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Analysis of the GT26 single-shaft gas turbine performance and emissions

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Abstract

The progressive developments in terms of gas turbine materials as well as blade cooling systems have led to a continuous growth in the turbine inlet temperature (TIT) and the overall pressure ratio (OPR). This means higher thermal efficiency and power output. Other techniques to achieve better performance can be the adoption of a heat recovery system, an intercooler system or the reheat, as well as a combined cycle application. Furthermore, the higher the TIT and OPR the higher the NOx emissions. Nowadays, with an always stricter emissions legislation, it is particularly important to keep emission levels as low as possible. In the present work, a performance analysis has been conducted with the in-house modular tool ESMS (Equation Solver Modular System). The software simply represents the engine with separate blocks, solving the energy and the continuity equations. Firstly, the design process has been performed on the Ansaldo Energia GT26 machine, equipped with reheat, based on the manufacturer datasheet. Secondly, off-design simulations have been done, changing respectively the fuel mass flow in the 1st burner (EV) and in the 2nd burner (SEV). Therefore, both TIT and power output change. A sensitivity analysis of the thermal efficiency η and the power output with respect to both fuel flows shows how, for part load operations with a half of the design power output, it is better to change the SEV fuel flow only. It can also demonstrate that the high-pressure turbine (HPT) power output is more insensitive to SEV fuel flow than the low-pressure turbine (LPT) one. EV fuel flow variations affect both the HPT and the LPT behaviour. Eventually, a correlation for the NOx emissions has been characterized and results illustrate that NOx emissions are strictly related to the EV fuel flow: in fact, the O_2 level in the SEV burner is sensibly lower than in the first one, thus contributing to lower emissions.

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Keywords: Gas turbine, Reheat, Performance, NOx emissions, ESMS, GT26

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1. Introduction

During last years, energy market required power plants with high flexibility because of the fluctuating energy demand associated with renewable energy. Steam turbine and combined cycle plants are not always capable of meeting these needs due to their high thermal inertia despite the high efficiency. In addition, investment costs of these plants are massive. In this context, the number of installed gas turbines is going up and consequently the need to improve the performances of each component as well as of the whole engine is increasingly becoming essential. The most effective way to increase gas turbine performances is acting on the parameters defining the Brayton-Joule cycle, i.e. Turbine Inlet Temperature (TIT) and Overall Pressure Ratio (OPR). A growth of these two quantities means higher thermal efficiency and power output. The previously mentioned goals are mainly pursued developing innovative gas turbine materials [1] and blade cooling systems [2,3]. However, such improvements have a negative effect on NOx emissions, strongly dependent on the flame temperature, which cannot be neglected because of the strict pollutant emission limits. On a parallel track, variants of the simple gas turbine were designed in order to obtain different performance improvements [4-6]. For example, a regeneration of the gas turbine plant can lead to augmented thermal efficiency. Instead, when an increase in power output is desired, intercooling system and reheat can be employed, the latter extending plant operating range thanks to a higher flexibility of the machine. A reheater is generally a combustor that reheats the exhaust flow exiting by high-pressure turbine before expanding in low-pressure turbines.

An indicative and rapid prediction of gas turbine performances under real part-load conditions is useful during power plant design in order to define the most effective plant solution that minimises operating and investment costs. This objective can be reached employing specific numerical tools, which requirements should be low computational cost, good accuracy, and modularity. These features are promptly met by modular codes [7-9] that simply represents the engine with separate blocks, solving the energy and the continuity equations.

In this work, part-load performances of a reheated heavy-duty gas turbine, i.e. Ansaldo Energia GT26 single shaft machine, has been analyzed with the modular code ESMS (Equation Solver Modular System) [10,11]. The aim is to investigate the off-design performance of a reheated gas turbine under the whole range and combinations of mass fuel regulation. The code was already successfully applied to performance analyses of different gas turbine power plants [12-16], also in reheated configurations [17,18]. Firstly, a brief description of the ESMS code is reported. Then, the design of the gas turbine is performed to obtain a faithful model of the analyzed machine. The last part of this paper is devoted to show and comment the results of the off-design analysis, varying fuel flow rate of combustor and reheater; here, a special focus is on NOx emissions.

Nomenclature

m	Mass/fuel flow [kg/s]	TIT	Turbine Inlet Temperature [K]
n	Rotational speed [rpm]	EGT	Exhaust Gas Temperature [K]
T	Temperature [K]	HPT	High-Pressure Turbine
W	Power [W]	LPT	Low-Pressure Turbine
ß	Pressure ratio [-]	ESMS	Energy System Modular Solver
η	Efficiency [-]	ISO	International Organization for Standardization
EV	Environmental burner	C	Axial compressor
SEV	Sequential EV	OPR	Overall Pressure Ratio
SCR	Selective Catalyst Reduction	α	Vitiated air mass ratio
f	Total fuel-to-air ratio	y	Fuel flow split

Subscripts

exh	exhaust
max	maximum
1	1st combustion chamber
2	2nd combustion chamber
s	Stochiometric value

2. ESMS Modular Code

Industrial plants with many possible configurations need a flexible and performing numerical tool to simulate and guarantee standard requirements. The Energy System Modular Solver (ESMS) is a modular code implemented by Carcasci et al. [10,11]. A large class of the plant's configurations is modelled by a library of elementary parts, with each plant component represented by equations that model fundamental mechanical and thermodynamic laws and produce a system of algebraic nonlinear equations. The proposed numerical procedure combines an outer iterative process that refines the plant's characteristic parameters and an inner one solving the arising nonlinear systems and consists of a trust-region solver for bound-constrained nonlinear equations. In order to solve the system, it is necessary that inputs are the same as the number of unknown parameters. Design and off-design analysis can be simulated imposing the correct conditions. The design simulation requires component design parameters (number of stages, isentropic efficiency, pressure loss) and thermodynamic parameters of the plant (temperature, power, shaft speed and mass flow rate) to define univocally the complete geometry of the plant components. In the off-design study, the geometry of the components is imposed and the thermodynamic parameter values in off-design conditions, such as different TIT or mass flow rate, are determined.

3. Gas turbine analysis

Ansaldo Energia Group has developed a low load operation capability for its combined-cycle power plants, which are based on the GT26 machine, the gas turbine analyzed in this paper. The fleet of GT26 is installed worldwide and has an excellent track record of availability, operational flexibility, and durability. GT26 robust sequential combustion design supports a wide range of fuel variations, including liquefied natural gas and synthetic gases. The GT26 combustion system uses the Environmental burner (EV) as first annular combustor followed by the Sequential Environmental burner (SEV) as the second combustion chamber stage, which is used to increase efficiency and operational flexibility with lower emissions.

The air is compressed by an axial Compressor (C) and after it is heated in the EV burner to a maximum temperature TIT by adding a percentage of the total fuel. The pressure is halved after the combustion gases expand through the single-stage High-Pressure Turbine (HPT). The remaining fuel is added into the SEV, where the combustion gases are heated a second time to a hypothesized temperature equal to TIT. The gases then expand through a four-stage Low-Pressure Turbine (LPT). Cooling air extracted from the axial compressor is sent to the two turbines (HPT and LPT). The gas turbine is a single-shaft type with a rotational speed of 50 Hz with an exhaust mass flow of 715 kg/s at baseload. The SEV combustor is used to increase efficiency and operational flexibility with lower emissions.

The basic data of GT26 gas turbine referred to ISO working conditions are listed in Table 1.

Table 1. GT26 datasheet [19]

Compressor stages	22
LPT stages	4
HPT stages	1
Rotational speed, n [rpm]	3000
Exhaust mass flow, m_{exh} [kg/s]	715
Exhaust temperature, T_{exh} [K]	889.15
Power output, W [MW]	345
Efficiency, η [-]	0.41
Pressure ratio, ß [-]	33
TIT [K]	1553

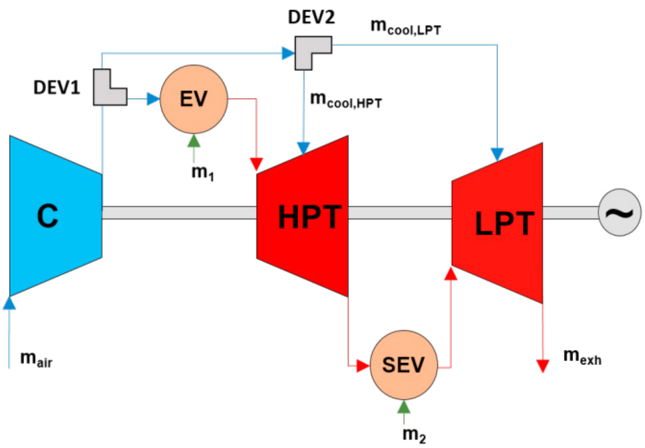


Fig. 1. GT26 gas turbine scheme

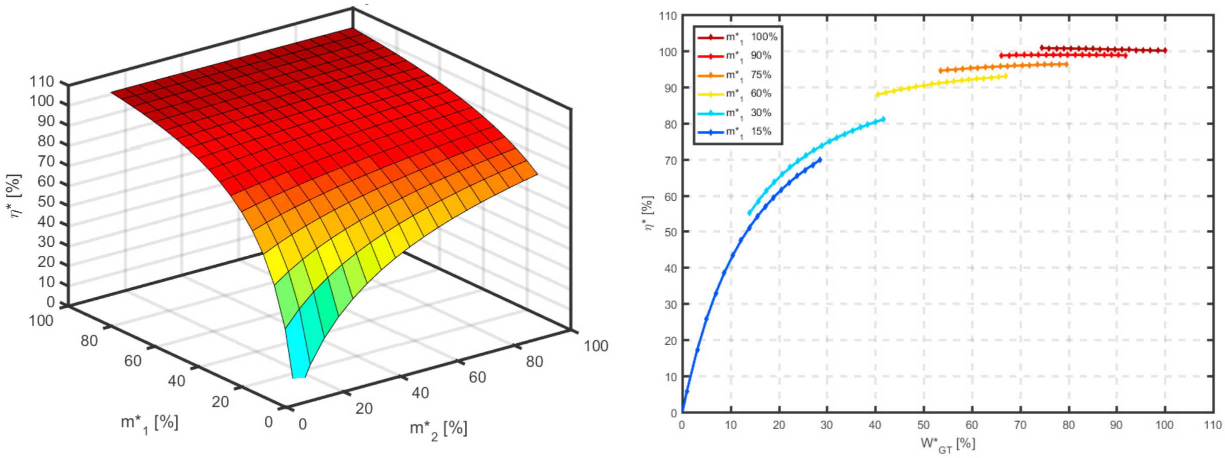
The design analysis of GT26 at ISO conditions using the ESMS gas turbine model in Figure 1 has been done. Air splitting elements (DEV) have been employed to model cooling system. Using the parameters in Table 1 the geometries have been determined. Resulting parameters of the plant determined in the analysis are very important to estimate the accuracy of the model. The exhaust temperature T_{exh} and plant efficiency η obtained from the simulations are in very good agreement with the performance data (Table 2). As expected design results highlight as fuel flow rate m_1 (EV) is greater than m_2 (SEV).

Table 2. Obtained gas turbine results from design analysis

Parameter	Value	Error
T_{exh} [K]	889.12	- 0.005%
m_1 [kg/s]	12.18	-
m_2 [kg/s]	5.36	-
η [-]	0.4181	+1.94%

4. Off-design

The off-design behavior has been investigated for different fuel flow rate m_1 and m_2. In particular, for each m_1 value considered, several m_2 values have been taken into consideration and results are plotted in a non-dimensional way referring to their design reference value. Firstly, the efficiency has been analysed with respect to variations of both m_1 and m_2. Efficiency has a maximum value (100%) when both fuel flows in the first combustion chamber and in the second one are in a design configuration. Whenever either m_1 or m_2 drops, the efficiency is going down. More specifically, the efficiency seems to be a lot more sensible for low values of m_1. Figure 2 better explains power output and efficiency in relationship to variations of m_1 and m_2. Initially, m_2 variations affect only the power output and do not impact on the efficiency. Also m_1 influences more power output than the efficiency for values close to the design ones. From values of m_1 of 50% and below, also m_2 starts to play an important role in the power output and efficiency drop. For power output ratio higher than 70%, efficiency can remain nearly the design one acting on m_2 only. Operating on both m_1 and m_2 may lead to a power output ratio of 50% still keeping the efficiency ratio above 90%.



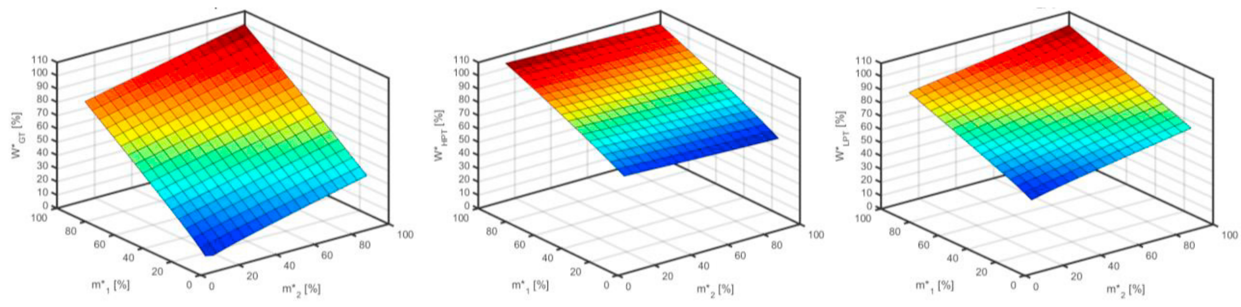
(a) (b)

Fig. 2. (a) Efficiency (b) Power output and efficiency

Figure 3 shows the power trend for the whole engine (a), for the HPT (b), and for the LPT (c).

Figure 3 (a) indicates that power output is more sensible to m_1 rather than m_2. In fact, at the design point, fuel mass flow consists of 70% of m_1 and 30% of m_2. The HPT is largely affected by m_1 variations. m_2 variations seem not to have a negative effect on the HPT power output; on the contrary, the lower m_2, the higher its power output. With a lower value of m_2 expansion ratio in LPT slightly decreases and, relying on matching considerations between turbines and compressor, HPT pressure drop must increase recovering almost the design compression ratio. Since air mass flow does not change due to the constant rotational speed of the machine, both HPT and LPT power output follow the trend of their expansion ratio along m_1 isolines. Moreover, the amount of coolant required for the second combustion chamber has dropped, and, consequently, the mass flow in the HPT features a small increase, so too the power output.

LPT is mostly affected by m_1 and it seems to reply the overall engine trend.



(a) (b) (c)

Fig. 3. (a) Engine power output (b) HPT power output (c) LPT power output

As far as the exhaust gas temperature is concerned, it is strictly connected with the TIT, and therefore with the amount of fuel injected into both combustion chambers, hence power output. Figure 4 illustrates the EGT map with respect to variations of m1 and m2. Almost constant EGT can be maintained acting only on m2 during part-load operation. EGT might be important thinking of a combined cycle application: the higher the EGT the better for the combined cycle. It means that more heat at the back end of the turbine can be converted into useful work.

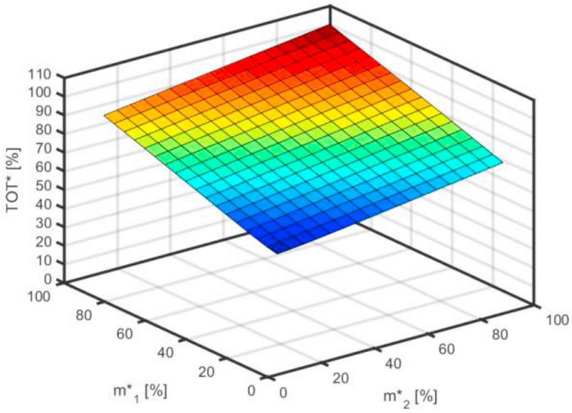
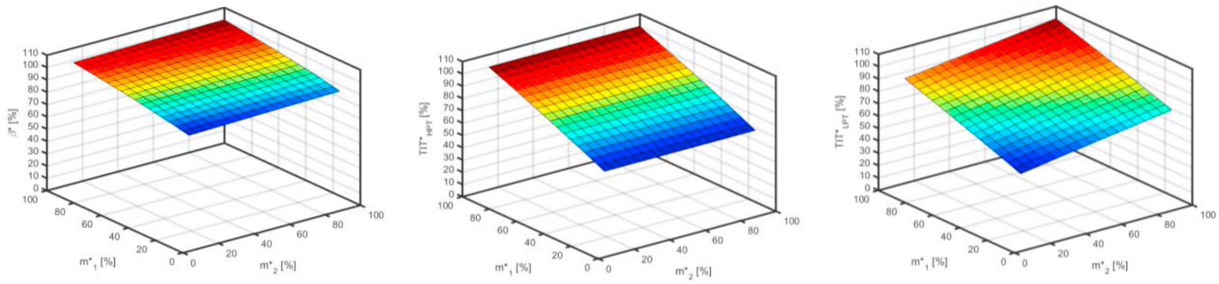


Fig. 4. EGT map

Figure 5 shows three parameters that are the main causes for EGT variations. In particular, Figure 5 (a) illustrates how the overall pressure ratio is mostly affected by m1 variations; with a lower pressure ratio, the area cycle in a T-s graph is going to decrease and therefore, less useful power will be available. Figure 5 (b) shows that m2 variation has no effect on the high-pressure turbine TIT; in Figure 5 (c) both m1 and m2 variations affect the 2nd combustion chamber exit temperature, however, the latter seems to have a lower impact on the final value. An additional consideration is that m1 reduction leads to a lower TITHPT: also with no changes in m2, the TITLPT is reduced from the design point. That is why m1 affects in a deeper way previous parameters.



(a) (b) (c)

Fig. 5. (a) Overall pressure ratio (b) HPT TIT (c) LPT TIT

5. Emissions

Pollutant emission is a key issue in the gas turbine plant operation because it can have a high environmental impact and cause damages to human health. The wide employing of methane fuel breaks down emission of CO, UHC, and SOx but the high temperature reached in the combustion chamber combined with the high excess of air involve a strong production of NOx pollutant, that must be reduced in order to meet the strict limits imposed by environmental regulations. Reduction methods can act directly in the combustor, employing Dry Low NOx or injecting steam or water in the reacting zone, but also in the turbine discharge zone with Selective Catalyst Reduction (SCR) systems. These methods usually increase investment and operating costs of the power plant. A prediction of NOx emission during part-load operations can be useful in the management of the gas turbine plant, especially when wet or SCR systems are exploited.

In order to mainly catch the trend of NOx emission in all the off-design range analyzed in Section 4, the Sullivan's correlation [20] has been employed. This correlation provides an approximate estimation of NOx emission for reheated gas turbine configuration. In square brackets, the NOx measured at the exit of the second combustor can be predicted by the following equation:

$$\frac{NOx}{NOx_0} = y^b + (1-y)^b \exp\left[\frac{\Delta TIT}{c} - 8.1\alpha\right] \quad (1)$$

where $y = \frac{f_1}{f_1+f_2}$ represents the fuel flow split, $\alpha = \frac{f(1+f_s)}{f_s - f}$ is the vitiated air mass ratio, f is the total fuel-to-air ratio while subscripts 1, 2 and s are respectively fuel-to-air ratio of first and second chamber and the stoichiometric value. $b = 1.5$ and $c = 250\ K$ are constants. The parameter $\Delta TIT = TIT_{LPT} - TIT_{HPT}$ is the increase in inlet temperature between EV and SEV burners. The NOx_0 value is the NOx emission of an equivalent single combustor burning the same total fuel-to-air ratio f and can be estimated by Equation (2):

$$NOx_0 = A_{NOx} P^{0.5} f^{1.4} m^{-0.22} \exp\left(\frac{TIT_{HPT}}{250}\right) \quad (2)$$

This is a particular Arrhenius law which includes dependency by maximum pressure P, fuel-to-air ratio f and mass flow rate m, this last accounting for residence time effect. The A_{NOx} constant has been calibrated to fit NOx emissions of GT26 machine at nominal operations reported in datasheet [19].

Results are shown in Figure 6, highlighting the dominant effect of the EV burner in the production of NOx, while SEV fuel flow rate has no impact on the NOx emission, as confirmed by the manufacturer. The NOx value is maximum at full-load condition and progressively reduces at low power conditions, due to the temperature reduction in the combustors. Figure 6 suggests that during part-load operations a reduction in m_1 should be preferred when the focus is in minimizing NOx emission, despite the negative effects on efficiency.

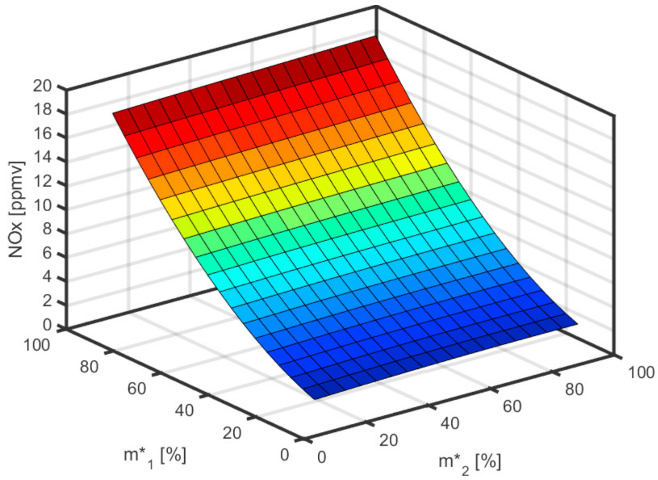


Fig. 6. NOx map

6. Conclusions

The aim of the present work was to investigate the performance and the emissions of the GT26 machine with respect to variations of the fuel flows in both the combustion chambers. The engine has been modelled through the help of a modular tool ESMS: from the datasheet, available in the open literature, the design point has been performed and the geometry useful for the off-design procedure has been carried out.

Off-design analyses have proved a high flexibility in the operation: it can be reached a power output up to 70% of the design one acting on m_2 only and keeping the efficiency almost the optimal one. Otherwise, acting on both m_1 and m_2, a half of the design power output can be reached with an efficiency of 90% the design one.

Considering the HPT power output variations, it is clear how, a reduction in m_2 causes the power to increase: this is due to the lower coolant requirement on the LPT and, thus, to the higher value of mass flow in the HPT.

NOx emissions calculated using the correlation explained in Section 5 are able to reproduce accurately manufacturer data. Almost all NOx produced derive from the EV burner, and, at partial load, lower NOx emissions have been found.

As a result, the modular tool has proved enough accuracy to investigate the performance of a reheated gas turbine and so too the correlation used for the NOx emissions.

Further studies and implementations could be including the reheated gas turbine in a combined cycle power plant and investigate on the overall power output and fuel consumption with respect to variations of m_1 and m_2.

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