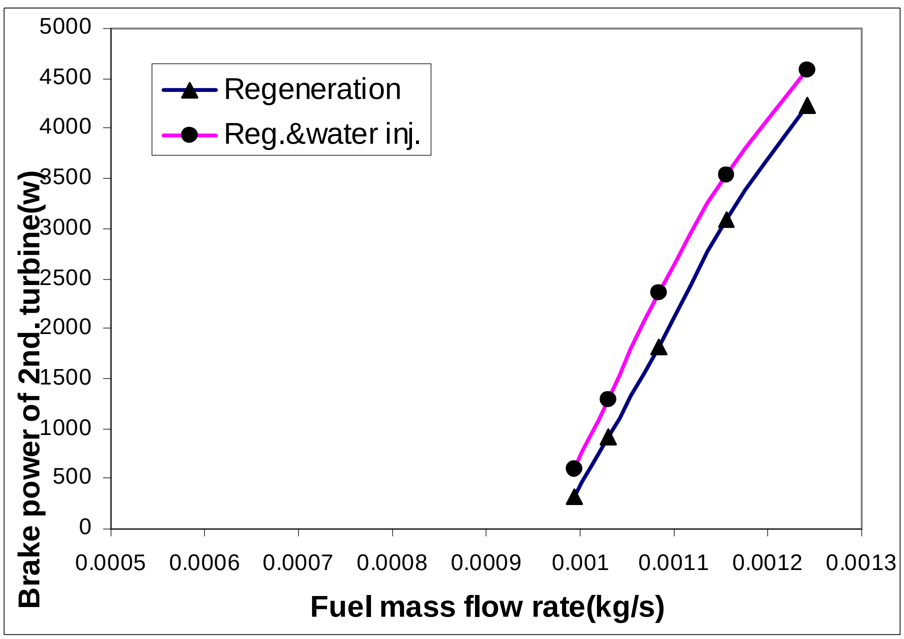

Figure (9) Brake power of power turbine vs. Fuel Flow rate

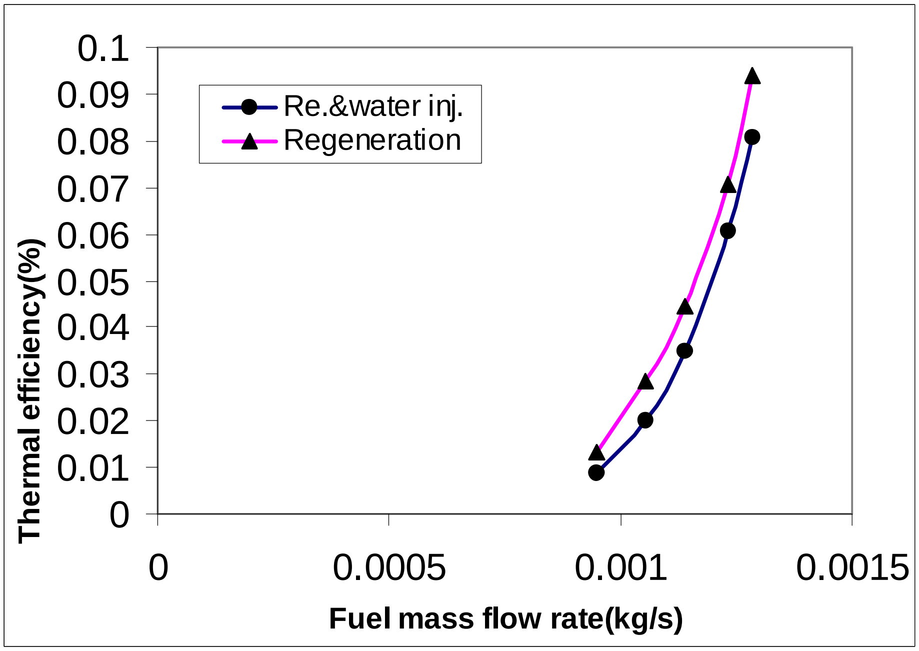

Figure (10) Thermal efficiency vs. Fuel Flow rate

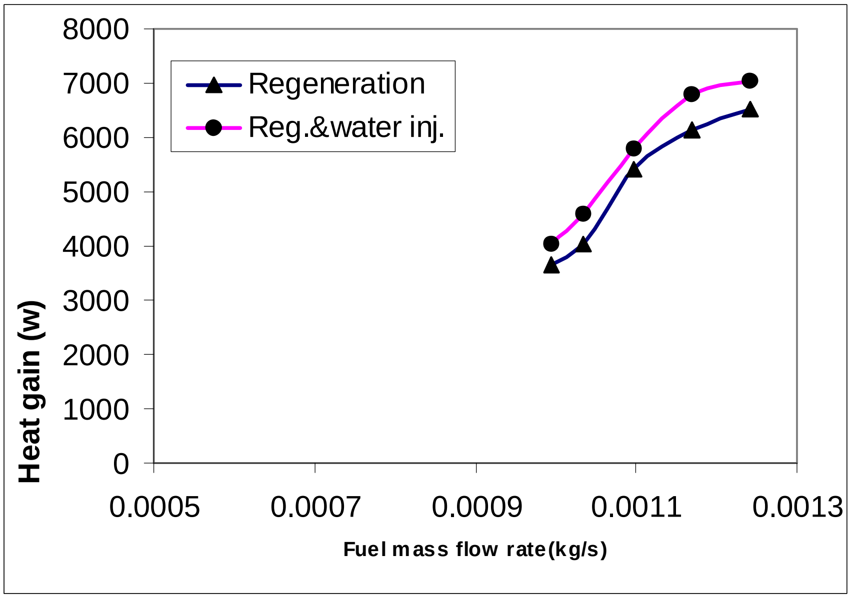

Figure (11) Heat transferred to the compressed air vs. Fuel Flow rate

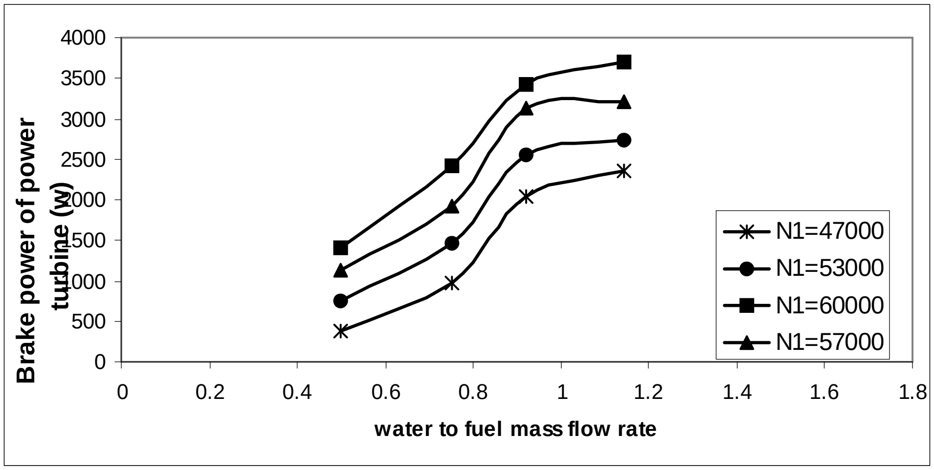

Figure (12) Brake power of power turbine vs. the ratio of injected water mass flow rate to fuel mass flow rate with different gas generator speed

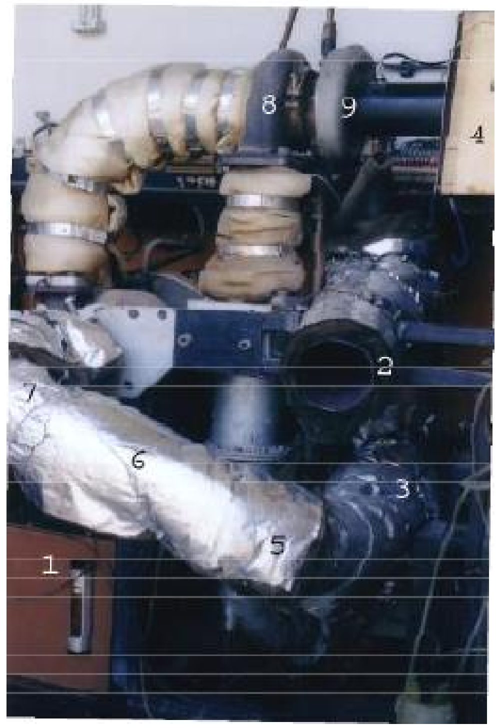

Figure (13) shows the gas turbine with regeneration.

1. Oil tank
2. Exhaust pipe from regeneration
3. Inlet pipe to the double pipe
4. Air inlet box
5. 2nd elbow of regenerator
6. Connecting pipe
7. 1st elbow of regenerator
8. 1st turbine
9. **9.** Air compressor