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EFFECTS OF VARIABLE-AREA TURBINE NOZZLE OVER THE IMPORTANT PARAMETERS OF GAS TURBINE PERFORMANCE

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Abstract. *Gas Turbines are designed to operate over a wide range of conditions. When operating at the design point, all their components efficiencies are optimized. At off-design the components loose performance due to the unfavourable flow characteristics. Variable geometry can be incorporated to the engine for improvement of its flow characteristics, thus the engine efficiency, or its sfc (specific fuel consumption). Common options for varying the geometry are the compressors and the turbines. This work deals with the Variable Geometry Turbine. A model for the performance prediction of variable stator geometry axial flow turbine has been implemented into a computer program for the estimation of engines performance. Therefore, all major important parameters, such as specific thrust or power, maximum cycle temperature, efficiency and fuel consumption for all settings of NGV (Nozzle Guide Vanes) angles can be studied. The minimum specific fuel consumption, for example, can be obtained for selected range of NGV settings. The results may be used for the choice of the gas turbine type and its operating points as a function of load, aiming at the most economical application.*

Keywords: *Gas Turbines, Turbine, Variable Area, Performance.*

1. INTRODUCTION

Sarvanamuttoo (1999), in his Gas Turbine Theory book, describes a handful of gas turbine applications, a few indicated below.

Mechanical power is produced most satisfactorily by means of turbine. This is due to the absence of reciprocating and rubbing members and means that balancing problems are few, lubricating oil consumption is exceptionally low, and that reliability can be high. This advantage was first realized using turbines and hydroelectric power that is still a significant contributor to the world's energy resources.

Steam turbines, besides its wide use as a marine power plant, became the most important prime mover for electricity generation. Production of high-pressure high-temperature steam involves the installation of bulky and expensive steam generating equipment whether it is a conventional boiler or nuclear reactor. The significant feature is that the hot gases produced in the boiler furnace or at reactor core never reach the turbine; they are merely used indirectly to produce steam as intermediate fluid. A much more compact power plant results when the water to the steam step is eliminated and the hot gases themselves are used to drive the turbine. Serious development of the gas turbine began not long before the World War II with shaft power in mind, but attention was soon transferred to the turbojet engine for aircraft propulsion. Gas turbine has the advantage for aeronautical propulsion when compared with another engines like the piston engine, because of its much higher power/weight ratio. Gas turbine began to compete successfully in other fields and it has made a progressively greater impact in an increasing variety of applications.

Due to the necessity to overcome long distances, to patrol the whole marine coast and several military activities, like war, gas turbine has been more used for aeronautical propulsion. If the gas turbine is used for aeronautical propulsion, the turbine is designed to produce just enough power to drive the compressor. The exhaust gas is then expanded to atmospheric pressure in a propelling nozzle to produce a high velocity jet. For aircraft propulsion various engine models are available: Turbofan, Turbojet, Turboprop and Turboshaft, each one, with its own characteristics and applications.

In this work attention is focused on industrial gas turbines for power generation. Distinction between 'aircraft gas turbine' and 'industrial gas turbine' has to be made for three main reasons: Firstly, the life required of an industrial plant without overhaul is much more than that for aeronautical power plant. Secondly, limitation of the size and weight of an aircraft power plant is much more important than in the case of most other applications of the gas turbine. Thirdly, the aircraft power plant can make use of the kinetic energy of the gases leaving the turbine, whereas it is wasted in other types and consequently must be kept as low as possible.

When gas turbines were originally proposed for industrial applications, unit sizes tended to be 10MW or less and, even with heat exchangers, the cycle efficiency was only about 28-29 per cent. The availability of fully developed aircraft engines offered the attractive possibility of higher powers. The early aero-derivative engines, produced by substituting a power turbine for the exhaust nozzle, produced about 15MW with a cycle efficiency of about 25 per cent. Modifications required included strengthening of the bearings, changes to the combustion system to enable it to burn natural gas or diesel fuel, the addition of a power turbine and a de-rating of the engine for longer life. In some cases a reduction gearbox was required to match the power turbine speed to that of the driven load, like a marine propeller. For other types of load, such as alternators or pipeline compressors, the power turbine could be designed to drive the load directly.

The widest applications of the aero-derivatives gas turbine have been in pumping sets for gas and oil transmission pipelines, electricity generation and naval propulsion.

The use of gas turbines for electrical power generation has changed dramatically in recent years. In the 1970s, gas turbines were primarily used for peaking and emergency applications; aero-derivative units with a heavy-duty power turbine were widely used. One of the outstanding advantages of this type was it ability to produce full power from cold in under two minutes, although this capability should be used only for emergencies because thermal shock would greatly reduce the time between overhauls. The aero-derivative units had a maximum rating of about 35MW, their efficiency was about 28 per cent and they burned expensive fuel so they were not considered for base load applications.

To improve the part-load efficiency of gas turbines, therefore, some means must be found to raise the turbine inlet temperature at low powers. In the majority of applications where good part–load economy is required, e.g. vehicular and marine, a free turbine would be used.

2. GAS TURBINE MODEL

This work aims to study effects of variable-area turbine stators over the important parameters of gas turbine performance. An existing industrial gas turbine (the Florence (Italy) based Nuovo Pignone PGT10B), capable of 11,699 MW ISA power output, was chosen as a basis to provide the relevant cycle parameters. It was chosen due to its power output (10 MW class) and a free power turbine layout. The complete specifications and additional details the reader my consult the GTW Performance Specs and GTW magazines quoted in the references. This engine is not equipped with variable NGV so that its turbine was replaced. Although this turbine was not designed specifically for the application, its geometry was considered adequate and its maps scaled.

A computer program that simulates numerically the steady state performance of complex gas turbines with NGV variable area was used (Barbosa and Bringhenti, 1999). Several runs provided the data for a number of NGV stagger settings, in the range of -15^{o} to $+ 15^{o}$, that is, closing and opening the NGV blade passages. For each run all thermodynamic parameters were calculated, from which a selection of appropriate data was taken to produce the graphs shown.

For this evaluation, only cycle efficiency, maximum cycle temperature and surge margin were considered, although any other parameters could be used as well. These parameters were chosen because they identify engines that would be utilised, that is, if the maximum temperature is exceeded, than the engine life would be decreased; if surge margin drops below certain limit, the engine would not function properly, unless a remedy is taken; the efficiency would jeopardize the powerplant profitability if a certain limit cannot be attained.

Main features relative to design point are show in Tab. (1).

Table 1. Chosen design point characteristics

Mass Flow (kg/s)	47.8
Compressor Pressure Ratio	16.1 to 1
Maximum Cycle Temperature (K)	1335
Shaft Output (MW)	11.699
Heat Rate (kJ/kWh)	12345
Isentropic Efficiency of Compressor	0.85
Combustor Chamber Pressure Loss	0.04
Combustion Efficiency	0.99
Isentropic Efficiency of Gas Generator Turbine	0.87
Mechanical Efficiency Gas Generator Shaft	0.99
Exhaust Gas Temperature (K)	754
Isentropic Efficiency of Free Turbine	0.87
Mechanical Efficiency of Free Turbine Shaft	0.99

Although the engine PGT10B has variable geometry compressor, with IGV followed by two variable stator rows and it is possibly used to avoid stall during acceleration at low speeds, it is considered that the data on Tab. (1) could be adequate for the proposed simulation.

The study was carried out varying the nozzle settings, which changes the power turbine throat area, and searching for the maximum efficiency at partial load conditions. Only the NGV variable area is considered but a combination of variable NGV and compressor stators would further improve the engine efficiency, attaining even lower fuel consumption.

The study was carried out using the GTAnalysis, a FORTRAN program developed at Instituto Tecnológico de Aeronáutica (ITA) as part of a research activity in gas turbines performance simulation. This program is being developed and has been used for many applications, together with other computer codes for design (Barbosa, 2001; Bringhenti and Barbosa, 2001) and performance prediction (Barbosa and Bringhenti, 1999), (Barbosa and Bringhenti, 2000). GTAnalysis handles steady state design and off-design performance of all major gas turbines in the market.

Because the engine is required to operate away from its design point, that is, at off-design due to load variation, performance deteriorates as a consequence of components operating at regions of low efficiency. The bad off-design matching of the components are due to their passage areas that are calculated at the design point conditions, therefore, limiting the operation at other conditions.

Flow control at the components, example of which is the variable geometry, is usually adopted in attempt to improve the off-design efficiency (or matching) of gas turbines components. Variable geometry has been used at several engine components such as compressors, turbines, nozzle, etc. (Bringhenti and Barbosa, 2001).

This work considers only variable geometry of the NGV in turbine. Major discussions and results are available in the references (Bringhenti et al., 2001).

Figure (1) is the sketch of the turbine under analysis. Major characteristics at design point are indicated in Tab. (1).

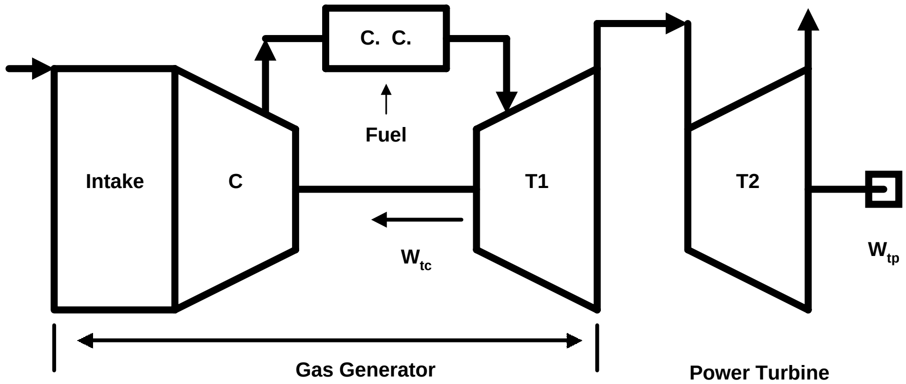

Figure 1. Free turbine unit

For Fig. (1), the component nomenclature is as follows: C = compressor, C.C. = combustor chamber, T = turbine, W_{tc} = compressor work and W_{tp} = power turbine work.

The calculations to produce the data for the curves shown in this work were carried out using GTAnalysis (Bringhenti, 1999). Table (1) shows main input data, obtained from manufacturers disclosed literature. It must be stressed that the manufacturers do not publish data coherently. Data taken from GTW Performance Specs (1997) and GTW Magazine (1997) must be read carefully. Major engine components parameters like compressors, turbines and combustor efficiencies are not disclosed for security reasons. They were set taking account the engine technology and prior cycle simulations (Gratz, 2000) and adjusted for the ISA SLS day, referred as design point.

Figure (1) shows the engine main model:

1) Intake- air inlet duct
2) c – compressor
3) cc – combustion chamber
4) T1 – GG turbine
5) T2 – Power turbine
6) s – exhaust duct & stack

Each block has its inlet and outlet stations, numbered such that two adjacent blocks have the same stations number that the first block outlet station number is the same number of the next block inlet station.

Compressors and turbines maps are selected among those in the library according to their specific applications, namely expected specific work.

This work covers the turbine NGV variable geometry only, but provisions for compressor stators variable geometry are being developed, so that it would be possible to combine both compressor and turbine variable stators in the search for best efficiency or other engine characteristics adequate for a chosen application.

Restrictions had to be made as far as engine operating parameters are concerned. The design point maximum cycle temperature was considered to be the maximum temperature throughout this study, while steady state surge margin was monitored.

At design point a surge margin of 15% was selected; at other operating conditions a decrease down to 12% was considered adequate, since it is not expected sudden load variation. If this has to happen, provision must be made to unload the compressor during such transients. This control activity is usually used in gas turbines, what would not impose additional constraint.

It was kept in mind that part load maximum efficiency would be the major concern. NGV and N1 settings have been determined at which the efficiency was optimized.

3. RESULT ANALYSIS

Gas turbines used for power generation must run at constant speed because generators work at either 50 Hz or 60 Hz. The engine model simulated in this work has the power turbine (T2) working at constant speed, so that at part load operation, for any NGV settings, only the gas generator speed is changed for the engine with the free turbine layout.

Data were obtained from cycle calculations for NGV settings in the range of -15^o to + 15^o, steps of 2^o, varying N1 from 100% down to 75%, steps of 5% relative to the design speed (100%). The power turbine speed was held constant. The constant power curves were interpolated from these data, using an auxiliary specially written computer program. At design point, turbine entry temperature is 1335 K but the maximum cycle temperature was limited to 1400 K as a means to foresee possible uprate problems.

Figure (2) through (6) show the results of simulations at several off-design conditions having the power output as the parameter, for varying gas generator (GG) speed N1.

Cycle efficiency, NGV setting angles, maximum cycle temperatures, surge margin and air mass flow were investigated among other parameters.

On Fig. (2) it is shown the efficiency curve for the turbine with fixed geometry (zero degree). The lower the power output the lower the efficiency, as expected for the fixed geometry gas turbine.

Capital letters A, B, C, D, E and F corresponds to NGV settings of -11^o, for different power settings. This unique blade setting was obtained because the maximum cycle temperature climbed up to 1400 K, a value above the design. It will be shown later that the blade settings will vary if the maximum temperature is fixed at the design value of 1335 K.

It may be also identified by capital letters A, B, C, D, E and F, the points of maximum efficiency for each power setting, what was achieved by means of changing the stator stagger.

Figure (3) indicates the NGV angle setting at which the maximum efficiency would be attained. From the figure it is possible to define the NGV schedule to be used by the control system.

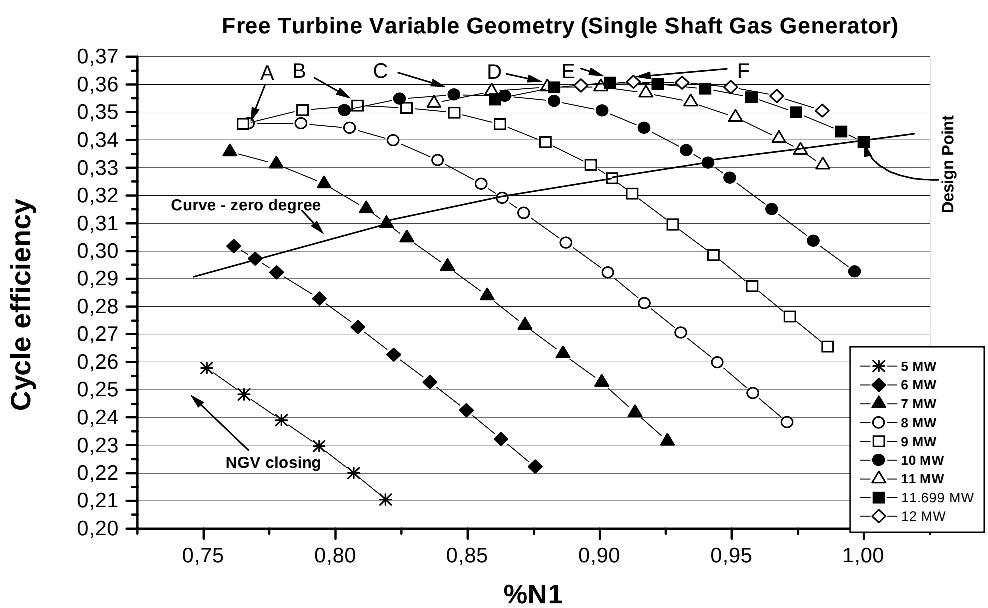

Figure 2. Cycle efficiency versus corrected speed

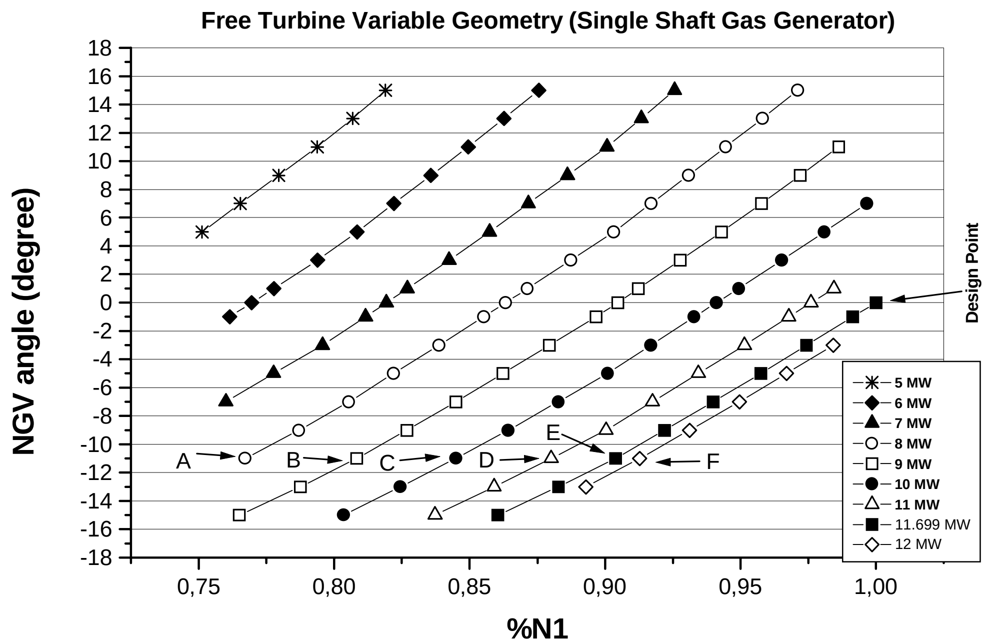

Figure 3. NGV angle versus corrected speed

Figure (4) indicates the maximum cycle temperatures, decreasing with decrease of load.

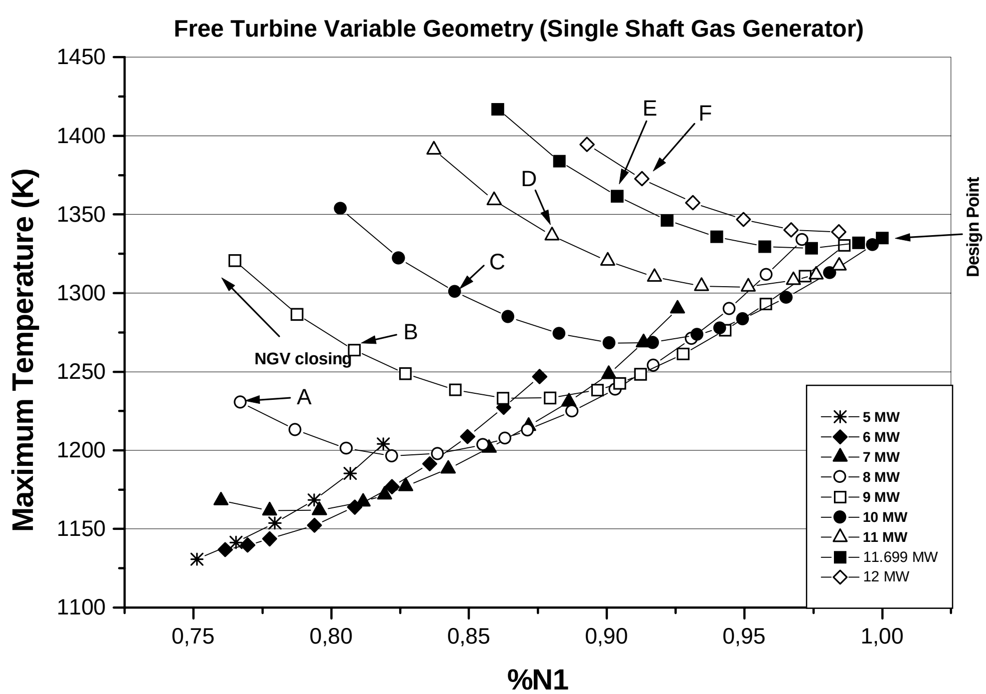

Figure 4. Maximum cycle temperature versus corrected speed

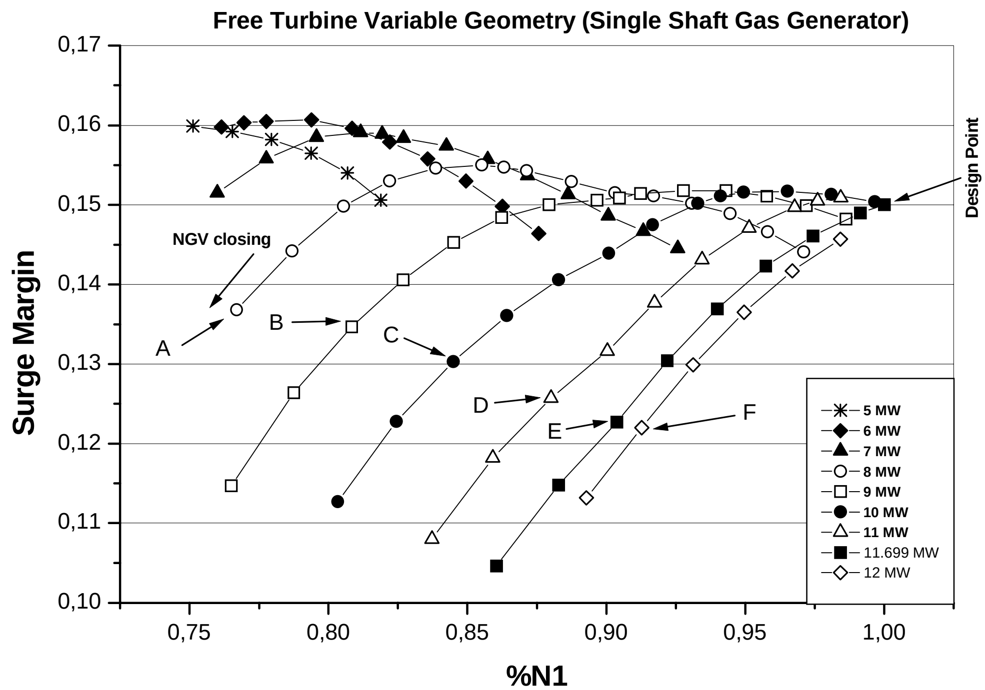

Figure 5. Surge margin versus corrected speed

Figure (5) brings to the attention the crucial problem of surge margin. Decreasing the power output and restaggering the NGV would result in a lower surge margin, what would be a problem as far as load variation is concerned. Since the surge margin was reduced to about 12%, for the power

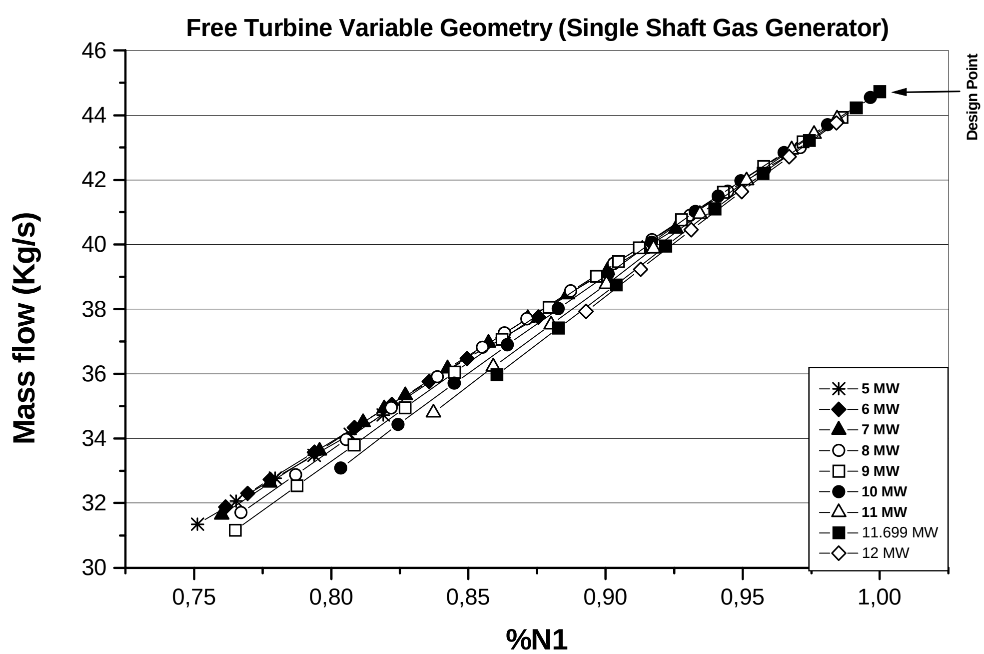

Figure 6. Mass flow versus corrected speed

uprate of 12 MW, it seems that the calculated NGV schedule would be acceptable. For fast load variation a means to avoid surge could be required.

Figure (6) indicates that the mass flow will be reduced almost at the same pace for all power setting, a characteristic of such engine configuration.

If the maximum temperature is limited to the design value of 1335 K, it is not possible to increase the power extracted independently of the NGV setting. The maximum efficiency for different power settings is obtained for different NGV settings, corresponding to -11^o, -11^o, -11^o, -9^o and -7^o respectively.

Surge margin did not change significantly, the lower being 13%. The same recommendations apply if load variation is considered.

From Fig. (2) to (6) it can be observed that for each shaft power output it is possible to find a NGV setting and a corresponding maximum efficiency, therefore minimum fuel consumption. In case of prime mover in an electric single cycle station, this is a must.

From Fig. (2), (3), (4) and (5), for powers above 8 MW, it can be seen that maximum efficiency is attained if the NGV is moved towards closing the passage areas, at same time surge margin decreases and the maximum cycle temperature increase, with increasing power output.

Moving away design point causes surge margin to decrease due to the inherent compressor mode of operation. Therefore, as mentioned above, fast transient operation would require unloading the compressor, what would be possible two-ways, a blow-off valve or a resetting of compressor stators or both, modification that may represent reprogramming of the FADEC (“Full Authority Digital Electronic Control”), for example.

Lower power output is always associated with compressor slowed down. Line “zero degree” on Fig. (2) shows the engine characteristics for the original NGV setting, in this paper identified with 0°. As expected, moving away from design point causes efficiency to decrease considerably but surge margin does not change considerably.

Even if NGV is considered above it is an adequate means to keep the engine operating approximately at constant efficiency at part load in a simple cycle. More complex cycles like intercooled and recuperated cycles with variable NGV are being already applied to marine and vehicular propulsion, combining parameters that improve even more the overall gas turbine efficiency.

4. COMMENTS AND CONCLUSIONS

An existing turbine with variable geometry whose maps were generated beforehand (Bringhenti and Barbosa, 2001), was used for the simulation carried out under this research. Therefore, it may not be the most recommended turbine to be used. If the turbine were specially designed for the application, the optimal efficiencies would probably be attained for other NGV angles setting, since the flow matching for this application was not taken into consideration during the turbine design. Nevertheless the conclusions drawn from the data presently disclosed are still valid.

If one seeks a turbine uprated to 12 MW, the maximum temperature of 1400 K would be achieved but there would not be much improvement to the cycle efficiency.

When the engine is running at part load the efficiency deteriorates as shown in Fig. (2) by the ‘zero degree’ curve. Surge margin decreases up to 12% from the 15% design surge margin. This may require extra attention mainly if severe load changes may occur.

For any power output required it is observed that better cycle efficiency is possible, what can be obtained by closing the NGV.

For a fixed power output, if the NGV setting is reduced, the airflow also decreases as indicated in Fig. (6). At the same time, the maximum cycle temperature increases for high power settings, as seen on Fig. (4), but in the other hand the surge margin decreases, as shown by Fig. (5), what influences the stability of the engine. For low power settings, the opposite can be deduced.

5. ACKNOWLEDGEMENT

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