STUDY OF THE AIR BLEED INFLUENCE IN THE INDUSTRIAL GAS TURBINE PERFORMANCE

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Abstract. *High performance of industrial gas turbine depends on its components technology, like compressor, combustion chamber and turbine. The study of engine performance requires the performance data of all its components and accessories. However, the most important influential components are the compressor and the turbine. These components must be well designed. During the engine design the performance maps are required, so that they must be synthesized. Axial compressors are usually equipped with bleed-off valves (BOV) to improve performance and engine acceleration. BOVs change the flow characteristics and therefore the compressor operation, due to decrease of the flow after the bleed insertion. This influences the engine operating line. Major changes are the reposition of the surge line and increase in the mass flow range at each compressor speed line.*
An axial compressor with BOV and VIGV (Variable Inlet Guide Vanes) was designed and its performance map calculated. The influence of the BOV on the engine performance was studied using the computational codes developed by Gas Turbine Group at ITA.

Keywords*: axial compressor, variable geometry, bleed-of-valve, gas turbines, performance.*

1. Introduction

Gas turbines are optimized at design point (DP). Their performance is poor at part-load. Due to the physics of the flow in its internal passages, choking and surge may cause performance deterioration. It is important therefore, that at an early design phase, the engine behavior be predicted in order to take actions to improve performance.

One technique to improve overall performance at part-load is to improve the engine components efficiency at part-load, mainly compressor and turbine. This may be accomplished by better components matching.

Bleed-off valve is used to accommodate high flow at compressor front stages and low swallowing capacity of the rear stages.

When the engine speed is reduced, the flow in the rear stages of an axial compressor is accelerated due to the density decrease. This may cause choking of the blade passages. Surge may occur at the front stages as consequence. To avoid surge one may move upwards the surge line. This may be accomplished by the action of a bleed-off valve. It acts to permit high mass flow at the front stages, while less flow is passed through the rear stages.

Similar results may be achieved with compressor variable geometry. Varying the stators staggers it is possible to better match the flow at every stage, therefore avoiding surge. Variable inlet guide vanes (VIGV) installed in front of the first rotor row have been effectively used as means of improving the compressor part-load operation. Sometimes, only the VIGV is sufficient to guarantee a good performance at low speeds. High performance compressors usually have VIGV and variables stators vanes at the front stages.

Bleed valves are used also to tap compressed air to cool blades, air conditioning system and other uses. Both variable geometry and BOV act in the direction of increasing the compressor surge margin.

VIGV moves upwards the surge line, increasing the stability area while the effect of bleed before the last stator is to lower the operation line at a given mass flow and to move upwards the stability line.

To change the operation line other resources can also be used: variable geometry at the turbine stator blades (industrial gas turbines) and variable nozzle in the engine exit (aero gas turbines). It can be inferred then that a good matching between compressor and turbine is necessary to evaluate the gas turbine behavior.

In this work a gas turbine with a 5-stage axial flow compressor, running at steady state, with variable inlet guide vanes (VIGV) and bleed-off valve (BOV), to improve the engine efficiency at part-load operation (Tomita and Barbosa, 2003) is chosen to demonstrate the influence of VIGV and bleed.

The engine performance was calculated using an engine deck developed at ITA (Bringhenti, 1999; Barbosa and Bringhenti, 1999 and 2000).

2. Axial Compressor

Table 1 summarizes the parameters of the compressor used in this work; it has been specially designed using high technological content, specially developed computer programs.

Table 1. Axial flow compressor design point parameters

number of stages	5
engine rotational speed	25650 rpm
mass flow	8.3 Kg/s
pressure ratio	5
isentropic efficiency	0.85
inlet axial Mach number	0.5
outlet axial Mach number	0.26

2.1. Bleed

Figure 1 shows the compressor map calculated using a stage-stacking compressor design program (Tomita and Barbosa, 2004) developed at ITA using Tab. 1 data. Neither VIGV nor bleed were used.

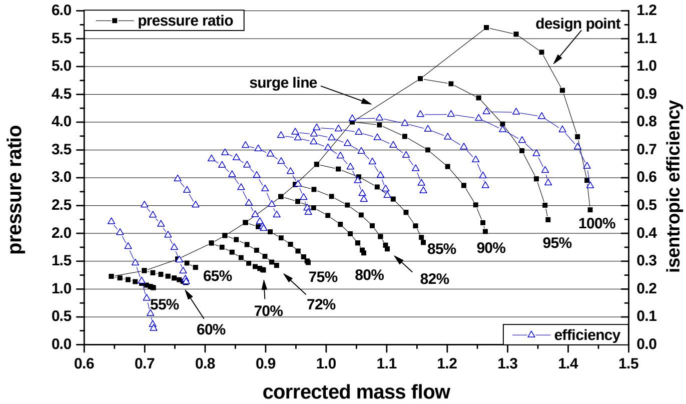

Figure 1. 5-stage axial flow compressor map

Compressor rotational speeds (N) vary from 55% (14107 rpm) up to 100% N (25650 rpm).

At lower speeds the operation range is small, so that a means to widen it is required. Bleed has been considered and tested; the results are shown in Fig. 2. Four different bleed schedules were used.

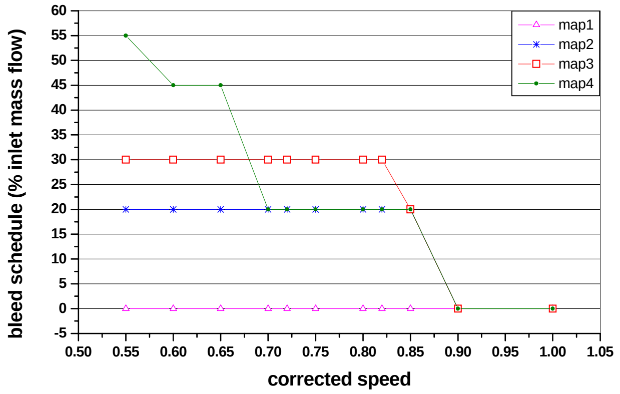

Figure 2. Bleed schedule

Plots of the calculated maps were superimposed as a visualization hint, from which it is possible to see the potential benefits from both pressure ratio and mass flow range increases. Figure 3 shows the bleed influence on the compressor performance. These maps were generated using the data of Tab. 1 and bleed schedule of Fig. 2.

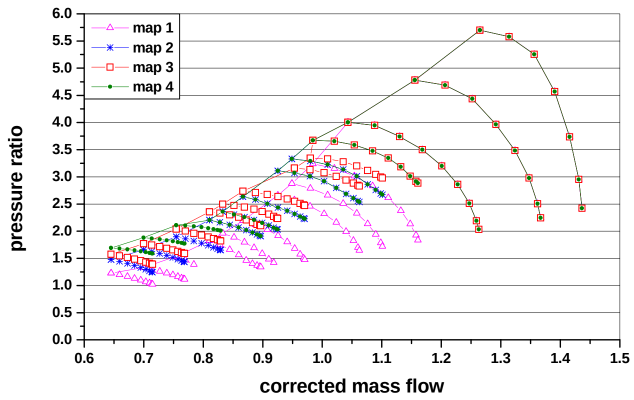

Figure 3. 5-stage compressor pressure ratio maps with different bleeding schedule

Figure 4 shows the corresponding compressor efficiency indicating improvement to the efficiency at low speeds, reflecting better flow matching when bleed is used.

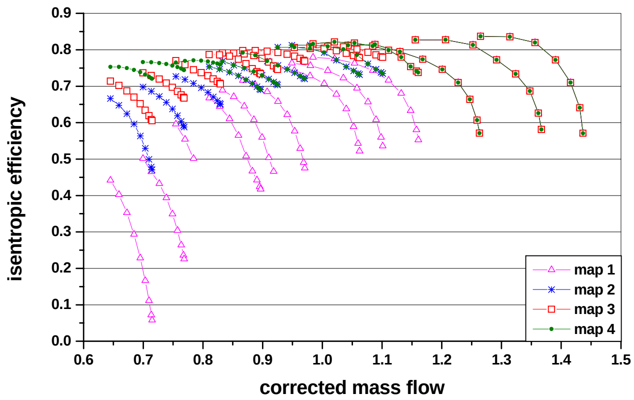

Figure 4. 5-stage compressor efficiency maps with different bleeding schedules

2.2. IGV – variable geometry

VIGV affects the position of the surge line, which is moved upwards, improving surge margin.

Figure 5 and Fig. 6 show 3 compressor maps superimposed to ease visualization of the calculated results.

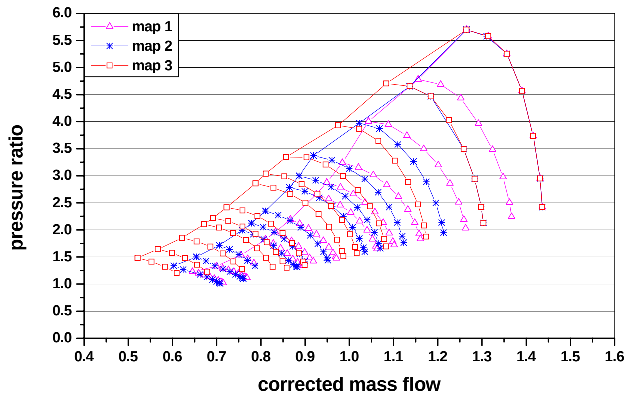

Figure 5. 5-stage compressor pressure ratio maps with VIGV

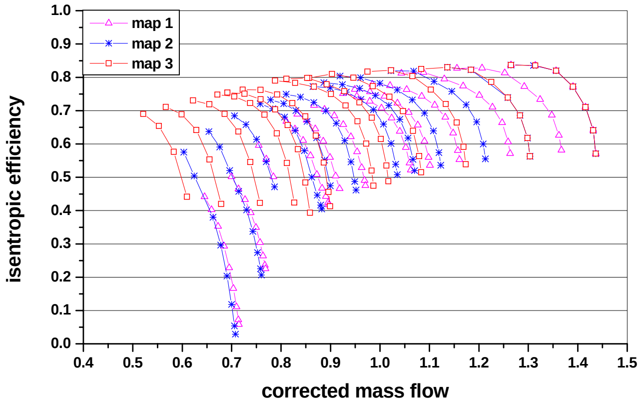

Figure 6. 5-stage compressor efficiency maps with VIGV

The VIGV schedules used for generation maps in Fig. 5 and Fig. 6 are summarized in Fig. 7.

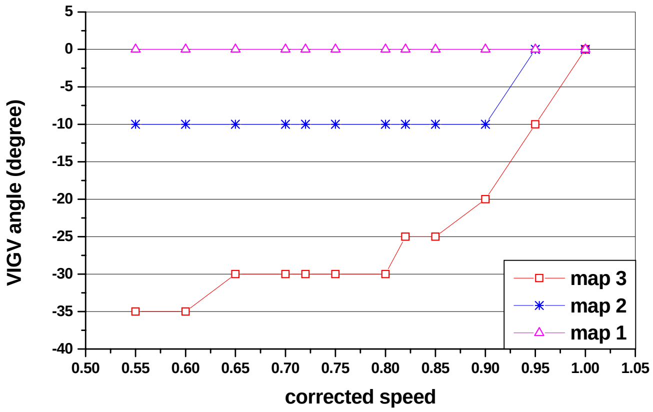

Figure 7. 5-stage compressor VIGV schedule

2.3. IGV variable geometry and Bleed

A study of IGV and bleed was carried out aiming at best part-load compressor performance.

Figure 8 shows the compressor map obtained when VIGV and bleed are used according to the schedule of Fig. 9. When VIGV is installed, the bleed necessity reduces because VIGV has already improved the flow matching.

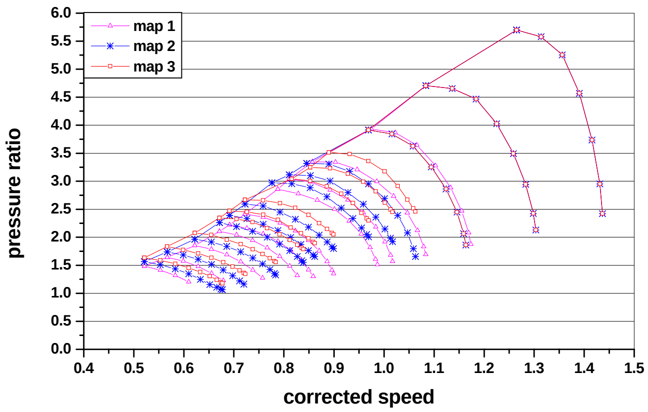

Figure 8. 5-stage compressor maps with VIGV and bleed

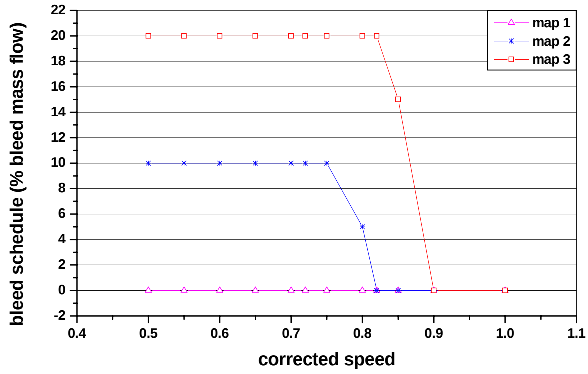

Figure 9. 5-stage compressor maps bleed schedule

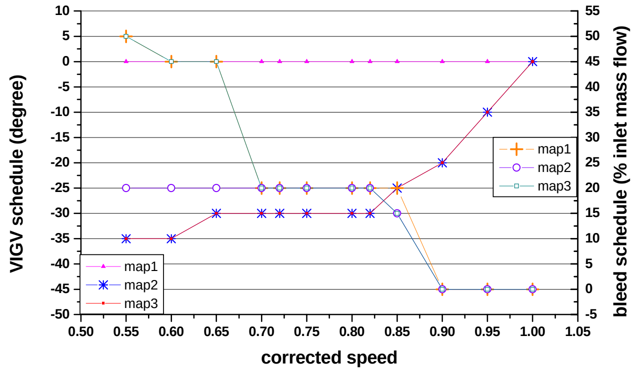

Figure 10. VIGV and bleed schedule

Figure 10 indicates bleed and VIGV settings for the compressors shown in Fig. 11.

Figure 11 shows different combinations of bleed and VIGV. Superimposed are 3 compressor maps showing the influences: a) bleed only; b) VIGV and bleed (map 2 in Fig. 10); c) VIGV and bleed (map 3 in Fig. 10).

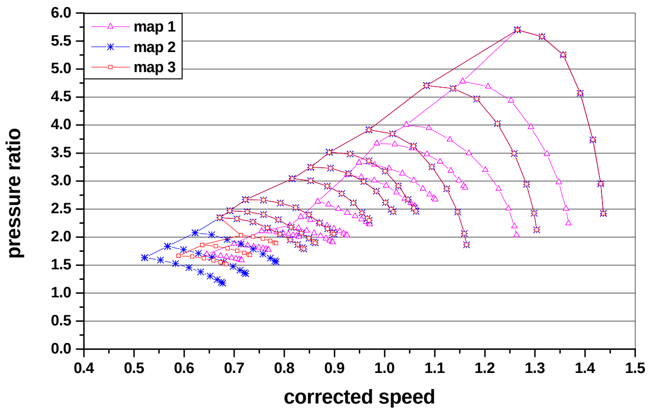

Figure 11. Calculated 5-stage compressor with bleed and VIGV

Figure 12 shows the corresponding efficiencies of the calculated compressors with bleed and VIGV settings of Fig. 10.

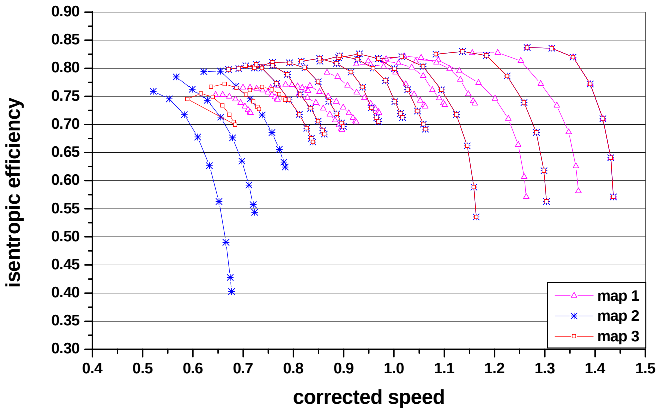

Figure 12. 5-stage compressor efficiency with VIGV and bleed and bleed only

Some comments may be made concerning the use of VIGV and bleeding:

1. VIGV is best than bleed for surge margin improvement;
2. VIGV requires more complex and expensive equipment than BOV.

No attempt for optimization has been made. Therefore, the conclusions might be different if optimization had been made.

3. Design point cycle parameters

In this work a computer program developed at ITA was used to simulate and analyze the steady state performance of a gas turbine in all its possible operating range. The program is based on engine functional blocks build-up, that easily model almost all gas turbines.

The gas turbine under study is an industrial gas turbine adequate for distributed power generation in the power range of 1 MW (Fig. 13). Bringhenti and Barbosa (2004a, 2004b) have been studying that gas turbine at the development of a single gas generator that could be used for both an industrial and an aero engine in the thrust range of 5 kN, to reducing production and development costs.

Bringhenti and Barbosa (2004a) concluded that: a) it is possible to design a gas generator for both applications and b) to reduce costs by choosing adequate design parameters. To comply with this design requirement the maximum cycle temperature was limited at 1173 K to avoid blade cooling, and a 5-stage axial compressor and pressure ratio of 5 was selected.

Bringhenti and Barbosa (2004b) extended their studies about the performance of an industrial gas turbine of 1 MW, the same quoted by Bringhenti and Barbosa (2004a). It was shown that to increase part-load operation it is necessary to incorporate variable geometry to the compressor.

The use of variable geometry (VG) in compressors, turbines and nozzle, incorporated into computer programs for gas turbine performance simulation, has been studied by Bringhenti (2003), Bringhenti and Barbosa (2001; 2002a and b; 2003; 2004b and c) and Bringhenti et al. (2001) . The use of VG has shown good results at gas turbine part-load operations, mainly improving surge margin and specific fuel consumption.

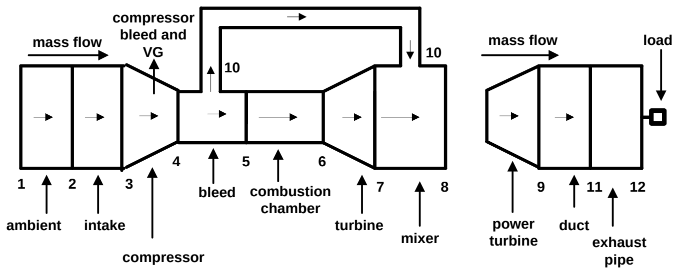

Figure 13. Sketch of a single shaft free power turbine unit

The main engine functional blocks used in this analysis were: ambient, intake, compressor, mass flow splitter, combustion chamber, turbine, mass flow mixer, power turbine, and exhaust pipe. At part-load gas generator speed N1 is lowered from 100% down to the point at which the surge margin vanishes. The power turbine is directly coupled to the generator, so that its speed is fixed at 60 Hz or 3600 rpm. For each chosen off-design point all thermodynamic parameters were calculated, from which appropriate data were selected to produce the graphs shown.

The engine design point main characteristics were chosen having minimal cost in mind, as shown in Tab. 2 (Bringhenti and Barbosa, 2004a, 2004b).

Table 2. Reference engine design point characteristics

parameters	values
mass flow (kg/s)	8.104
compressor pressure ratio	5.0
maximum cycle temperature (K)	1173.0
shaft output (MW)	1.2215
cycle efficiency	0.194
compressor isentropic efficiency	0.85
cooling bleed air at station 10	0.02
combustor chamber pressure loss	0.05
combustion chamber efficiency	0.99
gas generator turbine isentropic efficiency	0.85
gas generator shaft mechanical efficiency	0.99
exhaust gas temperature (K)	859
free power turbine isentropic efficiency	0.85
free power turbine shaft mechanical efficiency	0.99

The engine is required to operate off-design due to load variation. Performance deteriorates because at off-design the components operate at regions of lower efficiencies, caused by bad component matching. The bad-matching results from the passage areas, calculated at design point conditions, not being adequate to accommodate the flow at those operating conditions.

To improve off-design efficiency variable stator geometry is usually used to control the flow and to improve components matching (Bringhenti and Barbosa, 2003). Variable IGV is not the only device used to solve the surge margin problem at part-load operation. Blow-off valve is also used as an alternative method, diverting air bled from some intermediate stage of the compressor. Blow-off clearly involves a waste of turbine work, so that the blow-off valve must be designed to operate only over the essential part of the running range. Engine multi-spool configuration may also be used, but this approach was not considered in this work.

Compressor surge margin was set to 20%, according to the suggestions of Walsh and Fletcher (1998), at design and was monitored during the calculations at all part-load conditions.

4. Off-design performance analysis

Special attention has been given to the gas generator design since it would fit to a turboshaft and a turbojet (Bringhenti and Barbosa, 2004a and 2004b). The running line was calculated form 100% down to the point at which the surge margin vanished, maintaining constant the power turbine speed. Figure 14 and Fig. 15 show the simulation results at several off-design conditions.

For the sake of space only two superimposed compressor maps are shown in Fig. 14: in black, the compressor map without variable inlet guide vane (IGV) and bleed; in magenta, the compressor map with variable IGV and bleed, this being the map corresponding to the best part-load efficiency and surge margin. In this figure are shown the design point, running line, surge line and surge margin.

In Fig. 14, it can be seen that at part-load operation the running line, without IGV and compressor bleed, intercepts the surge line at approximately 88% N1 (0.7202 MW). When variable IGV and compressor bleed are used this value can be decreased down to 75% N1 (0.3218 MW). It is therefore desirable to use IGV and bleed for this engine configuration and application.

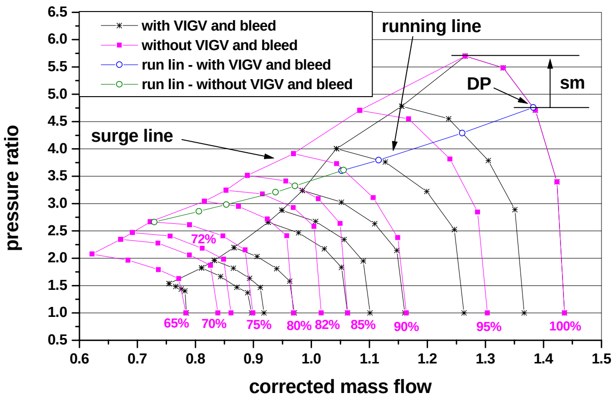

Figure 14. Compressor characteristics – pressure ratio

Figure 15 shows the isentropic efficiency of the two compressors shown in Fig. 14. It can be seen that variable IGV and compressor bleed keep the isentropic efficiency at highest values at part-load, nearly at the same levels as at DP.

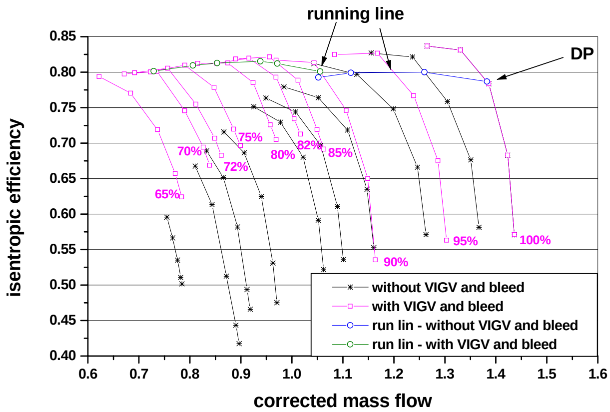

Figure 15. Compressor characteristics – isentropic efficiency

5. Conclusions

A 5-stage axial flow compressor was designed and performance maps were calculated using specially developed computer design code. Engine performance was calculated using a gas turbine performance code to which the compressor maps were incorporated.

Several combinations of VIGV settings and bleed were tried aiming at compressor design with good surge margin at part-load. Some of the combinations of VIGV and bleed were used in this work to show the adequacy of variable geometry and bleed to widen the range of surge-free operation of the gas turbine, at the same time that its efficiency is maintained at the same level as at design point.

6. Acknowledgements

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7. References

Bringhenti, C., and Barbosa, J.R., 2004 a , "Estudo de Um Gerador de Gases para Utilização em um Turboeixo e em um Turbojato", proceedings of CONEM 2004, paper 41042.

Bringhenti, C., and Barbosa, J.R., 2004 b, "Performance Study of a 1 MW Gas Turbine", proceedings of ENCIT 2004, paper CIT04-0089.

Bringhenti, C., and Barbosa, J.R. 2004 c, "Part-Load Versus Downrated Industrial Gas Turbine Performance", proceedings of ASME TURBO EXPO 2004, Power for Land, Sea, and Air, GT2004-54147, June 14-17, Austria Center Vienna, Vienna, Austria.

Bringhenti, C., and Barbosa, J.R. 2003, "Analysis of Gas Turbine Off-Design Safe Operation Using Variable Geometry Compressor", proceedings of the COBEM, COBEM2003-0230, São Paulo– SP, November 10-14, Brazil.

Bringhenti, C., and Barbosa, J.R. 2002 a, "Effects Of Variable-Area turbines Stators Over The Important Parameters Of Gas Turbine Performance", proceedings of the CONEM, CPB0272, João Pessoa – PB, Brazil.

Bringhenti, C., and Barbosa, J.R. 2002 b, "Study Of An Industrial Gas Turbine With Turbine Stators Variable Geometry", proceedings of the ENCIT, CIT02-0885, Caxambu – MG, Brazil.

Bringhenti, C. 2003, "Variable Geometry Gas Turbine Performance Analysis", Ph. D. Thesis, ITA, Brazil.

Bringhenti, C., and Barbosa, J.R., 2001, "An Overview Of Variable Geometry Gas Turbines", Proceedings of the COBEM, Energy and Thermal Systems, Uberlândia – MG, Brazil, Vol. 4, pp. 97-105.

Bringhenti, C., Barbosa, J.R., and Carneiro, H.F. de França Mendes, 2001, "Variable Geometry Turbine Performance Maps For The Variable Geometry Gas Turbines", Proceedings of the COBEM, Energy and Thermal Systems, Uberlândia – MG, Brazil, Vol. 4, pp. 87-96.

Barbosa, J.R., Bringhenti, C., 2000, "Simulação Numérica em Sala de Aula", CONEM, paper EC8840, Ensino de Engenharia Mecânica, pp. 2-9, Natal - RN, Brasil.

Barbosa, J. R., Bringhenti, C., 1999, "Simulação Numérica do Desempenho de Turbinas a Gás", Proceedings of COBEM 1999, Engenharia Aeroespacial S8, Águas de Lindóia - SP, 22 a 26 de novembro, Brazil.

Bringhenti, C. 1999, "Analysis of Steady State Gas Turbine Performance", M. Sc. Thesis, ITA, Brazil (In Portuguese).

Tomita, J. T., and Barbosa, J. R., 2004, "Design and Analysis of an Axial Flow Compressor for a 1 MW Gas Turbine", proceedings of the ENCIT, CIT04-0062, Rio de Janeiro – RJ, November 29 - December 03, Brazil.

Tomita, J. T., and Barbosa, J. R., 2003, "A Model For Numerical Simulation of Variable Stator Axial Flow Compressors", proceedings of the COBEM – Congresso Brasileiro de Engenharia Mecânica, 10-14/11/2003, São Paulo, SP, ID-0239, Brazil.

Walsh, P. P., and Fletcher, P., 1998, "Gas Turbine Performance", Blackwell Science.

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