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PART-LOAD PERFORMANCE OF A MARINE GAS TURBINE WITH INTERCOOLER AND RECUPERATOR.

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Abstract. *Gas turbines for marine application have been widely used, despite the inconvenient of high fuel consumption at part load. Improvement of fuel consumption has been achieved with the use of other engine types, as diesel, relying on the gas turbine at high power demand. New cycles have been designed to improve part load performance. This paper deals with the ICR, intercooled, recuperated cycle, with variable geometry in the power turbine nozzle guide vane, and a possible control strategy to maximize the engine efficiency at part load, that is, to minimize its fuel consumption.*

Key Words: *Gas turbines, performance, thermodynamic cycles, intercooling, reheat*

1. Introduction

Cohen et al [1] mentions that gas turbines had been used successfully in high-speed container ships until the rapid increase in fuel prices of the seventies led to the need of those ships being re-engined with diesels to decrease operational costs, although the consequential loss in both speed and cargo capacity. In other words, high speed could no longer be justified. For the naval operations, it is different however. Many navies, like the British, American, Canadian, Dutch, have accumulated gas turbine experience along all those years until present.

Gas turbine for naval application was first used in a Motor Gun Boat in 1947, and aero-type engines, like the well known Rolls-Royce Proteus, were first used in fast patrol boats in 1958. The Canadians realized the potential of aero-derivative engines for main propulsion of warships installing in the DDH-280 class a Pratt and Whitney FT-4´s for ´boost` power and FT-12´s for ´cruise`. The Royal Navy did the same with the Olympus as boost engine and the Roll-Royce Tyne for cruise, an arrangement that was also used by the Royal Netherlands Navy. Sadly, the Olympus and the Tyne are the only naval gas turbines proved in battle, operating in the Falklands War. Another aero-derivative from the GE CF6 engine was selected by the U.S. Navy, the LM 2500, an engine that has been widely used around the world.

Poor specific fuel consumption at part load is the major disadvantage of the naval gas turbine, since the ship will travel normally at cruise speed (around 30 km/h), so that the power requirements would be 8 times at max speed compared with the cruise power requirement, if one has de propeller power law in mind.

To overcome this problem, several combined power plant configurations, consisting of gas turbines in conjunction with steam turbines, diesel engines and other gas turbines have been suggested. Many funny names were then created, where CO standing for ´combined`; S, D, G for ´steam`, ´diesel` and ´gas turbine`; the final A or O for ´and`, ´or`, namely COSAG, CODOG, COGOG, COGAG, etc..

Diesel engine has the advantage of very good cruise fuel consumption in naval applications. Its disadvantage is being bulky and noisy underwater. The COGOG arrangement, having a small cruise gas turbine and a large boost gas turbine, has been widely used. Its success relies on the gas turbine running near full power where its efficiency is a maximum. The American and the British have used the COGAG arrangement, using identical gas turbines. Either four LM2500 or four Olympus engines were used in large destroyers and aircraft carriers.

To increase performance, that is, to decrease fuel consumption, different working cycles were designed. Intercooling, which has a similar effect upon the performance of the ideal heat-exchange cycle, as reheat does not suffer from the same defects. Even allowing for the additional pressure loss in the heat exchangers, there is, in addition to the marked increase in specific output, a worthwhile improvement in efficiency.

Being bulky and requiring cooling water resulted in the loss of self-contained nature. Nevertheless, the cycle is attractive for naval applications, because cooling water is easily available from the ocean. Thermal efficiency in excess of 40 per cent and also good part-load efficiency are obtainable with this complex configuration. It is therefore possible to use a single engine rather than one of a complex arrangement like the COGOG, thus offsetting the greater bulk and cost of the engine.

Good part-load performance of gas turbines for vehicular or naval application is of great importance because the considerable portion of the running time spent at lower power. Early studies for both applications resulted in the consideration of complex arrangements incorporating intercooling, heat-exchange and reheat. The sole justification for the increase in complexity was the great improvement in part-load specific fuel consumption.

Variable geometry, both at the compressor and the turbine, came into operation to improve even more the engine part load performance [2,3,4,5]. Other complex cycles, like the intercooled recuperated [6] are being used and claim to cut fuel consumption and therefore fuel costs in the order of 30% in a yearly basis, for a typical operation profile. Attached to the complex cycle there always must be the corresponding engine control schedule since it is not possible to control just only the fuel flow in order to control the engine. This work deals with a possible control strategy to maximize the engine efficiency at part load, that is, to minimize its fuel consumption. A particular engine was selected, namely the WR21 Westinghouse/Rolls-Royce joint development engine, because of the available data published in the open literature.

The WR21 engine is described by Crisalli and Parker [6], Wawkins et al [7] and by Rolls-Royce [8]. More than a decade ago, the American Navy awarded the the Intercooled Recuperated (ICR) Gas Turbine Advanced Contract to Westinghouse, for the development, build, test and evaluation of two ICR systems to be incorporated on naval surface combatants. Rolls-Royce was the engine gas-generator supplier (RB211 derived engine).

The most important benefit of the ICR for ship application is fuel economy, what can be translated in increased range. ICR engine would save 30% of fuel in an annual basis, due to the flat sfc versus power characteristic at part load. The engine is required to run at different power levels during the course of a year´s operation, according to the Navy´s technical specs.

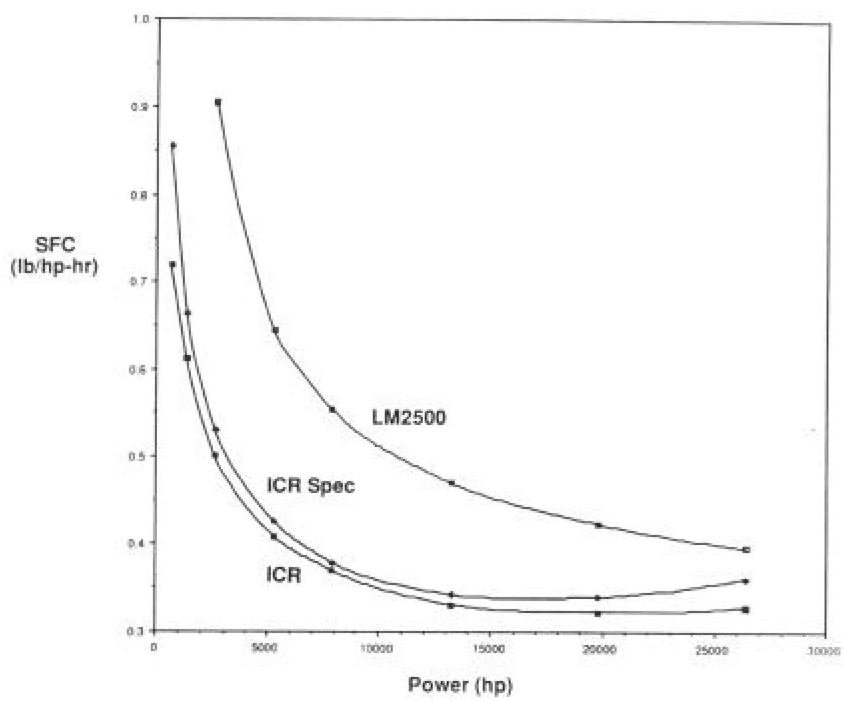

Figure 1 - Performance Comparison of simple and ICR cycles.

Figure 1 [6] shows the engine sfc for the simple and the ICR cycle, showing the roughly flat characteristic from 8 to 26 MW power range. Figure 2 [7] shows the block diagram of a ICR engine. It is worth noting that the simple cycle has been modified to incorporate an intercooler between the IPC and the HPC compressor, a recuperator to transfer heat from the exhaust gases to the compressed air leaving the HPC, and a variable nozzle guide vane arrangement at the power (free) turbine. The compressed air heat is removed at the intercooler by means of a closed cycle water system which rejects the heat to the sea water. A complex system of valves is also incorporated to by pass the flows during start up and some special operation requirement, whose details are available from [6].

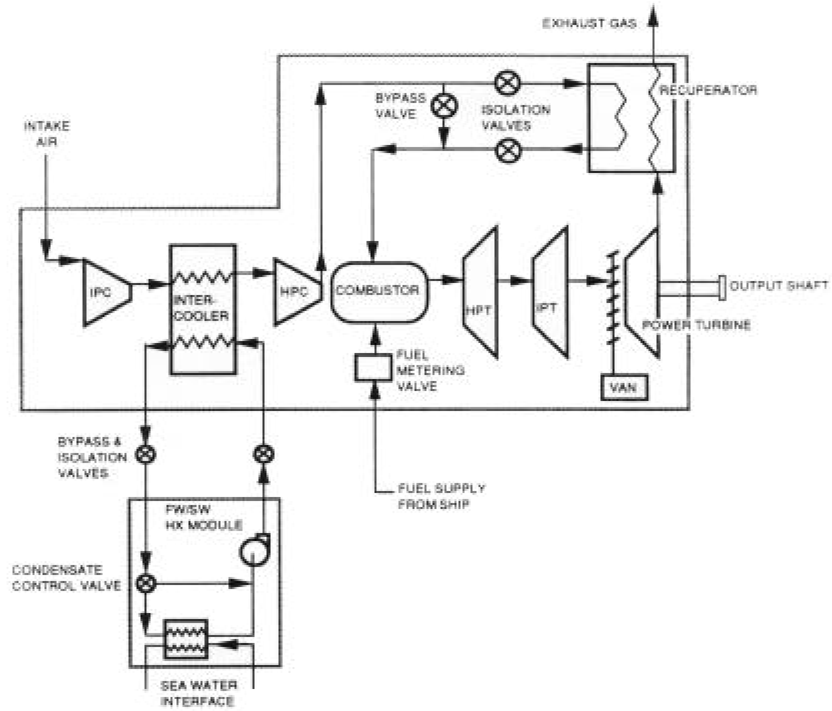

Figure 2 – ICR Functional Operation [12]

2. Engine Model
3.

Engine model was built upon available literature [6] and commercial leaflets [8]. No manufacturer data were available, so that results may be considered qualitatively. Fine tuning, if required for further studies, would require more precise data input like compressor, turbine, combustion chamber maps, along with relevant cycle parameters like desing point pressure ratio, inlet HPT and power turbine temperatures, air mass flow.

Engine numerical simulation was performed using the general deck of Alves [9] . The input file for that program is shown in Table 1

Table 1 - Input data for the numerical simulation of the WR21 engine.

```
ENTR 1
1 2 0. 0. 0. 1. 72.2 -1.
COMP 2
2 3 4.05 -.89 -1. -1. 4. -1. -1. 6200.
ECON 3
3 4 354. 290. 320. -1. 0.05
COMP 4
4 5 4.0 -.89 -1. -1. 4. -1. -1. 8100.
BIFU 13
5 6 14. 0.95 0. 1. 0. -1.
TROF 5
6 7 0.8 0.05
CAMA 6
7 8 0.06 0.99 1450. -1. -1. 1. -1.
MIST 14
14 9 8. -1. -1. -1.
TURB 7
9 10 -0.87 1. 0. 4. -1. -1. -1. -1. -1. 2. 0.000003 8100.
TURB 8
10 11 -0.87 1. 0. 2. -1. -1. -1. -1. -1. 2. 0.000003 6200.
TURB 9
```

```
11 12 -0.87 1. 0. -2. 1. 1.07 -1. -1. 1. 2. 0.000003 3600.
TROQ 10
12 13 5. 0.05 -1.
BOCA 11
13 1 -1.
FIM 20
```

4. Results

The simulations were carried out under the constraints below, in order to predict engine performance for varying loads from about 10% to 100%.

Attention was paid mainly to the engine stability limits represented by surge margin and maximum cycle temperature. At part load the maximum cycle temperature decreases, resulting in lower exhaust gas temperature and poor overall cycle performance. The power turbine variable nozzle guide vanes are then opened. Cycle maximum pressure decreases so that, to sustain the desired load, the maximum cycle temperature must be increased, resulting in higher exhaust gas temperature and, therefore, increasing the overall engine efficiency because the heat recuperation is increased.

Design surge margin was set to 15%.

Figures 4 and 5 were then plotted. They show that stability limits increase as load is reduced for the same NGV setting but decrease significantly with NGV area increase (opening the NGV).

The peculiar shape of curves on Fig. 4 are due to the turbine maps used for simulation. No tests were made using other maps since they were not relevant for the present work.

Figure 5 reproduces the standard shapes for the sfc dependence on load, that is, the increase of sfc with decrease of load. That increase of sfc is much more significant for the lower range of power. Nevertheless, if at the same time of loss reduction the NGV area increases, the sfc can be kept constant.

Figures 4 and 5 read together will show that the stability limits can be kept within the limit of 15% as well, down to about 50% design load, compatible with 80% of the ship design speed.

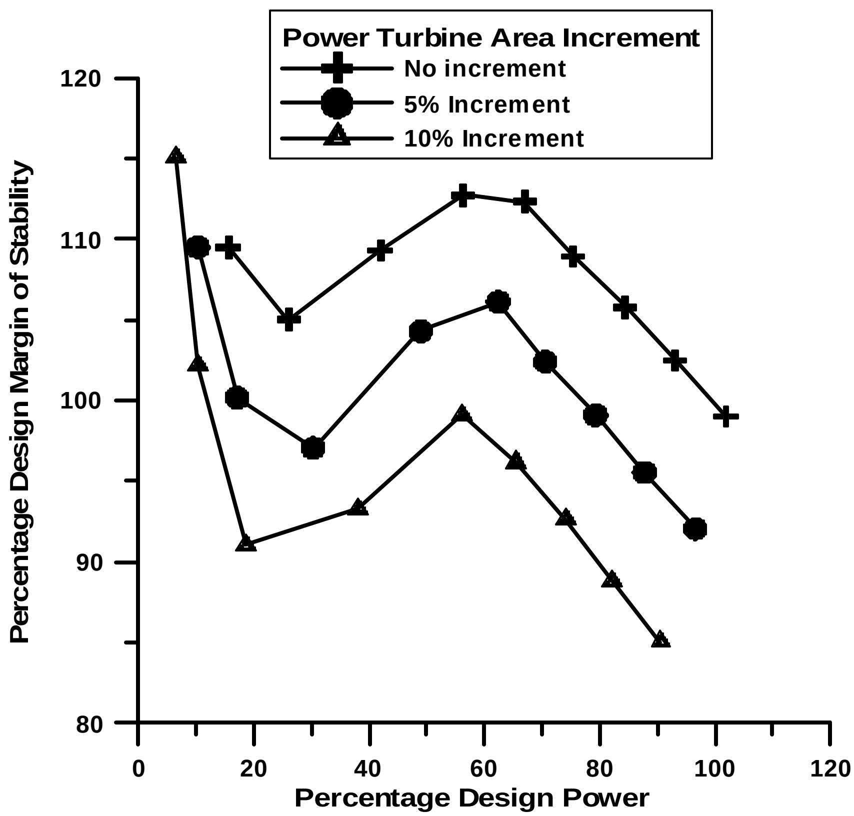

Figure 4 - Surge margin as function of load and NGV setting.

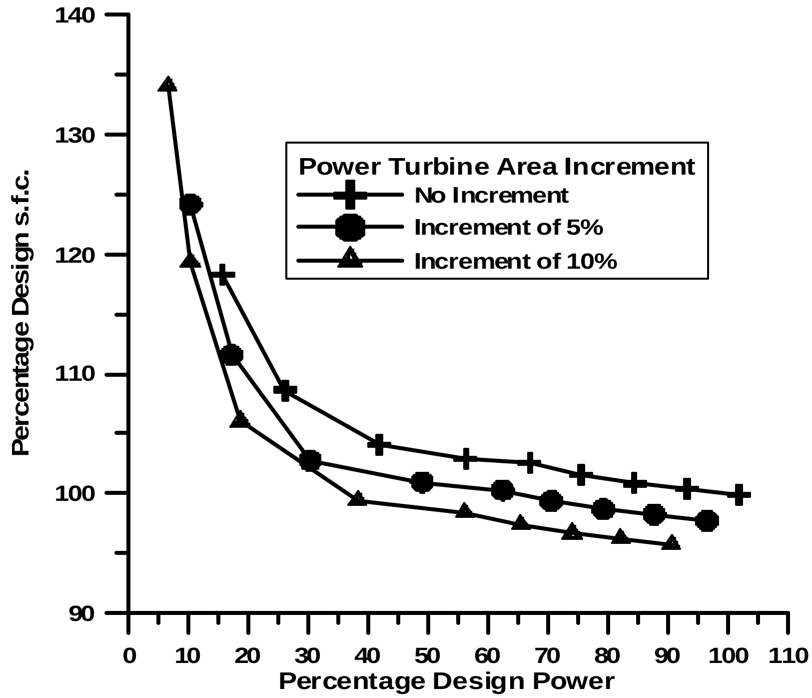

Figure 5 - Specific fuel consumption as function of load and NGV setting.

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