GAS TURBINE UPGRADE WITH HEAT REGENERATOR - NUMERICAL ANALYSIS OF ADVANTAGES AND DISADVANTAGES

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Abstract: *The paper presents analysis of industrial gas turbine and its upgrade with heat regenerator. Based on a gas turbine operational data from a thermal power plant (base process) it was investigated advantages and disadvantages of heat regenerator implementation in the gas turbine process. Regenerator efficiencies were varied between 75% and 95%. Heat regenerator causes decrease of gas turbine fuel consumption up to 0.621 kg/s with a simultaneous increase in gas turbine process efficiency up to 10.52%. The main disadvantages of heat regenerator implementation are decrease in turbine cumulative and useful power along with decrease in the cumulative amount of heat released from the process.*

KEYWORDS: GAS TURBINE, HEAT REGENERATOR, POWER, FUEL CONSUMPTION, EFFICIENCY

1. Introduction

Gas turbines are today widely used for power (and heat) production as stand-alone devices [1] and [2], or in combined [3] and cogeneration plants [4].

Scientists are intensively investigating improvements of such systems in which the gas turbine is essential operation element. The most used improvement of such power plants is integration of solar systems. As an example, Ameri and Mohammadzadeh [5] investigated a novel solar integrated combined cycle power plant, while Dabwan and Mokheimer [6] analyzed optimal integration of linear Fresnel reflector with gas turbine cogeneration power plant.

An interesting investigation of combined cycle power plants presents Kang et al. [7] which provide energy analysis of a particle suspension solar combined cycle power plant. Energy, exergy and economic (3E) analysis of integrated solar direct steam generation combined cycle power plant presented Adibhatla and Kaushik [8].

In this paper is investigated operation of gas turbine when the heat regenerator is implemented in its process. Heat regeneration process brings several advantages and disadvantages in the gas turbine process. The most important advantages are reduction of fuel consumption and significant increase in gas turbine process efficiency. This analysis and its results can be applied on any stand-alone gas turbine in power plants or in marine systems.

2. Base gas turbine process

Gas turbine base process operates according to the schema from Fig. 1. Turbo-compressor compresses air from the atmosphere and delivers it to combustion chambers. In the combustion chambers are produced combustion gases (heat addition by fuel combustion) and at the combustion chamber outlet maximum process temperature occurs. Combustion gases prepared at the combustion chamber outlet enters to the gas turbine and expanded. After expansion, combustion gases are released from the gas turbine process to the atmosphere (or can be used for any heating purposes due to a high enough temperature). Temperature-specific entropy diagram of the base gas turbine process is presented in Fig. 2.

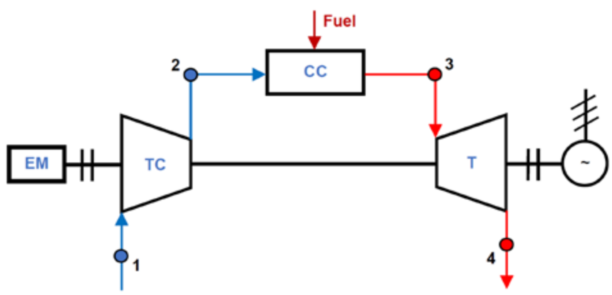

Fig. 1. *Base gas turbine process (EM = electric motor; TC = turbo-compressor; CC = combustion chamber; T = gas turbine)*

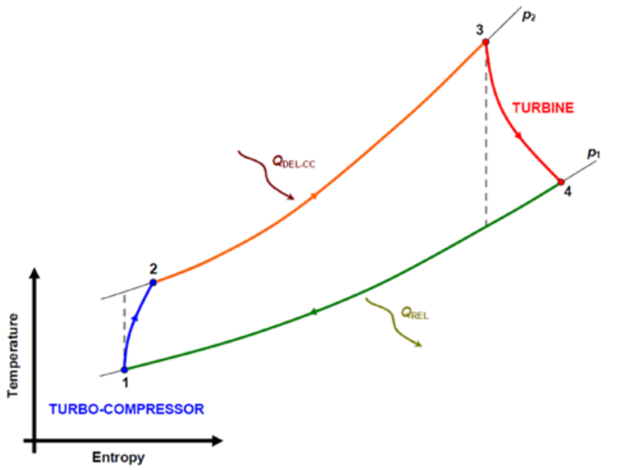

Fig. 2. *T-s diagram of the base gas turbine process*

3. Equations for the gas turbine base process analysis

All the equations for base gas turbine process analysis can be found in [9] and [10]. For each operating point of any gas turbine process (consequentially for the base gas turbine process) specific enthalpy of operating medium is calculated as:

$$h = c_{\mathrm{p}} \cdot T \tag{1}$$

where c_{p} is the specific heat capacity of operating medium at constant pressure and T is current operating medium temperature. Specific heat capacity at constant pressure (c_{p}) is a function of current temperature and is calculated by using polynomials presented in [11] for air, according to Eq. 2 and for combustion gases (cg), according to Eq. 3:

$$c_{\mathrm{p,air}}(T) = 1.0484 - 0.0003837 \cdot T + \frac{9.45378}{10^7} \cdot T^2 - \frac{5.49031}{10^{10}} \cdot T^3 + \frac{7.92981}{10^{14}} \cdot T^4 \tag{2}$$

$$c_{\mathrm{p,cg}}(T) = 0.936087 + \frac{0.010749}{10^2} \cdot T + \frac{0.0172103}{10^5} \cdot T^2 - \frac{0.07247}{10^9} \cdot T^3 \tag{3}$$

In both polynomials (Eq. 2 and Eq. 3) temperature T must be inserted in (K) to obtain c_{p} in (kJ/kg·K).

According to Fig. 1 and Fig. 2, the operating parameters of the gas turbine base process are:

- Turbo-compressor power:

$$P_{\mathrm{TC}} = \dot{m}_{\mathrm{air}} \cdot (h_2 - h_1) = \dot{m}_{\mathrm{air}} \cdot (T_2 \cdot c_{\mathrm{p,2}} - T_1 \cdot c_{\mathrm{p,1}}) \tag{4}$$

- Turbine developed power:

$$P_{\mathrm{T}} = \dot{m}_{\mathrm{cg}} \cdot (h_3 - h_4) = \dot{m}_{\mathrm{cg}} \cdot (T_3 \cdot c_{\mathrm{p},3} - T_4 \cdot c_{\mathrm{p},4}) \quad (5)$$

- Useful power:

$$P_{\mathrm{US}} = P_{\mathrm{T}} - P_{\mathrm{TC}} \quad (6)$$

- The amount of heat delivered in combustion chambers by fuel:

$$Q_{\mathrm{DEL\text{-}CC}} = \dot{m}_{\mathrm{cg}} \cdot (h_3 - h_2) = \dot{m}_{\mathrm{cg}} \cdot (T_3 \cdot c_{\mathrm{p},3} - T_2 \cdot c_{\mathrm{p},2}) \quad (7)$$

- The cumulative amount of heat released from the gas turbine process:

$$Q_{\mathrm{REL}} = \dot{m}_{\mathrm{cg}} \cdot (h_4 - h_1) = \dot{m}_{\mathrm{cg}} \cdot (T_4 \cdot c_{\mathrm{p},4} - T_1 \cdot c_{\mathrm{p},1}) \quad (8)$$

- Useful heat released from the process:

$$Q_{\mathrm{REL,US}} = \dot{m}_{\mathrm{cg}} \cdot (h_4 - h_{433.15}) = \dot{m}_{\mathrm{cg}} \cdot (T_4 \cdot c_{\mathrm{p},4} - 433.15\ \mathrm{K} \cdot c_{\mathrm{p},433.15}) \quad (9)$$

Useful heat released from the process is the heat amount which can be used for any additional heating. Combustion gases with temperature lower than 433.15 K cannot be used for additional heating because it will cause significant low-temperature corrosion.

- Gas turbine process efficiency:

$$\eta_{\mathrm{GT}} = \frac{P_{\mathrm{US}}}{Q_{\mathrm{DEL\text{-}CC}}} = \frac{P_{\mathrm{T}} - P_{\mathrm{TC}}}{Q_{\mathrm{DEL\text{-}CC}}} \quad (10)$$

- Combustion chamber efficiency:

$$\eta_{\mathrm{CC}} = \frac{Q_{\mathrm{DEL\text{-}CC}}}{LHV \cdot \dot{m}_{\mathrm{F}}} = \frac{\dot{m}_{\mathrm{cg}} \cdot (h_3 - h_2)}{LHV \cdot \dot{m}_{\mathrm{F}}} = \frac{\dot{m}_{\mathrm{cg}} \cdot (T_3 \cdot c_{\mathrm{p},3} - T_2 \cdot c_{\mathrm{p},2})}{LHV \cdot \dot{m}_{\mathrm{F}}} \quad (11)$$

where *LHV* is the lower heating value of used fuel in (kJ/kg) and $\dot{m}_{\mathrm{F}}$ is combustion chambers fuel mass flow in (kg/s).

- Specific fuel consumption:

$$SFC = \frac{\dot{m}_{\mathrm{F}}}{P_{\mathrm{US}}} = \frac{\dot{m}_{\mathrm{F}}}{P_{\mathrm{T}} - P_{\mathrm{TC}}} \quad (12)$$

4. Operating parameters of the gas turbine base process

Base gas turbine operating process, without additional heat regenerator implementation, is similar to process from [11]. Pressure drops in combustion chambers and at the turbine outlet are neglected. In accordance to Fig. 1 and Fig. 2, the operating parameters of the base gas turbine process are presented in Table 1.

Table 1. *Operating parameters of the base gas turbine process*

Operating point*	Temperature (K)	Pressure (bar)
1	293.15	1.00
2	608.15	11.68
3	1263.15	11.68
4	773.15	1.00
Air mass flow	119.97 kg/s	
Used fuel	Natural gas	
Fuel lower heating value (*LHV*)	50000 kJ/kg	
Fuel mass flow	2.79 kg/s	
Combustion gases mass flow**	122.76 kg/s	

* According to Fig. 1 and Fig. 2
** Combustion gases mass flow is the sum of air mass flow and fuel mass flow

5. Upgrade of the base turbine base process with a heat regenerator

Heat regenerator implemented in the base gas turbine process can be recuperative or regenerative heat exchanger. In the gas turbine processes, heat regenerators are mounted before combustion chambers, Fig. 3. Combustion gases from the gas turbine outlet are used in the heat regenerator with an aim to heat the air before its entrance into combustion chambers. In such way, air is additionally heated before combustion chambers, therefore, to obtain the same peak temperature of combustion gases in the combustion chambers will be used less fuel. On the other side, one part of heat from combustion gases at the turbine outlet will be utilized for additional heating. Based on a several analysis, implementation of heat regenerator decreases gas turbine fuel consumption and significantly increases gas turbine process efficiency. This investigation will present the range of fuel savings and process efficiency increase, along with analysis of other gas turbine operation parameters when heat regenerator of various efficiencies is implemented in the base gas turbine process.

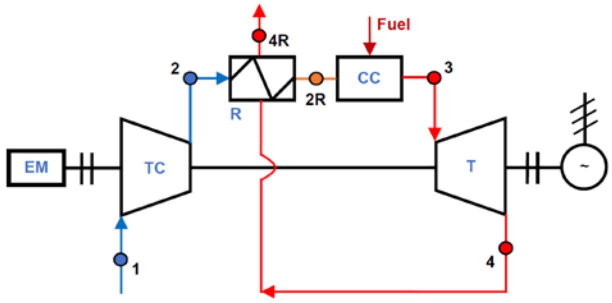

Fig. 3. *Base gas turbine process upgraded with heat regenerator (EM = electric motor; TC = turbo-compressor; R = regenerator; CC = combustion chamber; T = gas turbine)*

Temperature-specific entropy diagram of the gas turbine process with implemented heat regenerator is presented in Fig. 4. One part of heat contained in combustion gases (4 - 4R) is used for air heating after compression (2 - 2R). Air with temperature $T_{2\mathrm{R}}$ enters in combustion chambers.

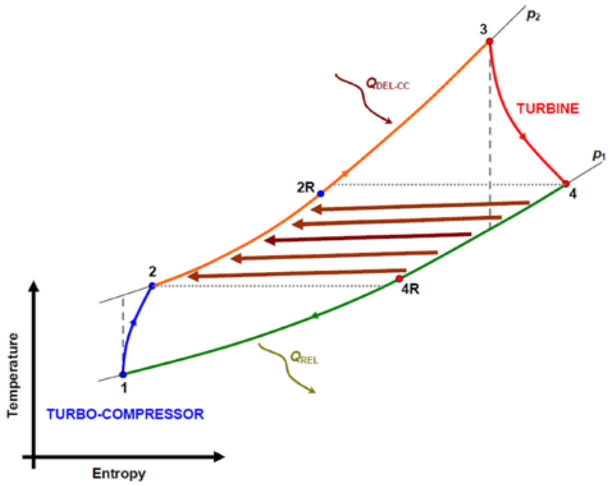

Fig. 4. *T-s diagram of the base gas turbine process with heat regenerator upgrade*

In the literature [12] is found that heat regenerator's efficiency (η_{reg}) frequently used in gas turbine power plants, varies between 75% and 95% what is adopted in this analysis. Heat regenerator efficiency is used to calculate the temperature of air after regenerator ($T_{2\mathrm{R}}$, Fig. 4). Temperature $T_{2\mathrm{R}}$ is calculated according to Fig. 4 by an equation:

$$T_{2\mathrm{R}} = T_2 \cdot \frac{c_{\mathrm{p},2}}{c_{\mathrm{p},2\mathrm{R}}} + \frac{\eta_{\mathrm{reg}}}{c_{\mathrm{p},2\mathrm{R}}} \cdot (T_4 \cdot c_{\mathrm{p},4} - T_2 \cdot c_{\mathrm{p},2}) \quad (13)$$

where $c_{\mathrm{p},2\mathrm{R}}$ is calculated as an average value of specific heat capacities at constant pressure between operating points 2 and 3, Fig. 4.

The air mass flow and combustion chamber efficiency remain the same in the process with heat regenerator as in the base gas turbine process. Heat regenerator decreases fuel mass flow used in the combustion chambers, so the fuel mass flow of the gas turbine process with heat regenerator is now calculated as:

$$\dot{m}_{\mathrm{F,reg}} = \frac{\dot{m}_{\mathrm{air}} \cdot (h_3 - h_{2\mathrm{R}})}{LHV \cdot \eta_{\mathrm{CC}} - (h_3 - h_{2\mathrm{R}})} = \frac{\dot{m}_{\mathrm{air}} \cdot (T_3 \cdot c_{\mathrm{p,3}} - T_{2\mathrm{R}} \cdot c_{\mathrm{p,2R}})}{LHV \cdot \eta_{\mathrm{CC}} - T_3 \cdot c_{\mathrm{p,3}} + T_{2\mathrm{R}} \cdot c_{\mathrm{p,2R}}} \quad (14)$$

In the gas turbine process with heat regenerator, turbo-compressor power, turbine developed power and useful power are calculated with the same equations as in the base process. As the heat regenerator causes a change in fuel mass flow, the combustion gases mass flow has also changed what influenced turbine developed power and useful power.

The amount of heat delivered in combustion chambers by fuel when the heat regenerator is applied is calculated according to Fig. 4 by an equation:

$$Q_{\mathrm{DEL\text{-}CC,reg}} = \dot{m}_{\mathrm{cg}} \cdot (h_3 - h_{2\mathrm{R}}) = \dot{m}_{\mathrm{cg}} \cdot (T_3 \cdot c_{\mathrm{p,3}} - T_{2\mathrm{R}} \cdot c_{\mathrm{p,2R}}) \quad (15)$$

The cumulative amount of heat released from the gas turbine process and useful heat released from the process with heat regenerator is calculated by using the same equations as for base gas turbine process (with a note that combustion gases mass flow is changed by implementing heat regenerator). Gas turbine process efficiency and specific fuel consumption also have the same equations in a process with heat regenerator as in the base gas turbine process.

6. Results of heat regenerator implementation in the gas turbine base process

In all of the figures which presented the results of conducted analysis, the change in gas turbine operating parameters during heat regenerator implementation is presented in relation to heat regenerator efficiency. Regenerator efficiencies were varied from 75% up to 95% what is an expected range of efficiency for the most practically applicable heat regenerators. The base gas turbine process does not include heat regenerator, so in the figures from this section operating parameters of the base process is shown with regenerator efficiency equal to 0%.

Fig. 5 presented reduction in gas turbine fuel consumption when the heat regenerator is implemented in the process. It can be seen that implementation of heat regenerator significantly reduces fuel consumption, even in the case of the lowest observed regenerator efficiency of 75%. Increase in regenerator efficiency causes further decrease of gas turbine fuel consumption.

Fuel savings are presented in comparison with the base gas turbine process. For the lowest observed heat regenerator efficiency of 75% fuel savings amount 0.491 kg/s. Increase in heat regenerator efficiency resulted in an increase in fuel savings. The highest fuel savings are obtained for the highest observed regenerator efficiency equal to 95% and amounts 0.621 kg/s.

Reduction of fuel consumption caused by heat regenerator will resulted with the decrease of combustion gases mass flow. As the gas turbine operates between two constant temperatures and two constant pressures, decrease of combustion gases mass flow will result with a decrease in turbine cumulative developed power, Fig. 6.

When compared with the turbine base process, from Fig. 6 it can be seen that the maximum decrease in turbine cumulative developed power caused by heat regenerator implementation will be in the range of 420 kW for the highest observed regenerator efficiencies. The same trend is visible in the change of gas turbine useful power which will be used for any power consumer operation.

Increase in heat regenerator efficiency resulted in a decrease of turbine cumulative and useful power due to combustion chambers fuel consumption decrease, Fig. 6.

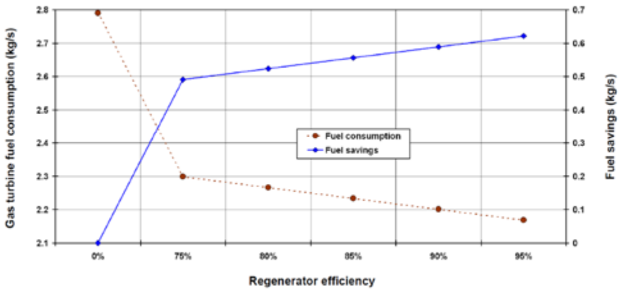

Fig. 5. *Gas turbine fuel consumption and fuel savings after regenerator implementation*

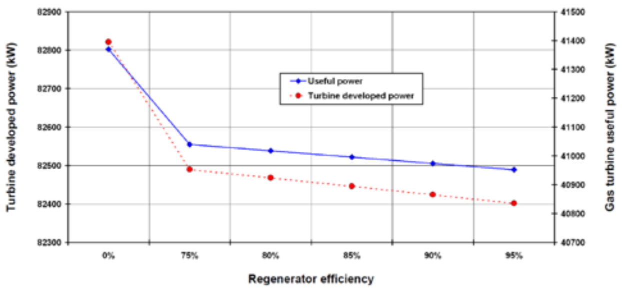

Fig. 6. *Gas turbine cumulative and useful developed power change in relation to regenerator efficiency*

Heat regenerator implementation in the gas turbine process reduces fuel consumption and significantly reduces heat amount delivered by fuel in the combustion chambers in comparison with a base gas turbine process (from 107597.22 kW in the base process to 88658.96 kW in the process with regenerator which efficiency is equal to 75%), Fig. 7. Increase in regenerator efficiency causes further reduction of heat delivered in the combustion chambers by fuel. Regenerator operation also reduces the cumulative amount of heat released by combustion gases from the gas turbine process and simultaneously reduces useful released heat.

In the base gas turbine process, air temperature at the combustion chamber inlet is equal to 608.15 K. Implementation of the heat regenerator increases air temperature at the combustion chamber inlet, which is the primary purpose of heat regeneration process. When heat regenerator has an efficiency of 75%, air temperature at the combustion chamber inlet (air temperature after regenerator) is equal to 702.5 K and increases with an increase in regenerator efficiency, Fig. 8. At the highest regenerator efficiency of 95%, air temperature at the combustion chamber inlet is equal to 738.34 K.

In Fig. 8 is visible that an increase in the air temperature at the combustion chamber inlet is directly proportional to increase in gas turbine process efficiency. Efficiency of the base gas turbine process is equal to 38.45%. Implementation of the heat regenerator increases gas turbine process efficiency to 46.29% when applied the regenerator which efficiency is 75%. The highest gas turbine process efficiency amounts 48.97% and is obtained with a regenerator which efficiency is the highest observed (95%).

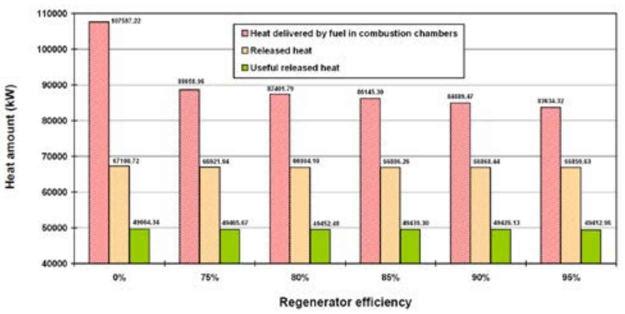

Fig. 7. *Gas turbine delivered and released heat amount change in relation to regenerator efficiency*

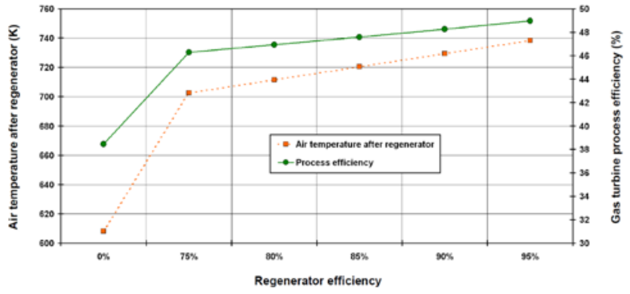

Fig. 8. *Change in gas turbine process efficiency and air temperature after regenerator in relation to regenerator efficiency*

Specific fuel consumption is calculated as a ratio of fuel consumption and useful produced gas turbine power. The base gas turbine process has specific fuel consumption equal to 242.78 g/kWh, Fig. 9. Implementation of heat regenerator in the gas turbine process reduces specific fuel consumption because fuel consumption decreases faster than useful power, regardless of regenerator efficiency. At the lowest observed regenerator efficiency of 75% specific fuel consumption amounts 201.67 g/kWh, while at the highest observed regenerator efficiency of 95% specific fuel consumption has the lowest value of 190.64 g/kWh, Fig. 9.

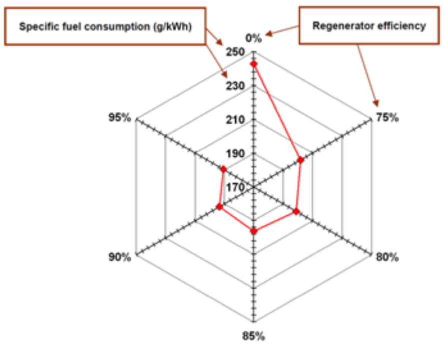

Fig. 9. *Change in gas turbine specific fuel consumption in relation to regenerator efficiency*

7. Conclusions

Implementing a heat regenerator in the base gas turbine process resulted with several advantages and disadvantages. The main advantages are:

- Heat regenerator significantly reduces fuel consumption what is the most important advantage because the fuel costs are dominant elements in complete gas turbine operation costs. Increase in regenerator efficiency causes further reduction of gas turbine fuel consumption.
- Consequentially with fuel consumption reduction, heat regenerator also significantly reduces heat amount delivered by fuel in the combustion chambers.
- Gas turbine with heat regenerator has significantly higher process efficiency when compared to the base gas turbine process. Process efficiency increases with the increase in heat regenerator efficiency.
- Heat regenerator significantly decreases gas turbine specific fuel consumption.

The main disadvantages of heat regenerator implementation in any gas turbine process are:

- Heat regenerator implementation resulted in a decrease in gas turbine developed and useful power due to decrease in combustion gases mass flow. Increase in regenerator efficiency causes further decrease in gas turbine developed and useful power.
- The cumulative amount of heat released from the gas turbine process and useful heat released from the process decreases with heat regenerator implementation. Such disadvantage can be very important if the heat released from the gas turbine is used for additional heating purposes.
- In the gas turbine process heat regenerator is not applicable for a large pressure ratio (p_2/p_1).
- Heat regenerator brings significant additional mass in complete gas turbine process, so it can be applied only in the industrial or marine gas turbines.
- Heat regenerator is a heat exchanger, so it can be expected additional heat transfer and pressure losses (usually with additional maintenance costs).

Finally, for the analyzed base gas turbine process it can be concluded that the implementation of heat regenerator will bring several useful benefits and reduction of operational costs. This conclusion is valid in a situation when the gas turbine operates as a stand-alone power production machine. If such gas turbine operates in combined-cycle power plant, benefits of heat regenerator implementation will be lost due to the additional heat addition (by fuel) in heat recovery steam generator (or more of them).

8. Acknowledgment

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9. References

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