EXPERIMENTAL INVESTIGATION OF STEAM INJECTION IN GE-F5 GAS TURBINE NOX REDUCTION APPLYING VODOLEY SYSTEM

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ABSTRACT

VODOLEY system is a steam injection system, which is known as a self-sufficient one in steam production. The amount of water vapor in combustion products will become regenerated in a contact condenser and after passing through a heat recovery boiler is injected in the transition piece after combustion chamber. In this paper the influence of steam injection in Mashad Power Plant GE-F5 gas turbine parameters, applying VODOLEY system, is being observed. Results show that in this turbine, the turbine inlet temperature (TIT) decreases in a range of %5 to %11 depending on ambient temperature, so the operating parameters in a gas turbine cycle equipped with VODOLEY system in 40º C of ambient temperature is the same as simple gas turbine cycle in 10º C of ambient temperature. Also, results show that thermal efficiency increases up to %10, but Back-Work ratio increases in a range of %15 to %30. Injected steam also reduces NO_x formation during the combustion process. In this paper result of experimental investigation of Mashad Power Plant GE-F5 gas turbine steam injection on NOx reduction applying VODOLEY system is being discussed. Results show that applying this system NO_x formation reduces in the range of %30 to %43 but CO production will increase up to %60.

Keywords: Gas Turbine, Combustion, VODOLEY System, NOx Reduction

NOMENCLATURE

a Moles of Carbon
b Moles of Air
n Number of Moles in Wet Base
D Number of Moles in Dry Base

INTRODUCTION

Steam injection in gas turbines has been used for many years to increase both the power output and efficiency of the system. [2, 3, 4, 10, 11]

VODOLEY system is a steam injection system, which is known as a self-sufficient one in steam production. The amount of water vapor in combustion products will become regenerated in a contact condenser and after passing through a heat recovery boiler is injected in the transition piece after combustion chamber. In VODOLEY system the net power output increases because the injected steam in transition piece increases the total mass flow through the turbine without adding more fuel. A major disadvantage of steam-injected gas turbine is the large water consumption. Placing a condenser in VODOLEY system makes it possible to recover the injected steam.

Rice [2], Larson and Williams [3], De Paepe and Dick [4], etc. have studied the thermodynamic performance of steam injected cycles.

In present work experimental investigation of steam injection in GE-F5 gas turbine combustion products, especially on NOx reduction, applying VODOLEY system, is being observed by developing a computer code, which is based on the measured data of combustion products of this cycle.

SYSTEM DESCRIPTION

A Schematic diagram of VODOLEY system is shown in Figure 1. In Gas turbine, unit (1), while operating under VODOLEY cycle, the exhaust flow after passing through the boiler (2), is discharged into contact condenser (3). Contact condenser is able to extract water from exhaust gas

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and recycle it through the system. It is installed on the discharge flange of waste heat recovery boiler. Cooling water cools down the exhaust gas flow below dew point temperature, condenses the water and passes it through a filter and then collects it in the reservoir tank (5). Two pumps (7,8) have been used to pump the water to contact condenser and boiler. Water returns to main tank, (6), is chemically treated and recycled.

WET CONDENSER

In Figure (1) the VODOLEY system has been shown. In this figure No. 3 is the wet condenser; the condenser is located after the steam generator. The exhaust flow energy is decreased in the steam generator. Combustion products then arrive to the wet condenser. In the wet condenser injecting cooling water reduces the exhaust flow temperature. Cooling water increases the mole fraction of water. This means that there is a dew point in the wet condenser. However a special mechanism exists in the wet condenser that reduces the exhaust flow motion to make the flow possible to be condensed. Always there is some water that passes the wet condenser. But it should be considered that water injection makes the possibility to collect more water from the exhaust gas flow.

SYSTEM IMPLEMENTATION:

Steam Injection Application on Frame 5 Gas Turbine

For the purpose of investigating the results of injected steam on gas turbine parameters, a steam injection system is applied on the GE-F5 gas turbine of Mashad Power Plant. The steam is supplied from the Boiler of 60 MW SKODA Steam Turbine Power Plant in 350°C temperature and 20 bar pressure, as shown in Figure 2.

VODOLEY CYCLE CHARACTRISTICS

-Working fluid is Air as an ideal gas with variable specific heats.
-Low heat Value of Fuel equals to 49884 kJ/kg according to Mashad natural gas chemical analysis.
-The Injected Steam is in 350° C temperature and 20-bar pressure
-Combustion chamber pressure loss is about 2%.
-The average turbine exhaust flow temperature is assumed to be 500°C for maximum output of gas turbine [7].
-Combustion efficiency is computed and can be assumed to be equal to %98.5, [8].

COMBUSTION PROCESS

As the GE-F5 gas turbine fuel is CH_4 which is provided from Sarakhs refinery plant near Mashad , the combustion process of GE-F5 gas turbine is as follows:

$$aCH_4 + b(O_2 + 3.76N_2) \rightarrow n_{CO_2}Co_2 + n_{CO}Co + n_{H_2}H_2 + n_{O_2}O_2 + n_{H_2O}H_2O + n_{N_2}N_2 + n_{NO}No + n_{NO_2}No_2 \quad (1)$$

According to the above reaction there are 10 unknowns which 5 unknowns as CO_2, CO, O_2, NO and NO_2, are measured by Testo Analyzer 350 in percent or ppm of exhaust gas flow.

Using conservation equations for the atoms, which take part in the above reaction, equations (2) To (6) are obtained:

$$12a = 12n_{CO_2} + 12n_{CO} \quad (2)$$

$$4a = 2n_{H_2} + 2n_{H_2O} \quad (3)$$

$$32b = 32n_{CO_2} + 16n_{CO} + 32n_{O_2} + 16n_{H_2O} + 16n_{NO} + 32n_{NO_2} \quad (4)$$

$$7.62 \times 28b = 28n_{N_2} + 14n_{NO} + 14n_{NO_2} \quad (5)$$

$$n_{CO_2} + n_{CO} + n_{H_2} + n_{O_2} + n_{H_2O} + n_{N_2} + n_{NO} + n_{NO_2} = 100 \quad (6)$$

Converting Dry Base parameters to Wet Base parameters:

Exhaust flow contains water vapor, but Testo 350 has measured essential data in dry base so equations (2) to (6) should be converted to wet base using equation (7):

$$\frac{D_X}{100 - n_{H_2O}} = \frac{n_X}{100} \quad (7)$$

Where, D_X is the percent of X in combustion products, which is measured by Testo Analyzer.
n_{H_2O} is the number of H_2O moles in 100 moles of combustion products.
n_x is the number of X moles in 100 moles of combustion products in wet base.
So using equation (7), equations (2) to (6) should be written as follows:

$$aCH_4 + b(O_2 + 3.76N_2) \rightarrow \frac{D_{CO_2}}{1-\frac{n_{H_2O}}{100}}Co_2 + \frac{D_{CO}}{1-\frac{n_{H_2O}}{100}}Co + \frac{D_{H_2}}{1-\frac{n_{H_2O}}{100}}H_2 \quad (8)$$

$$+\frac{D_{O_2}}{1-\frac{n_{H_2O}}{100}}O_2 + n_{H_2O} + \frac{D_{N2}}{1-\frac{n_{H_2O}}{100}}N_2 + \frac{D_{No}}{1-\frac{n_{H_2O}}{100}}No + \frac{D_{No_2}}{1-\frac{n_{H_2O}}{100}}$$

$$12a \rightarrow 12\times\frac{D_{CO_2}}{1-\frac{n_{H_2O}}{100}} + 12\times\frac{D_{CO}}{1-\frac{n_{H_2O}}{100}} \quad (9)$$

$$2a \rightarrow \frac{D_{H_2}}{1-\frac{n_{H_2O}}{100}} + n_{H_2O} \quad (10)$$

$$2b = \frac{2D_{CO_2}}{1-\frac{n_{H_2O}}{100}}Co_2 + \frac{D_{CO}}{1-\frac{n_{H_2O}}{100}}Co + \frac{2D_{O_2}}{1-\frac{n_{H_2O}}{100}}O_2$$

$$+n_{H_2O} + \frac{D_{N2}}{1-\frac{n_{H_2O}}{100}}N_2 + \frac{D_{No}}{1-\frac{n_{H_2O}}{100}}No + \frac{D_{No_2}}{1-\frac{n_{H_2O}}{100}} \quad (11)$$

$$7.52b \rightarrow 2\times\frac{D_{N2}}{1-\frac{n_{H_2O}}{100}}N_2 + \frac{D_{No}}{1-\frac{n_{H_2O}}{100}}No + \frac{D_{No_2}}{1-\frac{n_{H_2O}}{100}}No_2 \quad (12)$$

$$D_{CO_2} + D_{CO} + D_{H_2} + D_{O_2} + D_{H_2O} + D_{N_2}$$

$$+ D_{NO} + D_{NO_2} = (100 - n_{H_2O})(1 - \frac{n_{H_2O}}{100}) \quad (13)$$

Again in the above equation, there are 10 unknowns; D_{Co2}, D_{Co}, D_{O2}, D_{No} and D_{No2} are known according to Analyzer measurements in dry base. So there are 5 equations with 5 unknowns.

Combustion Products Calculation after Steam Injection

Since the steam is injected in transition piece between combustion chamber outlet and turbine inlet so it doesn't have any role in combustion process, but it effects on chemical equilibrium in turbine and exhaust gas flow. So combustion products are obtained from equations (8) to (13). Measured data are shown in Table 1.

RESULTS AND DISCUSSION

Variations of fuel consumption versus output power are shown in Figure 3 for both without steam injection and VODOLEY system. Figure 3 shows that fuel consumption in VODOLEY system is less than fuel consumption in simple cycle.

Figure 4 shows the variation of CO_2 versus output power for both without steam injection and VODOLEY system. CO_2 reduces in VODOLEY system. This is because of lower fuel consumption in gas turbines equipped with VODOLEY system. This results CO to get increased, which is shown in Figure 5.

Also reduction of CO_2 in VODOLEY system causes O_2 to get increased according to reaction below:

$$CO + \frac{1}{2}O_2 \rightleftharpoons CO_2 \quad (14)$$

This is shown in figure 6.

According to reduction of fuel consumption in VODOLEY system the amount of water vapor in combustion products reduces in VODOLEY system, which has shown in Figure 7.

Steam injection effects in chemical equilibrium reduces the reaction between Nitrogen and Oxygen and thus Nitrogen is more in VODOLEY system which has shown in Figure 8.

The maximum temperature in VODOLEY cycle is about 5% less than the one in simple cycle, [7]. It means that the injected steam acts as a heat sink, resulting in a lower maximum temperature, thereby reducing the amount of NOx Formation as it is shown in Figure 9.

Since NOx reduces in VODOLEY system, reaction (15) shows another reason for N_2 Increment.

$$\frac{1}{2}N_2 + \frac{1}{2}O_2 \rightleftharpoons NO \quad (15)$$

Also according to Figure 10 it is clear that the more the steam injects the less NOx will produce. But there is an optimum steam injection in VODOLEY system for maximum NOx reduction. For GE-F5 gas turbines equipped with VODOLEY system, when the mass flow rate of the steam becomes more than 13.5 (kg/sec) it doesn't affect on NOx reduction anymore.

CONCLUSION

1-Fuel consumption in VODOLEY system is less than without steam injection.

2-VODOLEY systems produce less NOx emission due to change the chemical equilibrium in turbine and exhaust gas flow if steam injection applies in transition piece.

3-VODOLEY systems reduce CO_2 emission but increase carbon monoxide, due to change in chemical equilibrium in turbine and exhaust gas flow after steam injection.

4-There is an optimum steam injection in VODOLEY system for maximum NOx reduction. For GE-F5 gas turbines equipped with VODOLEY system, when the mass flow rate of the steam becomes more than 13.5 (kg/sec) it doesn't affect on NOx reduction anymore.

Table 1- Measured data of GE-F5 gas turbine with Testo analyzer (top: without steam injection, bottom: VODOLEY system)

Product	Unit	No Load	10 MW	15 MW	20 MW
O2	%	18.6	17.4	16.4	15.6
CO2	%	1.3	1.9	2.4	2.8
CO	ppm	224	89	18	11
NO	ppm	13	22	37	50
NO2	ppm	0	0	0	1
Nox	ppm	13	22	38	50
SO2	ppm	0	0	0	0

Product	Unit	8.2 MW	15 MW	20 MW
O2	%	16.9	15.9	15.3
CO2	%	2.1	2.7	3
CO	ppm	186	55	0
NO	ppm	12	28	48
NO2	ppm	3	2	0
Nox	ppm	14	30	48
SO2	ppm	0	0	0

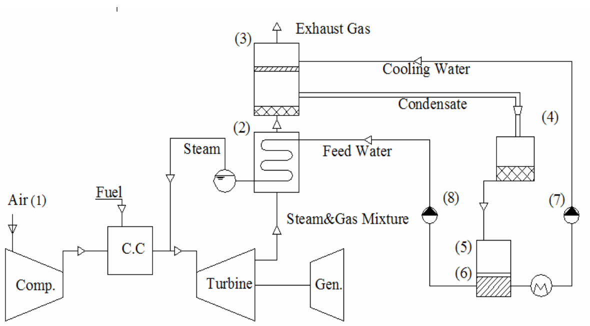

Figure 1: Schematic diagram of VODOLEY system

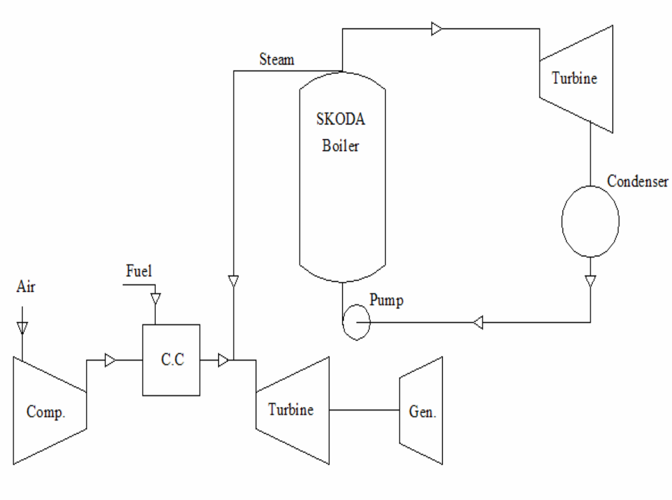

Figure 2: Experimental setup for Mashad Power Plant GE-F5 gas turbine

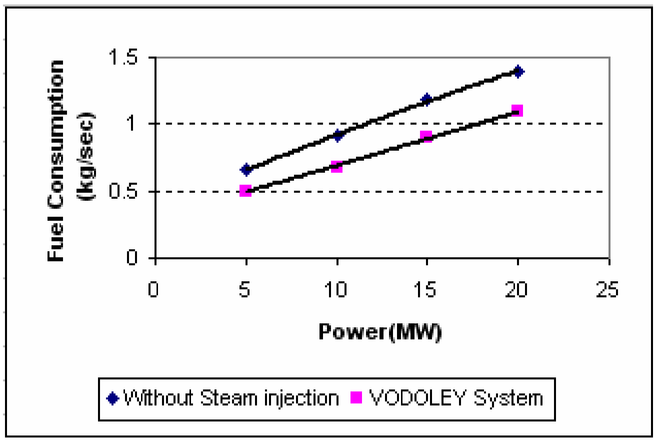

Figure 3: Variations of GE-F5 fuel consumption versus power output

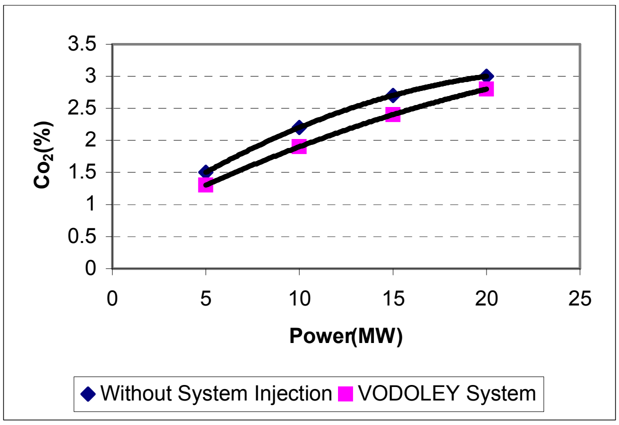

Figure 4: Variations of CO_2 in combustion products versus power output

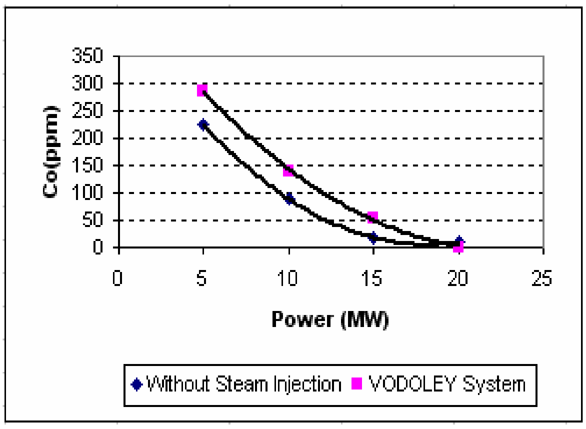

Figure 5: Variations of CO in combustion products versus power output

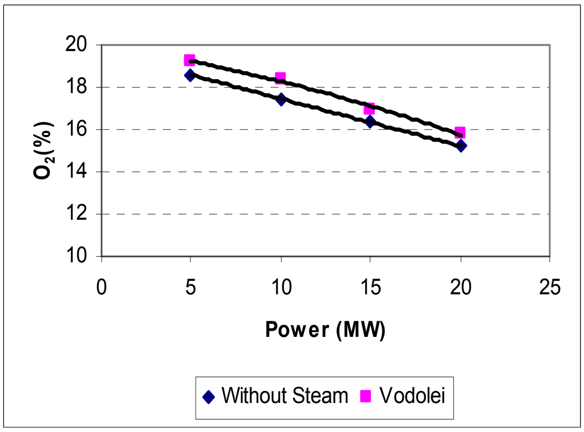

Figure 6: Variations of CO in combustion products versus power output

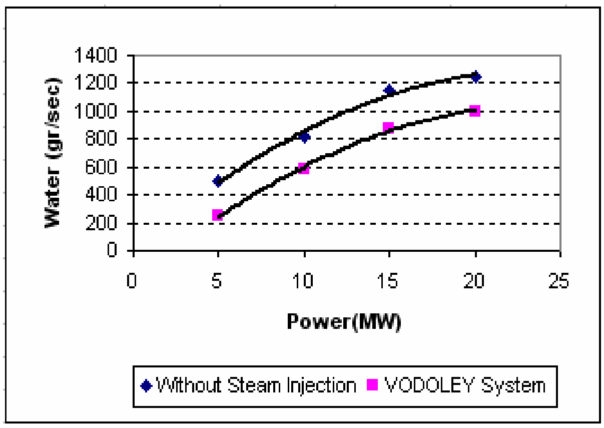

Figure 7: Variations of water vapor in combustion products versus power output

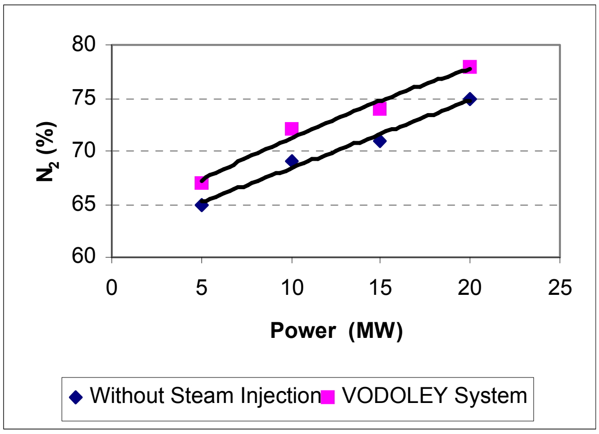

Figure 8: Variations of N_2 in combustion products versus power output

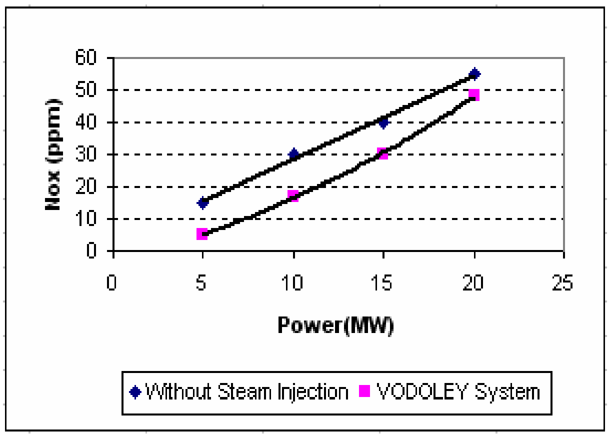

Figure 9: Variations of NOx in combustion products versus power output

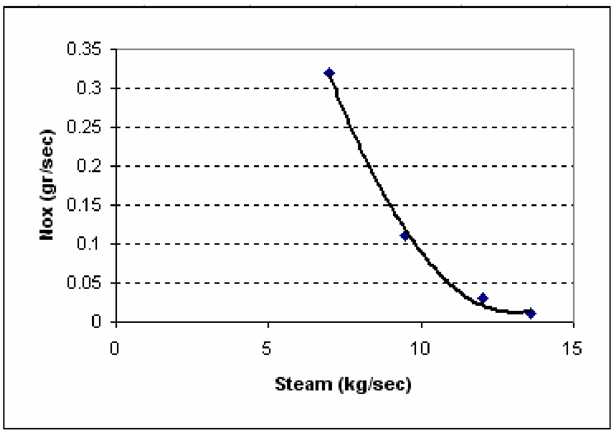

Figure 10: Variations of NOx in combustion products versus mass flow rate of steam injected

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REFERENCES

[1] Rice, I.G, 1995, *Steam-Injected Gas Turbine Analysis: Steam Rates* ASME J. Eng. For Gas Turbine and Power, Vol. 117,pp. 347-353.

[2] Larson, E. D. and Williams, R.H., 1987, *Steam-Injected Gas Turbine*, ASME J. Engineering For Gas Turbines and Power, Vol. 109, p.55-63.

[3] De Paepe, M. and Dick, E., 1997, *Steam Injected Gas Turbines: Cycle Analysis and Feasibility of Water Recuperation,* European Journal of Mechanical and Environmental Engineering, Vol.42, No.2, pp.67-77.

[4] Kim T.S., Song C.H., Ro S.T., Kauh S.K., 1999, *Influence of Ambient Condition on Thermodynamic Performance of The Humid Air Turbine Cycle*, Department of Mechanical Engineer, Seel National University, South 151-742 South Korea.

[5] Cârdu M., Baica M., 2001, *Gas Turbine Installation with Total Water Injection in the Combustion Chamber*, Energy Conversion and Management 2395-2404.

[6] Ghazikhani M., 1993, *Spark ignition Engine Warm-Up and Emissions: Effect of Inlet Air Preheat and Steam Injection,* Dept. of Fuel and Energy, The University of Leeds, Ph.D. Thesis.

[7] Ghazikhani M., Manshoori N. , Tafazoli D. , 2002, *Investigation of Steam Injection in GE-F5 Gas Turbine,* B.S. Thesis, Dept. of Mechanical Engineering, Ferdowsi University of Mashad, Mashad, IRAN.

[8] Ghazikhani M., Manshoori N., Tafazoli D., 2003, *Investigation of Ambient Temperature on GE-F5 Gas Turbine Performance*, Iranian Journal of Energy, Vol. 7, pp. 7-15.