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A method to determine the economic cost of fouling of gas turbine compressors

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HIGHLIGHTS

- Compressor fouling cost was defined through Heat Rate and power loss calculation.
- Relationship between compressor and turbine performances was analyzed.
- Ambient correction factors applied to an isolated compressor were obtained.

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ABSTRACT

A method to determine the economic cost of gas turbine compressor fouling was developed. The method is based on the calculation of the influence of the drop of compressor performances (isentropic efficiency, pressure ratio and air mass flow) on Heat Rate and full load power of the gas turbine. A statistical procedure to quantify the drop of compressor performances with fouling and to obtain ambient correction factors for the compressor was also developed. Finally, this method was applied to a real gas turbine in order to check its validity. It was demonstrated that the application of the correction factors obtained worked well. The method was used to check the evolution of the compressor efficiency over time and the effects of off-line washings on compressor performances. It could be concluded that the loss of maximum power is the most important factor to take into account to schedule off-line washings.

1. Introduction

During recent years, the Department of Thermal Engineering of the Universidad Politécnica de Madrid has conducted several studies about Combined Cycles. Some of them are related to the heat recovery steam generators [1,2] or to the thermoeconomic optimization of combined cycle using genetic algorithms [3]. Continuing with this research line, it was decided to carry out a study about fouling of gas turbine compressors, which is currently being studied by a number of authors like Sánchez et al. [4] or Aretakis et al. [5].

Like any other machine, the performance of gas turbines is affected by wear and tear over time. Kurtz and Brun [6] list the mechanisms which cause the degradation of gas turbines. Some of these mechanisms are commonly referred to as "non-recoverable", especially those related to hot gas path components, which might require maintenance such as welding or eventually the replacement of a damaged component. Compressor fouling is said to be "recoverable" by means of light maintenance such as washing. It is caused mainly by particle deposition on the blades and annulus surfaces of the compressor due to the ingestion of dust mixed with the air and not blocked by the inlet filter.

Compressor blade fouling reduces the flow capacity, the isentropic efficiency and the pressure ratio. Zwebek and Pilidis [7] explained that fouling affects the thermal efficiency and output power of the engine. Lakshminarasimha et al. [8] said that fouling is one of the most common causes of performance reduction encountered by gas turbines. According to Vigueras [9], the economic production of a 240 MW gas turbine is, on average, 106 million USD per year and, if the fouling affects 1% the compressor pressure ratio, the cost of fouling is about 6.25 million per year. The study performed by Sánchez et al. [4] concluded that a good scheduling maintenance tasks could save electrical companies 200.000 €/year/gas turbine. So it is essential to adopt a correct strategy to carry out the washing processes, which may be done on-line or off-line. Gülen et al. [10] described the different methods

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employed to clean compressors. In an on-line wash, distilled water is injected into the compressor during normal operation in order to remove deposits. However, complete performance recovery can only be achieved by an off-line wash, where distilled water mixed with a special detergent is sprayed into the gas turbine which is rotated by the starter. Fig. 1, similar to a Figure used by Naga and Achutha [11], shows the qualitative effects of performing off-line or on-line washings on compressor efficiency. Different methods for scheduling compressor washings have been proposed by Sánchez et al. [4], Aretakis et al. [5], Naga and Achutha [11] or Hovland and Antoine [12].

This paper provides a simply and accurate method to calculate the economic cost of fouling which can be used in methods for scheduling compressor washings like the aforementioned. In order to achieve this goal, the paper is divided into 3 different parts.

Section 2 explains the two effects that compressor fouling may cause: over-consumption (Heat Rate increase) and drop of full load power. This section also shows the way used to quantify economically these effects.

Section 3 shows the method used to find the influence of the compressor performances (CPs) (isentropic efficiency, pressure ratio and air mass flow) on Heat Rate and maximum power.

Sections 4 and 5 explain the way used to know the CPs drop due to fouling. CPs are significantly influenced by environment. The papers of De Sa and Zubaidy [13] and Meher-Homji and Bromley [14] explain the influence of environment. It is not a simple task to compare CPs between clean and dirty compressor under different ambient conditions. In order to solve this problem, correction factors are defined to refer gas turbine's features to ISO conditions ($T_a = 15\,^{\circ}$C, $p_a = 1$atm). Original Equipment Manufacturers (OEMs) usually provide correction factors for the whole gas turbine cycle but not for the isolated compressor.

Finally, the whole method to calculate the economic cost of fouling was applied to a real gas turbine in Section 6. This allows checking the aforementioned method and to carrying out a study that quantified the economic cost of the fouling.

2. Calculation of cost due to fouling

When CPs drop as a consequence of fouling, the maximum power of the gas turbine is affected in two different ways. Firstly, the drop of the air mass flow reduces the power of the turbine at full load. Secondly, the drop of compressor isentropic efficiency raises the compressor's power consumption, and therefore, reduces the net power of the gas turbine. Eq. (1) shows the difference between the power at full load that would be generated if the compressor were clean P_{cl} and the actual power capacity with a dirty compressor P_{dt}.

$$\Delta P(t) = P_{cl}(t) - P_{dt}(t) \quad (1)$$

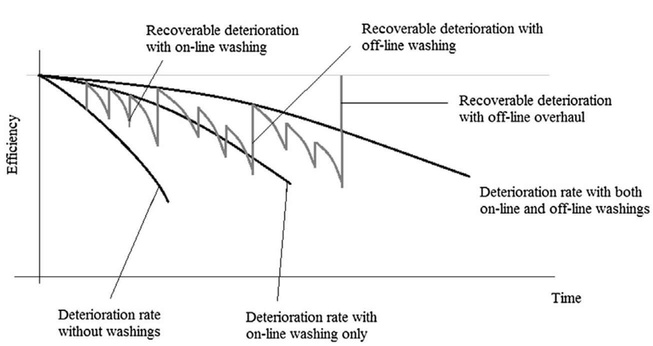

Fig. 1. Influence of washings on compressor efficiency.

The CPs drop also implies an increase of the Heat Rate. Eq. (2) shows the difference between fuel consumption in dirty and clean conditions caused by the increase of Heat Rate.

$$\Delta \dot{m}_f(t) = \frac{P_{dt}(t)}{\eta_{dt} \cdot \mathrm{LHV}} - \frac{P_{cl}(t)}{\eta_{cl} \cdot \mathrm{LHV}} \quad (2)$$

where LHV is the fuel Lower Heating Value and η_{dt} and η_{cl} are the gas turbine efficiency in dirty and clean conditions respectively.

The instantaneous cost per unit time IC [€/s] due to compressor fouling is defined in Eq. (3), where C_p and C_f are the energy sell price [€/W*s] and the cost of fuel [€/kg] respectively.

$$\mathrm{IC}(t) = C_p(t)\Delta P(t) + C_f(t)\Delta \dot{m}_f(t) \quad (3)$$

3. Influence of the CPs drop on Heat Rate and maximum power

A suitable method to determine the influence of the drop of CPs owing to fouling on Heat Rate (HR) and maximum power (P_{max}) is to determine the improvement in HR and P_{max} after washing the compressor, as it can be seen in Fig. 1. However, historic data of compressor washes are not always available. In such a case, it is necessary to develop an alternative method to know the relationships between CPs and HR and P_{max}.

The gas turbine simulation software GasTurb11 [15] was used to establish these relationships. It is assumed that the compressor performances change from clean to dirty conditions and therefore, the map of the compressor characteristics curves (which relates CPs between them) changes as a consequence of fouling. Fig. 2 (where η is compressor isentropic efficiency, $\dot{m}_a$ is air mass flow and R pressure ratio) shows an example of the fouling effects on a generic map of compressor characteristic curves, where the arrow indicates the change in working conditions induced by fouling, with a loss in pressure ratio, air mass flow and isentropic efficiency. This happens because the change of the blades' roughness and air direction due to fouling as was explained in detail by Meher-Homji and Bromley [14] or Bons [16]. The alteration of the blades' roughness modifies the boundary layer and the variation of air direction modifies the velocity triangles of the compressor and both affect directly to compressor performances.

The procedure to determine the relationships between CPs and HR and P_{max} is the following:

- The design parameters required by GasTurb11 are introduced in order to simulate the compressor studied in clean conditions.
- In order to reproduce the consequences of fouling, the values of CPs are reduced maintaining the other parameters constant and HR and P_{max} are checked. This is the same as simulating a different compressor with a different map of characteristic curves (like the example shown in Fig. 2). It can be checked that this procedure is similar to the one applied by Zwebek et al. [7] and also to that suggested by Gülen et al. [10].
- Finally, it necessary to compare the values of HR and the P_{max} obtained in both simulations in order to establish the wished relationships.

In order to check the results using GasTurb11, these can be compared to the results obtained by Boyce and González [17] which are very close (there is an increase of 0.4% in Heat Rate due to 2% drops of CPs). In order to apply this procedure, it is necessary to work with the same ambient conditions because they affect significantly CPs. However, gas turbines usually work in many