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Studies on Reduced Inlet Temperature of Compressor and Water Injection to Enhance the Thermal Efficiency of Gas Turbine

Vishnu M. Mohan
Assistant Professor, Department of Mechanical Engineering, College of Engineering, Munnar, Munnar, Kerala, India
Rejith G. Krishnan
Assistant Professor, Department of Mechanical Engineering, College of Engineering, Munnar, Munnar, Kerala, India
Issac Thomas
Assistant Professor, Department of Mechanical Engineering, College of Engineering, Munnar, Munnar, Kerala, India
Saloop T. S.
Assistant Professor, Department of Mechanical Engineering, College of Engineering, Munnar, Munnar, Kerala, India
Sandeep Kumar M.
Assistant Professor, Department of Mechanical Engineering, College of Engineering, Munnar, Munnar, Kerala, India

Abstract:
Burning of hydrocarbons and recovering the thermal energy through gas turbines and producing useful work is a widely used method of thermal power generation. In simple Brayton cycle the amount of work needed for compression is high. It affects net useful work and efficiency of the cycle. Inter cooling is used as a method for reducing compressor work. Studies on inter cooling with water injection will give an idea of how the efficiency varies as a function of temperature, pressure and amount of water injected. We cannot lower the inlet temperature of air to compressor indefinitely; as it affects the net useful work and efficiency in the form of cooling work. The conversion efficiency increases with increase in temperature at inlet of turbines. However, consideration on the material properties often places limitations on the highest temperature which can be used in operation. Also for reducing the NO_X *production during combustion, the inlet temperature should be controlled. The inlet temperature can be controlled by managing the excess air used or by injecting water into the combustion chamber. This paper theoretically analyses the variation of thermal efficiency of gas turbine cycle for different configurations of operations.*

Keywords: *Brayton cycle, cooling, gas turbine, water injection*

1. Introduction

In the simple Brayton cycle, atmospheric air is compressed to high pressure by using single or multistage compressor. Due to the compression process temperature and pressure of air is increased. The high pressure, high temperature air proceeds to the combustion chamber, where fuel is injected. After the combustion, temperature of air fuel mixture i.e., flue gas is further increased. The hot and high pressure flue gas is expanded in a single or multistage gas turbine to produce work. Apart of the work produced is used to drive the compressor and remaining is the net useful work.

Several modifications are suggested by several investigators to simple Brayton cycle to enhance thermodynamic efficiency. Kyoung Hoon Kim *et al.* [1] investigate mechanism of after fogging process in gas turbine systems. In this case evaporation of water droplets during the after fogging process occurs under the conditions of elevated temperatures or pressures, and the results show that gas turbine system with after fogging process could have much greater potential for performance enhancement compared to that within let fogging process. Mehaboob Basha *et al.* [2] examined Performance analysis of different gas turbine power plants. The work includes the effect of humidity, ambient inlet air temperature and types of fuels on gas turbine plant configurations with and without cooling technologies. The study noticed that variation of RH does not affect the performance appreciably but the variation in ambient inlet air temperature has significant effect on the plant net output and efficiency, regardless of the type of fuel. Y.Haseli *et al.* [3] examined the exergetic performance of a high temperature solid oxide fuel cell combined with a conventional recuperative gas turbine plant. This study concludes that, an increase in pressure ratio or turbine inlet temperature leads to higher rate of exergy destruction of the plant and the exergy, thermal efficiency of the integrated cycle can become as high as 57.9% and 60.6% respectively

The present study is confined to atmospheric condition of 25°C temperature and 100 kPa pressure and zero humidity. The fuel is taken as methane gas. In this study temperature of the inlet air to the compressor is varied. There is a need to study the relative effectiveness these modification under varying operating conditions. By using above assumption simple Brayton cycle are studied in the paper Vishnu. M.Mohan and K Sankaran *et al.* [10]
In each configuration, performance is computed for four different temperatures at the inlet temperature to the gas turbines, namely 1500K,1300K, 1000K and 800K. The temperature of inlet air to the compressor is varied by using refrigerator. The inlet air temperature to the compressor is 273K and 260K. The COP of refrigeration system is assumed as 4.5. It is assumed that the flue gas exit from the turbines is at atmospheric pressure, 100 kPa.
In each configuration, the thermodynamic efficiency is computed as the ratio of the network produced to the energy supplied by the fuel used. This is plotted as a function of the pressure ratio used in compression.

2. Performance Analysis for Simple Brayton Cycle

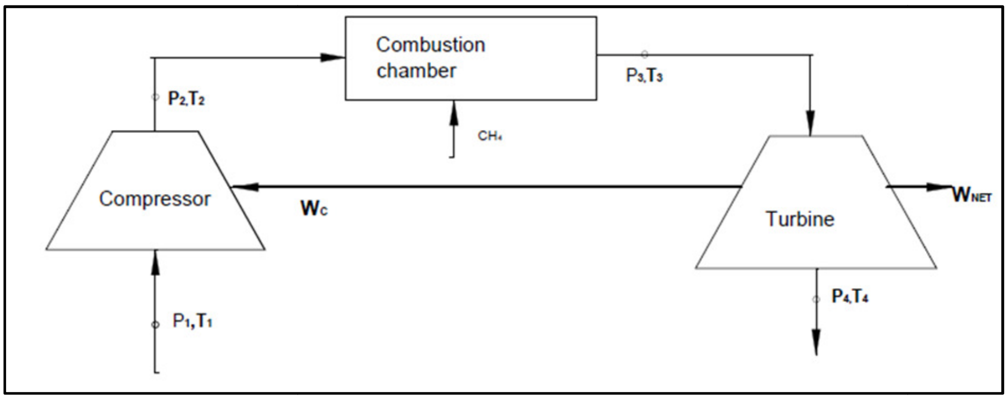

Figure 1: Schematic of simple Brayton cycle

The configuration analysed is shown in Figure 1.For all computations here all the gases are assumed to be ideal gases. Atmospheric air (for calculations, air is assumed to be mixture of oxygen and nitrogen only)at condition 1is compressed in compressor to higher pressure and temperature represented by condition 2 and fed into combustion chamber together with sufficient amount of methane. During combustion it is assumed that the methane is completely burnt to carbon dioxide and water vapour. What comes out of the combustion chamber at condition 3 is a mixture of carbon dioxide, water vapour, excess oxygen and nitrogen. These are fed to the gas turbine to be expanded to condition 4. We assume that the pressure at condition 4 is the atmospheric and the isentropic efficiency of both the compressor and turbine is 80%.

$$\left(\frac{T_{2S}}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \quad (1)$$

$$\frac{(T_{2S} - T_1)}{(T_2 - T_1)} = \eta_C \quad (2)$$

Therefore, for a predetermined pressure ratio $\frac{P_2}{P_1}$, T_2 can be found from solving equations (1) and (2).

$$\left(\frac{T_3}{T_{4S}}\right) = \left(\frac{P_3}{P_4}\right)^{\frac{k-1}{k}} \quad (3)$$

$$\frac{(T_3 - T_4)}{(T_3 - T_{4S})} = \eta_T \quad (4)$$

For a particular value of T_3, T_4 can be computed using equation (3) and (4). It may be noted that $\left(\frac{P_3}{P_4}\right) = \left(\frac{P_2}{P_1}\right)$.

The reaction taking place in the combustion chamber can be written as

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O \qquad (-\Delta H)_{298} \quad (5)$$

Hence, the enthalpy balance over the combustion chamber per mole of air entering can be written as

$$0.21h_{O2,T2} + 0.79h_{N2,T2} + x(-\Delta H)_{298} = (0.21 - 2x)h_{O2,T3} + 0.79h_{N2,T3} + xh_{CO2,T3} + 2xh_{H2O,T3} \quad (6)$$

$$W_C = 0.21\left(h_{O2,T2} - h_{O2,T1}\right) + 0.79\left(h_{N2,T2} - h_{N2,T1}\right) \quad (7)$$

$$W_T = (0.21 - 2x)\left(h_{O2,T3} - h_{O2,T4}\right) + 0.79\left(h_{N2,T3} - h_{N2,T4}\right) + x\left(h_{CO2,T3} - h_{CO2,T4}\right) + 2x\left(h_{H2O,T3} - h_{H2O,T4}\right) \quad (8)$$

$$W_{net} = W_T - W_C \quad (9)$$

Heat input is given by

$$Q_{in} = x(-\Delta H)_{298} (10)$$

Thermal efficiency for converting heat to work can be expressed as

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad (11)$$

Values of η as function of pressure ratio $\left(\frac{P_2}{P_1}\right)$ and temperature T_3 are shown in Fig. 2 .

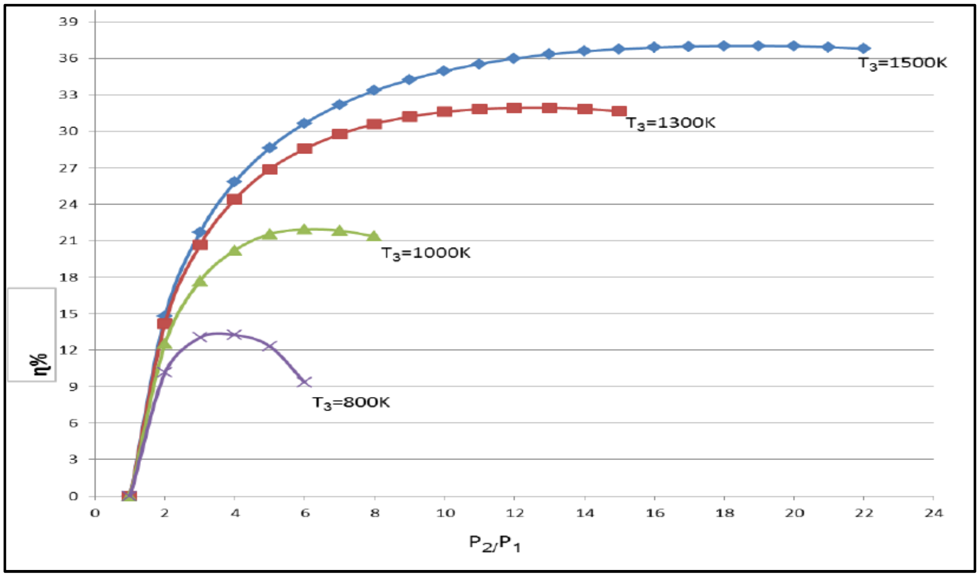

Figure 2: Efficiency Vs. pressure ratio for different temperature. simple Brayton cycle

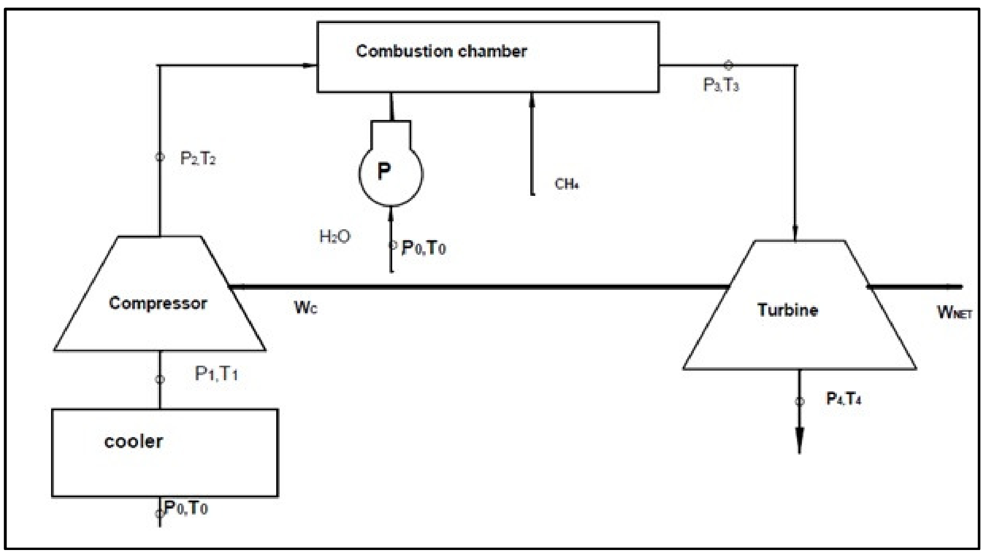

Figure 3: Brayton cycle with reduced inlet temperature of compressor and water injection

3. Brayton Cycle with Reduced Inlet Temperature to Compressor and Water Injection

Here atmospheric air is at temperature T0 and pressure P0. It is passed through a cooler and temperature is reduced to T1 and pressure to P1. The cooled air is compressed in the compressor to the pressure P2 and temperature T2. The compressed air is fed in to combustion chamber, where methane and water is injected. The product from the combustion chamber at pressure P3 and temperature T3 are expanded through the gas turbine to pressure P4 and temperature T4.

We assume that P0= P1= P4

Temperature T2 and T4 are computed using equations (1) to (4)

Temperature T1 has taken two values T1 =273K and 260K

The amount of water injected can be independently varied. Let 'w' be the moles of water injected per mole of air taken to compressor. Let 'w' be the moles of water injected per mole of air taken to the combustion chamber. The enthalpy balance around the combustion chamber can be written as

$$0.21h_{O2,T2} + 0.79h_{N2,T2} + x(-\Delta H)_{298} + w(\lambda_{H2O}) = (0.21 - 2x)h_{O2,T3} + 0.79h_{N2,T3} + xh_{CO2,T3} + (w + 2x)h_{H2O,T3} \quad (12)$$

x (amount of methane)is determined by solving equation (12)

Enthalpy difference takes place in the cooler

$$(\Delta H)cooling = \quad 0.21(h_{O2,T0} - h_{O2,T1}) \qquad + 0.79(h_{N2,T0} - h_{N2,T1}) \qquad (13)$$

Coefficient of performance (COP) of cooler is given by

$$COP = \frac{(\Delta H)cooling}{cooling\ work} \qquad (14)$$

In this calculation, the COP of cooling system is assumed to be 4.5. Hence cooling work is calculated from equation (14)

Work required in pumping water can be computed by

$$W_P = \frac{(P_2 - P_0)}{\rho_W} \times w \times 18 \qquad (15)$$

Work required at the compressor we can be given by equation (7).

Work produced in the turbine is given by

$$W_T = (0.21 - 2x)(h_{O2,T3} - h_{O2,T4}) + 0.79(h_{N2,T3} - h_{N2,T4}) + x(h_{CO2,T3} - h_{CO2,T4}) + (w + 2x)(h_{H2O,T3} - h_{H2O,T4}) \qquad (16)$$

Work produced in the turbine given by equation (16). Work required in the pumping water can be computed by equation (15).

$$W_{net} = W_T - W_C - W_P - Wcooling \qquad (17)$$

The heat input is given by equation (10). Thermal efficiency can be calculated using equation (11). Value for efficiency as a function of pressure ratio, temperature, and amount of water injected are shown in figure

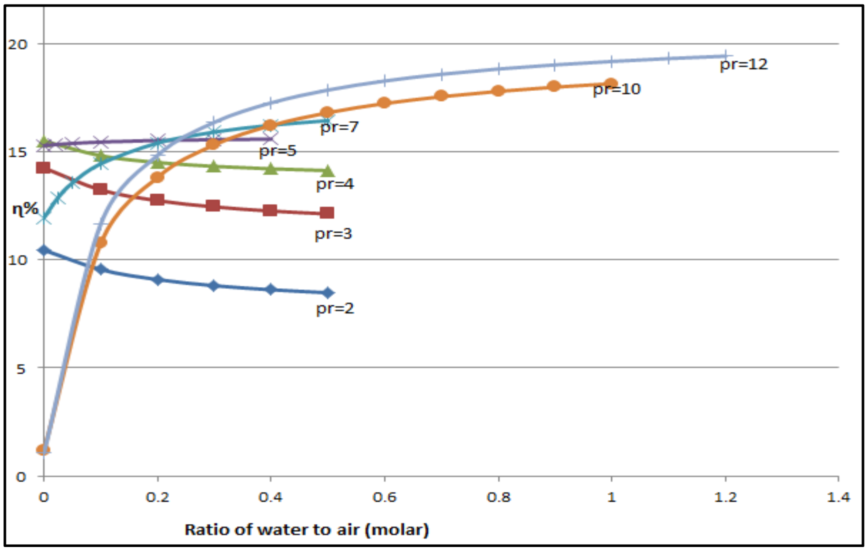

Figure 4: Efficiency as a function of water injection with cooling the inlet air of compressor temperature 273K and pressure ratio at temperature 800K of inlet to turbine

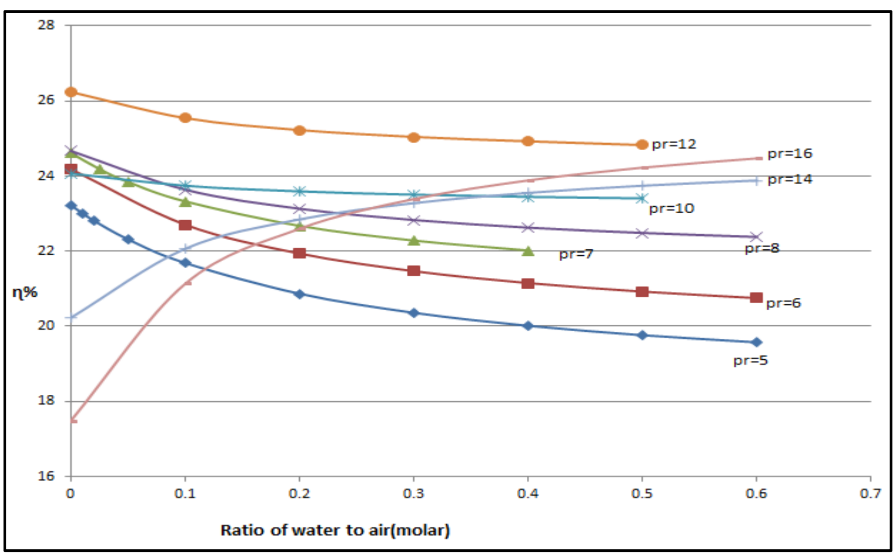

Figure 5: Efficiency as a function of water injection with cooling the inlet air of compressor temperature 273K and pressure ratio at temperature 1000K of inlet to turbine

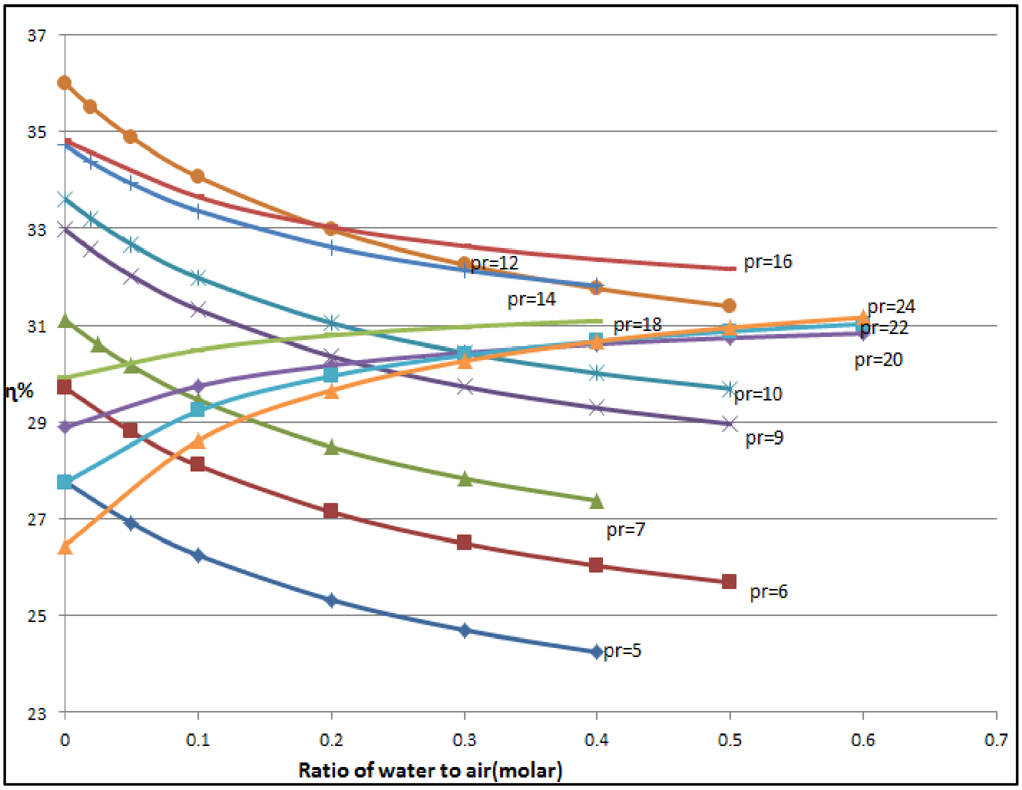

Figure 6: Efficiency as a function of water injection with cooling the inlet air of compressor temperature 273K and pressure ratio at temperature 1300K of inlet to turbine

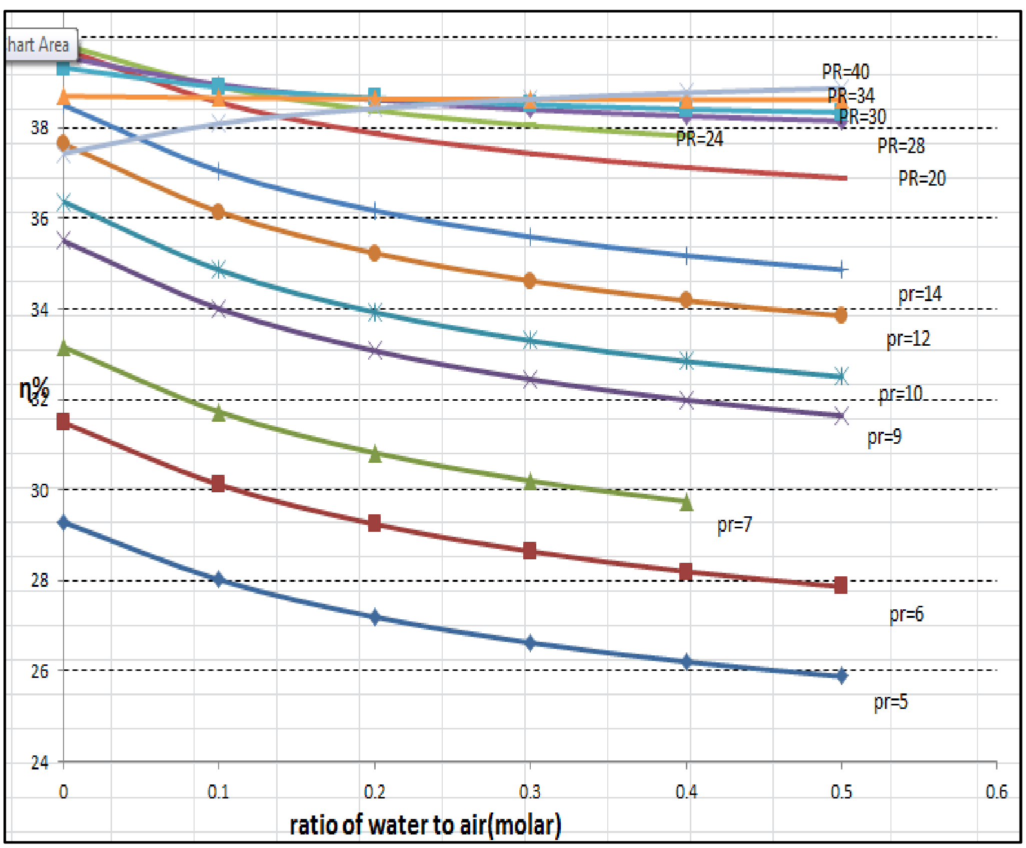

Figure 7: Efficiency as a function of water injection with cooling the inlet air of compressor temperature 260K and pressure ratio at temperature 1500K of inlet to turbine

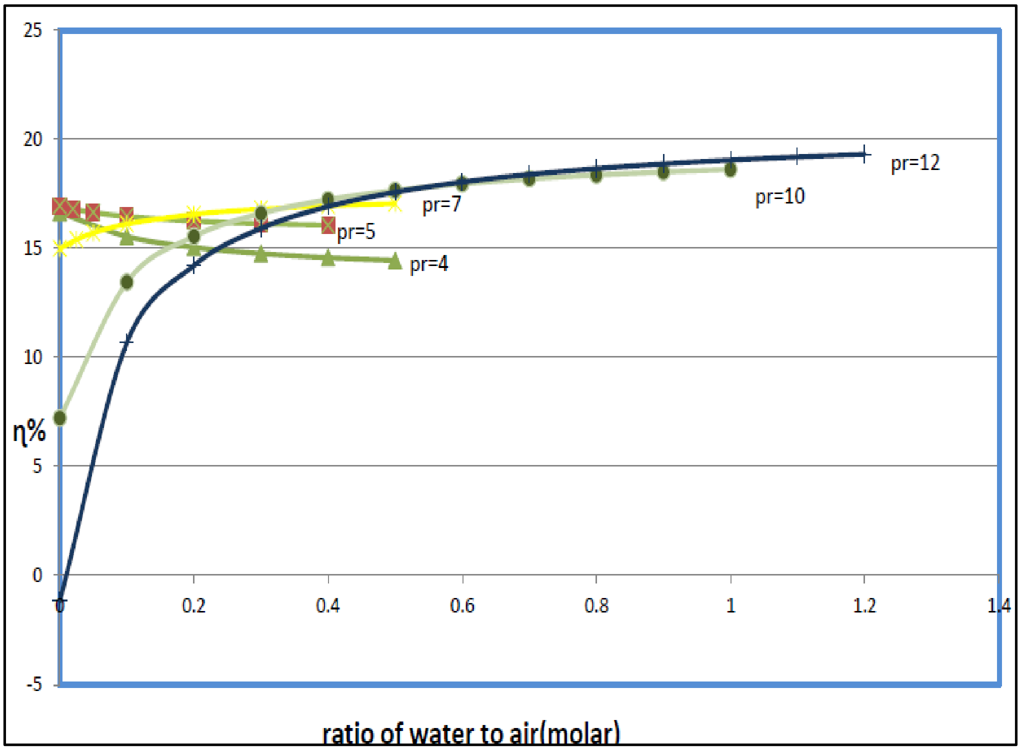

Figure 8: Efficiency as a function of water injection with cooling the inlet air of compressor temperature 260K and pressure ratio at temperature 800K of inlet to turbine

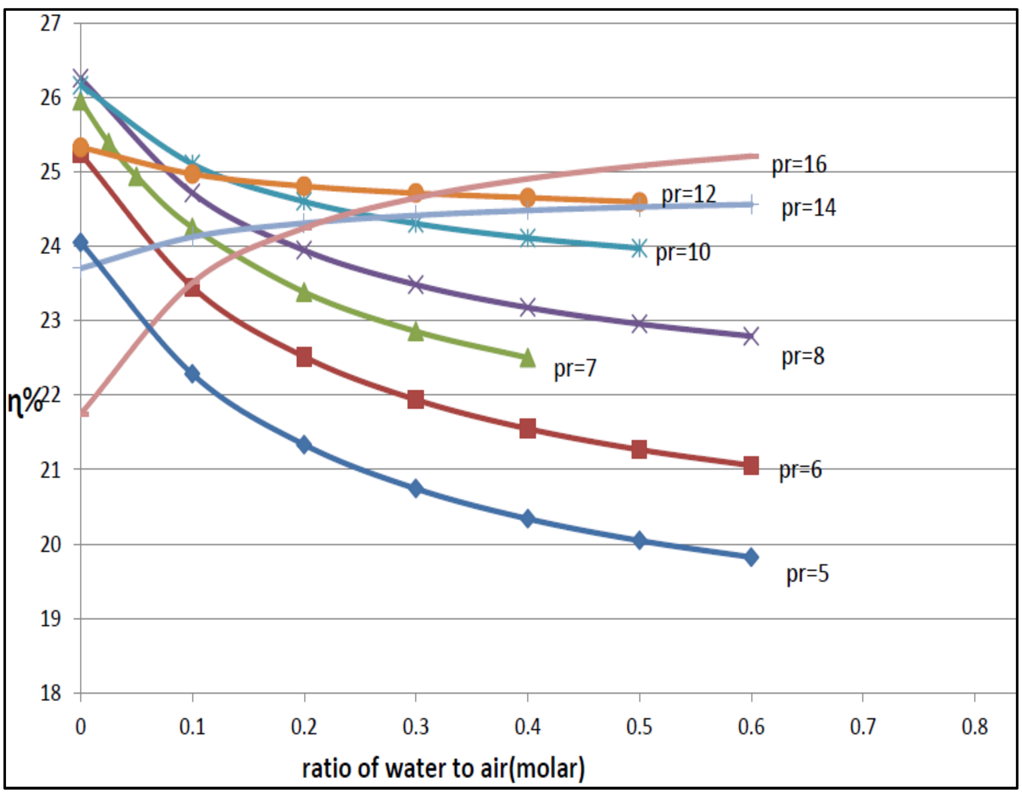

Figure 9: Efficiency as a function of water injection with cooling the inlet air of compressor temperature 260K and pressure ratio at temperature 1000K of inlet to turbine

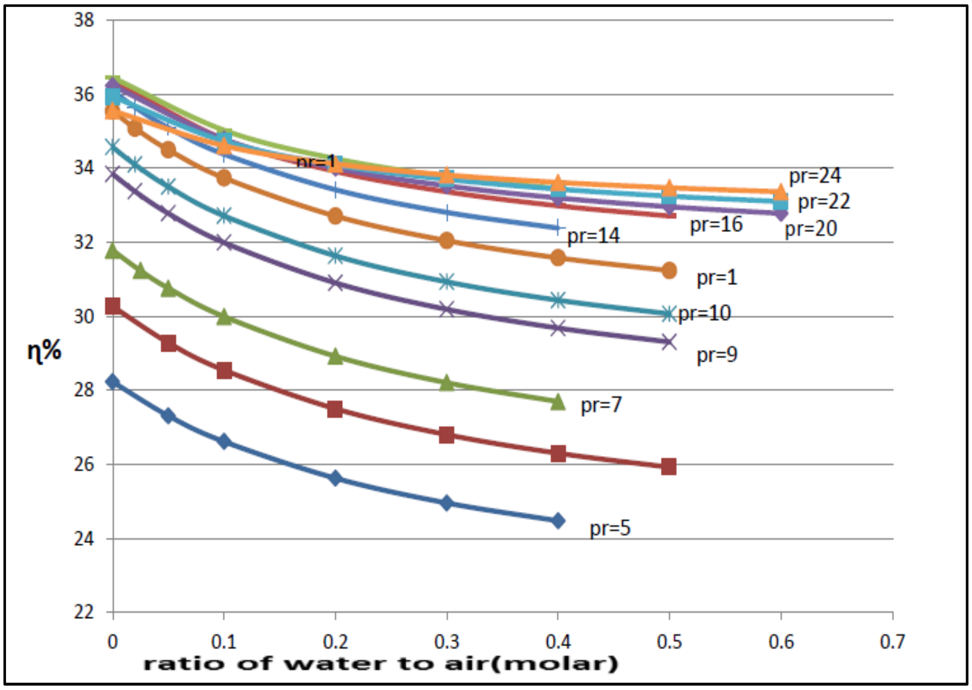

Figure 10: Efficiency as a function of water injection with cooling the inlet air of compressor temperature 260K and pressure ratio at temperature 1300K of inlet to turbine

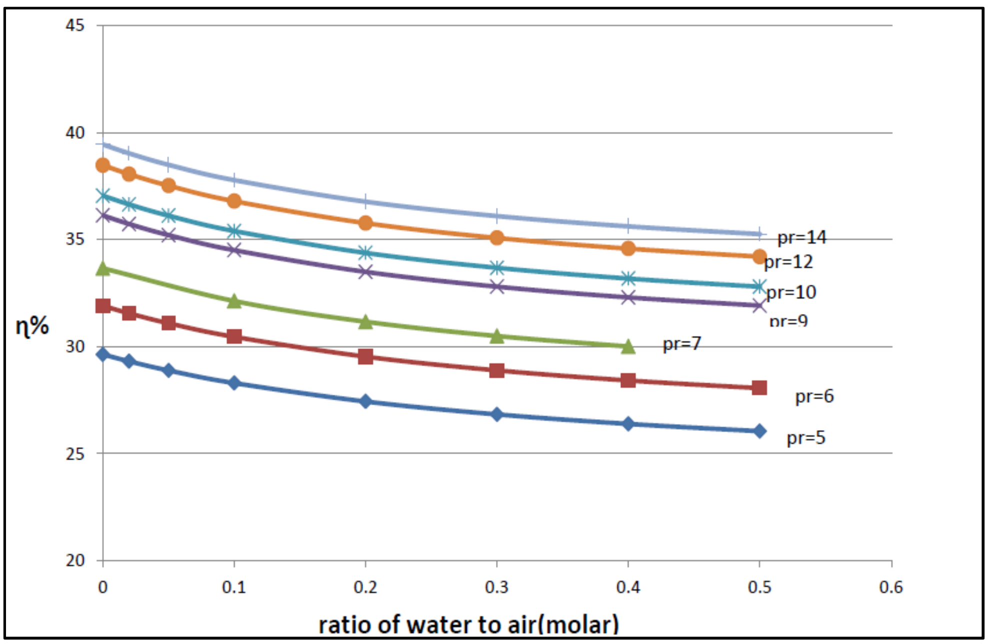

Figure 11: Efficiency as a function of water injection with cooling the inlet air of compressor temperature 260K and pressure ratio at temperature 1500K of inlet to turbine

4. Results and Discussions

It can be seen from the results that for each temperature there is an optimum pressure ratio at which maximum efficiency occurs. This optimum pressure ratio becomes higher as the temperature of operation increases. As observed by several earlier investigators, water injection improves the thermal efficiency. If compressor inlet temperature decreases, the amount of energy needed for compressor work is reduced. It will increase the efficiency. However the present investigation proves that the improvement in efficiency by reduced inlet temperature of compressor with water injection can be achieved only above a certain pressure ratio. At lower pressure ratio, in the case of reduced inlet temperature of compressor and water injection, the amount of water injection increases the efficiency decreases. At medium and higher pressure ratio the efficiency increases with water injection. At each turbine inlet temperature there is an optimum pressure ratio at which thermal efficiency nearly same at different value of water injection However, we have to appreciate that the exhaust gases from the gas turbines can form the thermal energy source for further downstream processes.

Nomenclature	
T	Temperature, K
P	Pressure, kPa
Subscripts	
1,2,3,4,5	Refers to property at conditions 1, 2,3,4 and 5 respectively
O2,N2,H2O,CO2 and CH4	Property of oxygen, nitrogen, water, carbon dioxide and methane respectively
s	Isentropic process
h	Enthalpy kJ/Kmol (Sat. Vapour at 298 K is taken as the datum)
λ	Latent heat of vaporisation kJ/Kmol
$(-\Delta H)_{CH4}$	Heat of combustion reaction of methane kJ/Kmol of methane
w	Kmol water injected per Kmol of air
x	Kmol of methane used per Kmol of air
η	Efficiency
W	Work done kJ/Kmole of air
Q_{in}	Heat input kJ/Kmol of air
Subscript C, T,th,	Compressor, turbine and thermal respectively.
k	Ratio of specific heats C_P/C_V

Table 1

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