RETROFITTABLE SOLUTIONS CAPABILITY FOR A GAS TURBINE COMPRESSOR

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ABSTRACT
The increasing introduction of renewable energy capacity has changed the perspective of operation of conventional power plants introducing the necessity of reaching extreme off-design conditions. There is a strong interest in the development and optimization of technologies, that can be retrofitted to an existing power plant to enhance flexibility, as well as increase performance and lower emissions.

Under the framework of the European project TURBO-REFLEX, a typical F-class gas turbine compressor designed and manufactured by Ansaldo Energia has been studied. Numerical analyses were performed using the TRAF code, which is a state-of-the-art 3D CFD RANS/URANS flow solver. In order to assess the feasibility of lower Minimum Environmental Load operation, by utilizing a reduction in the compressor outlet mass-flow rate, with a safe stability margin, two different solutions have been analysed: blow-off extractions and extra-closure of Variable Inlet Guide Vanes. The numerical steady-state results are compared and discussed to an experimental campaign, which was performed by Ansaldo Energia. The purpose is to identify feasibility of the technologies and implementation opportunity in the existing thermal power plant fleet.

KEYWORDS
Axial Compressor, Off-design, Computational Fluid Dynamics, Minimum Environmental Load, Gas Turbine

NOMENCLATURE
\(w\) relative velocity
\(w_\theta\) circumferential velocity
\(\beta\) pressure ratio
\(\eta\) efficiency
\(\sigma\) solidity
\(\phi\) flow coefficient
\(\psi\) load coefficient
Acronyms:
DF diffusion factor (Lieblein), $DF = 1 - \frac{w_{\text{out}}}{w_{\text{in}}} + \frac{\Delta w_{\theta}}{2\sigma w_{\text{in}}}$
FF inlet flow function
MEL minimum environmental load
TET total exit temperature

INTRODUCTION
Renewable energy solutions represent a great revolution for the energy market. Despite their rapid development expected over the next decades, gas-fired power plants are required to maintain a key role in the energy horizon, in order to ensure grid stability and peak demand, and so to reach extreme off-design conditions. The increasingly restrictive regulations imposed by the European community have led to strong interest in the development and optimization of technologies, that can be retrofitted to an existing combined-cycle power plant to enhance flexibility, as well as increase performance and lower emissions (General Electric [12], Alstom Power [18], Ansaldo Energia [3]).

Under the framework of the European project TURBO-REFLEX, some retrofittable solutions have been developed to enhance the minimum environmental load (MEL) capability in axial flow compressors. In fact, the goal is to reduce the MEL in order to have an increase reserve of power to support the stability of the grid.

Possible actions to reduce the MEL of a gas turbine, without detrimental effects on carbon dioxide emissions, include blow-off extraction, the inlet guide vanes (IGV) extra-closure, and inlet bleed heating. The first allows a high mass flow rate to be extracted from the compressor and discharged into the turbine diffuser. The second allows the compressor mass flow rate to decrease, while the load decreases for the same firing temperature. Finally, the third, also called anti-icing, consists in heating the inlet air (e.g. recirculating air from the outlet, or using a dedicated heat exchanger). These solutions, which make it possible to significantly reduce the mass flow rate and the power output of the gas turbine, must be carefully analysed and evaluated in terms of rear stages stability [6, 5], ice formation on the first stage blade and vane rows [7, 15], unsteadiness, vibrations, and noise emissions, and Heat Recovery Steam Generator (HRSG) temperature limit [13].

This paper wants to evaluate the capability and the robustness of a 3D CFD flow solver to predict the feasibility of lower full-compressor MEL operation, by adopting different solutions: blow-off extractions and IGV extra-closure. A typical F-class gas turbine compressor designed and manufactured by Ansaldo Energia has been studied in the framework of the TURBO-REFLEX European project. Numerical analyses were performed using the TRAF code, a state-of-the-art 3D CFD RANS/URANS flow solver [1].

In the first part, numerical steady-state results referring to MEL and other operating conditions with IGV extra-closure will be presented and validated with experimental data available. In the second part, three challenging operating conditions (MEL, MEL with blow-off extraction, MEL with IGV extra-closure and blow-off extraction) have been proposed in order to identify feasibility of the technologies and implementation opportunity in the existing thermal power plant fleet.
COMPUTATIONAL FRAMEWORK

In the present work, a state-of-the-art, in-house-developed, RANS/URANS flow solver (TRAF code [1]) has been used. The 3D Reynolds-averaged Navier-Stokes equations are written in conservative form in a curvilinear coordinate system and solved for density, absolute momentum components, and total energy. A second-order Jameson, Schmidt, Turkel (JST) central scheme [10] with scalar artificial dissipation was considered for the discretization of the convective terms, while for the turbulence closure the high-Reynolds number formulation of the Wilcox $k–\omega$ model [20] was selected. The code has been recently validated for the prediction of the characteristics of a multistage axial compressor [2].

Domain Discretization

The computational domain takes into account the full compressor module composed by 15 stages. Each blade row was discretized using O-type grids with about $1.4 \times 10^6$ cells per block. The compressor inlet and outlet guide vanes have been discretized with H-type meshes with about $1.0 \times 10^6$ cells per block. The mesh density has been selected on the base of a preliminary grid dependency analysis. To guarantee a proper resolution of boundary layers, the $y^+$ value of the grid nodes closest to the blade surface is between 1 and 2.

The impact of blade tip clearance modelling has been evaluated by comparing two different approaches. The baseline tip model referred to as “open tip” in the following was used in a previous study [14]. It exploits a periodic boundary across a non-meshed region over the top of the blade tip to treat the clearance flow as an orifice flow with no change in mass, momentum, and energy across the blade tip. In the second model, called “meshed tip”, the blade tip gap region is fully discretized using an O-type mesh (Figure 1(a)) that matches the external grid in the blade-to-blade plane. The two models adopt the same number of cells in the spanwise direction. The mass flow rate distribution along the entire compressor, with and without the meshed tip rotor, is reported in Figure 1(b). The operating condition is the reference one, at the working point, with five mass-flow extractions that are located along the meridional flow-path. It can be easily observed how for the “open tip” model, the outlet mass flow is reduced by 1.8%, and so it is less conservative as opposite to the “meshed tip” one. For this reason, the new accurate “meshed tip” has been chosen for modelling the compressor rotor blade tip clearance.

![Figure 1](a)

![Figure 1](b)

Figure 1: View of the rotor tip gap grid block (a) and mass flow rate distribution for the compressor, with and without the meshed tip rotor (b).
Boundary Conditions

The inlet boundary condition enforces the measured radial distributions of total pressure, total temperature, and flow angle. The inlet turbulence intensity and turbulent length scale are 1.0% and 0.01% of span respectively. At the outlet of the computational domain the static pressure value has been imposed at the hub and the radial equilibrium was used to obtain the spanwise distribution.

The compressed fluid is humid air and was modelled as a real gas. In all the presented simulations, mixing planes with non-reflecting boundary conditions (Giles [8, 9]) have been adopted to couple consecutive rows. A local matching interface was used between the last stator and the OGV since they share the same blade count [4, 3].

RESULTS

An industrial, F-class axial compressor designed, manufactured and experimentally tested by Ansaldo Energia has been studied in the present work. The configuration corresponds to 15-stages plus IGV and OGV, with five mass-flow extractions located along the meridional flow-path, some positioned on the hub end-wall and others at the casing. All the vanes, excluding IGV and OGV are shrouded. The effects of seal cavity flow on the mainstream have been considered using a simplified one-dimensional correlation-based cavity model [16].

In order to regulate the elaborated mass-flow, and so the power output of the gas turbine, two solutions have been analysed: blow-off extractions and IGV extra-closure. The IGV and the first stator blade have a variable stagger configuration. The stagger angle of these two rows can be modified independently. The IGV blade is considered always in contact with the internal/external wall.

In the first part of the work, numerical steady-state results referring to MEL and other operating conditions with IGV extra-closure will be discussed and validated with experimental data available. In the second part, three challenging operating conditions of MEL with/without blow-off extraction and IGV extra-closure have been proposed in order to assess the feasibility of the technological solutions and their possible implementation in the existing combined cycle power plant fleet.

For all the 3D CFD TRAF simulations, the computational time was of the order of nine hours, running with 64-core processor, Intel® Xeon® CPU E5 – 2680 v2 @2.80GHz for each operating point, with a computational domain as previously described. The RMS residual experiences a four decades drop in about 5000 multi-grid cycles on two grid levels. One may argue that the two-equation turbulence model could impair convergence when strongly separated flow is encountered. Actually, this was not found to be the case in the discussed calculation, as the number of time steps needed to achieve the aforementioned convergence level was approximately the same for all the calculated operating points.

Comparison with measurements

The first part of the work is dedicated to the operation of the compressor in the off-designing condition designated as MEL with IGV extra-closure. This practice can significantly reduce the mass flow elaborated and the power output of the gas turbine, however a careful analysis of the compressor aerodynamics is required to assure that no stability issues will afflict the compressor.

The experimental campaign was carried out by Ansaldo Energia, testing the machine at three different IGV extra-closure configurations, with the current MEL operating condition. An
assessment of the CFD results is presented by a detailed comparison with the corresponding experimental data. In particular, the computational model was validated for the T23 configuration (representing the MEL one), and for the T24 and T26 configurations, that have an IGV and first stator blades stagger variation with respect to standard MEL, which can been modified independently. The inlet total temperature for the T23 and T24 configuration are almost identical, while the T26 has a lower inlet value ($\Delta T \approx 8^\circ$). In terms of inlet total pressure, the tests with IGV extra-closure have a slightly higher value with respect to the one at T23 ($\Delta p \approx +0.4\%$).

The numerical results in terms of predicted mass-flow at compressor inlet and outlet are compared with the experimental data in Figures 2(a) and 2(b), respectively. The inlet flow function values are scaled as: $FF = (FF_x - FF_{ref}) / FF_{mean, T23}$, where $x$ is equal to T23, T24 and T26. The agreement between numerical results and measured data is good, particularly for the analyses obtained with the meshed tip rotor. Surprisingly, from Fig. 2(b) it can be inferred that for the T26 condition, the value of outlet mass flow predicted by the open tip model is in better agreement with the experimental one. This is to be an artifact due to non perfect conservation by the open tip model. By looking the overall picture (see Fig. 2(a)), the meshed tip model always does a better job. In particular, on T23 the open tip prediction appears quite off. The outlet total temperature predicted by the two computational models is practically the same (Figure 2(c)). Consequently, CFD analyses tend to overestimate the total-to-total adiabatic efficiency and to underestimate the compressor’s work input.

![Figure 2: Compressor inlet (a) and outlet (b) mass flow rate, and outlet total temperature (c).](image)

Figure 3 shows the static pressure distribution at the casing compared with the values measured by eight pressure taps along the meridional channel. For all the configurations considered there is a really good agreement between numerical results and experimental data. Slight discrepancies can be observed for the last measuring station, located upstream of the rotor row of stage nine.

**Minimum environmental load reduction strategies**

Some operating conditions are analysed with the same compressor inlet boundary conditions (total temperature, total pressure and absolute flow angle). The discharge pressure of the compressor was varied in a wide range, in order to find the numerical surge margin of the compressor.
Three operating conditions have been considered: the reference one, at the minimum environmental load (MEL), the one with an open blow-off valve located before the sixth rotor leading edge (MEL Blow Off), and finally the one with an IGV extra-closure, which have a stagger variation with respect to the standard case (MEL IX Blow Off). These operating conditions share the same inlet boundary conditions, and numerical setup. The reduction of MEL condition by these two different strategies (IGV extra-closure and blow-off valve) will be presented in this section.

Figure 4 shows the total pressure ratio and efficiency characteristics. All values are reported with respect to the working line at MEL condition. These curves are obtained by progressively increasing the outlet static pressure, starting from the working line condition.

The combined opening of the blow-off valves and the extra-closure of the IGV (MEL IX Blow Off) reduces the power plant output, and penalizes the compressor efficiency. Both strategies reduce the gas turbine pressure ratio with respect to standard MEL, as reported in Figure 4(a). In particular, the IGV extra-closure reduces the mass flow with respect to standard MEL. The
mass flow reduction led to a lower pressure ratio then, if flame temperature is fixed, it results in a Turbine Exit Temperature (TET) increase. The blow-off opening reduces more the mass flow in the last stages of the compressor, the combustion chamber, and the turbine. Provided the blow-off mass flow is reinjected into the turbine diffuser, it may greatly reduce the TET.

The main operating differences between the three configurations can be appreciated in terms of stage flow coefficient (Figure 5(a)) and load coefficient (Figure 5(b)). For stages 4, 5 and 6 there is a load reduction towards the bleed position, followed by a gradually increase towards the end in which the highest value is reached at the stator outlet.

The flow parameters were found to change with the blow-off opening in a predictable way as shown in Figure 6(a). The blow-off is located at rotor 6, or row 12, and the figure shows that as the flow approaches the bleed, the diffusion factor decreases. Overcoming the bleed, the diffusion factor increases sharply, until the last stage (stator 15), where it reaches the highest value. If in addition to the open blow-off we consider the IGV extra-closure, the diffusion factor increases further in the final stage. Therefore, with these two solutions (MEL Blow Off, and

![Flow Coefficient](image1)

**(a)**

![Load Coefficient](image2)

**(b)**

**Figure 5:** Stage flow coefficient (a) and load coefficient (b).

![Diffusion Coefficient](image3)

**(a)**

![Part-load MEL](image4)

**(b)**

**Figure 6:** Diffusion coefficient comparison between analysed MEL configurations (a) and part-load standard MEL operating condition (b).
MEL IX Blow Off), there is a reduction of the load in the first part of the compressor (rows 6-24), and then an increase of the load in the last three stages, as confirmed by Figure 5(b).

Figure 6(b) shows the diffusion factor at MEL condition, varying the discharge pressure of the compressor in a wide range up to 18% of the working line. In the last stator (vane 15, or row 31) are concentrated the main differences. Up to 10%, the diffusion factor has the highest values for the entire compressor. Then, at 14%, it starts to decrease, and at 18% there is a drastic drop. In fact, based on CFD stage characteristics (Figure 7(a)), stage 15 reaches the numerical stability margin at 14% of the discharge pressure.

Figure 7 reports the compressor map for the stages 11-15. The numerical stability limit is identified using the peak stage pressure ratio. The numerical surge margin is defined on the base of the numerical stability limit.

![Figure 7: Compressor stages map.](image)

Recirculation regions close to the compressor endwall for the stages from 10 to 15 with OGV are reported in Figure 8. They suggest that, if the hub corner separation is assumed to be most relevant source of instability, the stall mechanism does not change for the three operating conditions. Considering stage 15 characteristic (Figure 7), the numerical stability margin for MEL, IX and IX blow-off operating conditions respectively is progressively reduced. Such observation is in agreement with stage 15 diffusion factor at working point (Figure 6(a)) which for IX and IX with blow-off operating conditions is progressively higher than MEL one.

The numerical analysis predicts a wide corner separation at the hub of the stator rows (Vo, 2008 [19], Lei, 2008 [11]). This flow structure is more visible for the fourteenth stator row and increases its dimension on the CV15 and OGV. Increasing the back-pressure, the hub corner stall increases both in terms of size and spanwise penetration, indicating that the last stages are about to give up [17].

**CONCLUSIONS**

In the present work, the capability and robustness of a 3D CFD flow solver to predict the feasibility of lower full-compressor MEL operation have been evaluated. Two different solutions have been analysed: blow-off extraction and IGV extra-closure.

Numerical steady-state results at three different IGV extra-closure configurations with the current MEL operating conditions have been presented and validated with experimental data.
available. Superior accuracy in terms of calculated mass flow rate and total temperature has been achieved by employing a meshed tip gap with respect to an open tip strategy. Even for the most critical condition, the CFD results are perfectly in line with the experimental ones. The significant reduction of mass flow rate and power output gas turbine was well reproduced.

In the second part, three challenging operating conditions have been analysed: standard MEL, with an open blow-off valve, and an IGV extra-closure. The combined strategies reduce the power plant output. In particular, the blow-off opening increases more the diffusion factor and reduces the mass flow in the last stages of the compressor. Furthermore, if it is considered an IGV extra-closure, there is a greater reduction of mass flow rate and a further increase in the diffusion factor of the final stages. The main differences between the considered operating conditions are found to be concentrated in the last stator row. In particular, stage 15 characteristics show that the numerical stability margin for MEL, IX and IX blow-off operating conditions is progressively reduced. The numerical analysis predicts a wide hub corner separation in CV14, CV15 and OGV that increases in size when increasing the back pressure.

The viability of both technologies in the existing thermal power plant feet has been verified. By opening blow-off valves or extra-closing the IGV, the gas turbine is able to operate with less mass flow at constant flame temperature, and therefore to produce less power and burn less fuel than in the standard case.

It is believed that the proposed numerical framework and setup is feasible, and able to provide reliable performance figures in the analysis of industrial compressors operating in strong off-design conditions.
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REFERENCES


