Design of hydrogen marine gas turbine

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Marine gas turbines are in use in different naval ships since the 1970's, but only at the beginning of the 21^{st} century it found its way to the commercial market with generator drives on cruise ships and recently as propulsion power plants for LNG tankers. Due to the increased worldwide concerns about the harmful emissions, many researches have introduced solutions to this problem including the adoption of new cleaner fuels. This paper follows the same trend by implementing the hydrogen as fuel for marine gas turbines. The design and analysis for such an engine is demonstrated here with some details.

منذ سبعينات القرن الماضي و تعمل بعض السفن الحربية بالتوربينات الغازية، و لكن تلك المحركات وجدت طريقها للسفن التجارية في بداية القرن الحالي، من أمثال ذلك تشغيلها كمحركات رئيسية في ناقلات الغاز الطبيعي المسال أو كمولدات للكهرباء على متن سفن الركاب. و نظرا للاهتمام العالمي المتزايد بالانبعاثات الغازية الضارة، فقد قدمت عدة أبحاث حلولا لهذه المشكلة البيئية مثل استخدام أنواع أ نظف من الوقود. و هذا البحث يتبع هذا المنهج عن طريق استخدام الهيدروجين كوقود للتوربينات الغازية البحرية حيث يتم مناقشة و عرض تصميم و تحليل هذه المحركات بشئ من التفصيل.

Keywords: Gas turbine, Hydrogen, Marine power plant

1. Introduction

Several issues must be taken into consideration when trying to adopt a new type of fuel, especially when this fuel is intended to be used in the marine field where strict rules and regulations control the design and manufacture of waterborne vehicles. Safety and storage problems are the main problems arising when talking about the use of hydrogen as fuel. These issues in addition to the methods of hydrogen production are discussed by the author before [1].

1.1. Marine gas turbine overview

Since 130 BC, when Hero of Alexandria attempted the first reaction steam turbine and the experiments didn't stop to invent a fully working steam or gas turbine. Until 1900, none of the trials were successful to produce a gas turbine, until Dr. Franz Stolze succeeded in producing a prototype; it has the main components as today's gas turbine, based on his researches dated back to 1872. But this unit never ran successfully [2].

Regarding the marine use of gas turbines it didn't start until the 1970's, the major client for marine gas turbines is the naval units where lots of naval forces worldwide use them as main or auxiliary power generators for their ships [3].

Recently, the marine gas turbine started slowly to penetrate the commercial market as auxiliary power units especially in large cruise liners as Queen Mary II, and it is anticipated to penetrate more and more in other commercial sectors as many favorable issues are convincing the ship owners to use gas turbines rather than diesel engines in new built ships. Table 1 shows the main characteristics of modern gas turbines.

1.2. Gas turbine cycle

The gas turbine engine is designed based on the Brayton cycle, which is an ideal cycle working with a perfect gas [4]. In the preliminary stages of design the working fluid is assumed to be only air, but in the next stages this assumption is modified to include the fuel type used by modeling the main properties of the mixture.

Fig. 1 shows the temperature – entropy and pressure – volume diagrams for the Brayton cycle. Compression takes place in the compressor eqs. (1-2), this compressor may be

Table 1
Main characteristics of conventional marine gas turbine [6]

Process	Simple cycle	Advanced cycle
Construction	Twin shaft	Twin shaft
Output power range [kW]	26000 - 6000	24000
Output speed range [rpm]	3600 - 7000	3600
Fuel type	Marine distillate fuel	Marine distillate fuel
Spec. fuel cons. [g/kWh]	240 - 280	200
Spec. air cons. [kg/kWh]	10 - 15	10.5
Spec NOx emissions [g/kWh]	2 - 5	3
Specific mass [kg/kW]	1.0 – 1.4	1.8
Specific volume [dm^3/kW]	2.5 – 4.5	4.1
Specific cost [Euro/kW]	180 - 280	470

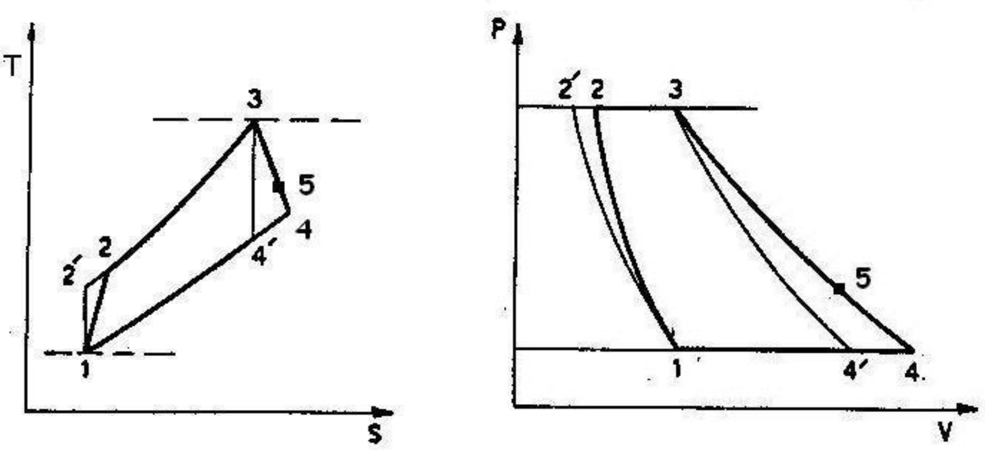

Fig.1. T-S and P-V diagram for ideal gas turbine cycle with free power turbine.

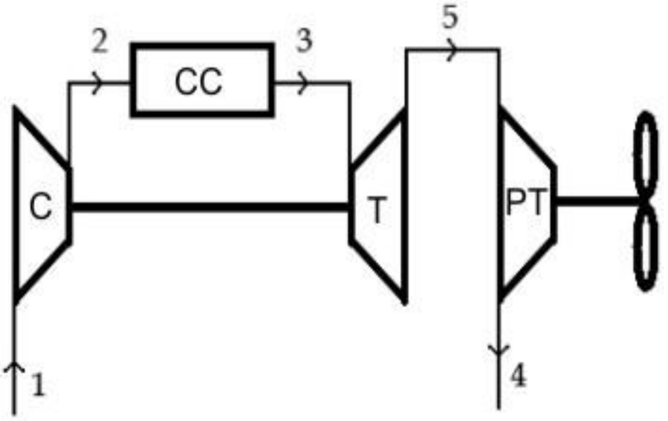

Fig. 2. Schematic diagram of the split shaft marine gas turbine.

of the axial or centrifugal type according to the engine rating, where axial compressors are most suitable forhigh power gas turbines [5]. Next to the compression, combustion or heat addition takes place eqs. (2-3) where temperatures in the order of 1200 K to 1500 K may be reached [6].

After the combustion, the high pressure hot gases enter the turbine to extract their energy by expansion eqs. (3-4), this process takes place on two stages; the first in the compressor turbine eqs. (3-5) where only enough power to run the compressor is generated, the second stage in the power turbine eqs. (5-4) where the remaining energy in the hot gases is extracted to generate useful work.

This configuration (see fig. 2) is called split or twin shaft gas turbine since each turbine run on separate shaft with different speeds.

Where

C is the compressor,
CC is the combustion chamber,
T is the turbine, and
PT is the power turbine.

1.3. Thermodynamic cycle

As any other design problem, the main design requirements should be clearly defined first. For a marine gas turbine, the power and output shaft speed are considered to be the main design criteria needed to start with the first step which is the thermodynamic analysis of the working cycle, for the case studied in this paper (for details see ref. [1]), a power of 3 MW and shaft speed of 7200 rpm is chosen (Note: this speed seems to be high but this engine is designed to operate a 60 Hz electric generator after a 2:1 reduction gear).

The enthalpy of the first point is determined after choosing the ambient conditions in which the engine will operate, in this design 27°C and 1 bar are the ambient temperature and pressure [7].

One of the very important issues in the design of gas turbines is the choice of compression ratio, this value is preferred to be of a high value to have smaller engine and higher efficiency (see fig. 3), but many other factors affect this choice like the technological development and the price of the equipment. A compression ratio of 40 is chosen here.

Due to the irreversibility of the compression process, the adiabatic efficiency of the compressor should be taken into account, and therefore adjusting the point (2') to (2).

$$\eta_c = \frac{h_2' - h_1}{h_2 - h_1} . \tag{1}$$

Where

η_c is the compressor adiabatic efficiency = 85 % [2], and
h_1, h_2, h'_2 are the enthalpy of points 1, 2 and 2' respectively.

Point eq. (3) is determined by adding the amount of heat resulting from the constant pressure combustion to the enthalpy of point eq. (2).

To calculate the amount of heat resulting from the combustion, first the lower calorific value (LCV), the air fuel ratio (AF) of the hydrogen and the excess air factor (λ) must be determined [LCV = 130 MJ/Kg. AF = 34.78, λ = 4] [7].

Then, the mass of air per Kg. of fuel is calculated;

$$M_{air} = \lambda . Af. \tag{2}$$

then, the amount of fuel calorific value per Kg of air is calculated;

$$LCV_{air} = \frac{LCV}{m_{air}} . \tag{3}$$

An isentropic expansion process adjusted using the adiabatic efficiency of the turbine is used to get point eq. (4).

$$\eta_T = \frac{h_3' - h_4}{h_3 - h_4'} . \tag{4}$$

Where

η_t is the turbine adiabatic efficiency = 90 % [2], and
h_3, h_4, h'_4 are the enthalpy of points 3, 4 and 4' respectively.

Point eq. (5) is obtained by subtracting the amount of compressor work (w_c) from the enthalpy of point eq. (3). The amount of work from point eq. (5 to 4) is the useful work on the output shaft.

1.4. Cycle analysis

After determining the cycle, an analysis is made to determine the main characteristics of this gas turbine. The first important result is the temperatures along the air path from the inlet duct to the exhaust duct. Table 2 shows the temperature at each point across the cycle.

It is important to note that due to the use of hydrogen, the combustion temperature is higher than that of a normal gas turbine and makes more difficult the design and choice of materials for the combustor and turbine blades.

Table 3 Groups the main characteristics of the gas turbine from the cycle analysis and the design conditions.

1.5. Gas turbine design

The main design of the engine itself includes the calculation of the number of stages required for the compressor, the compressor turbine and the power turbine, the design of the blades of each rotary component and the design of the combustor. In this paper, only the preliminary design is made which include the calculation of the number of stages since the design of blades and combustor necessitates more thermo-fluid analysis which is not in the scope of this paper.

The basic rule of design applied to calculate the number of stages of any turbomachine is to have constant energy rise or drop between stages rather than constant pressure variation [7- 8].

In order to have constant energy variation, the temperature variation must be kept constant, and then the number of stages may be calculated. For the compressor a temperature rise of 35°C between stages is chosen, for the compressor turbine 50°C and for the power turbine 20°C [7].

According to these values the number of stages of each component is as follows: Compressor 18 compressor turbine 19 power turbine 19.

Also the diameter of each rotating component may be determined without deep analysis, this is based on limiting the peripheral speed which is the linear speed at the tip of the rotating blades, this speed is limited to avoid damage due to creep resulting from high temperature gases flow.

Table 4 shows the values of peripheral speeds used in calculations and the corresponding diameter of each component.

1.6. Design parametric study

A parametric study is made to clarify the effect of compression ratio (π), excess air factor (λ), ambient temperature and shaft speed on the performance and dimensions of the hydrogen gas turbine. The next graphs show the results of this study.

2. Discussion of results

From the previous section, it is clear that the ambient temperature has an effect on the gas turbine's performance figs. 3, 4 where an increase of 20° causes an efficiency drop by 1%.

Table 2
Temperature at each point of the cycle

Point	1	2	3	4	5
Temperature (K)	300	920	1709	792	1163

Table 3
Summary of engine characteristics

Total power produced	7673 kW
Compressor consumed power	4670 kW
Output Power	3003 kW
Compression ratio	40
Output shaft speed	7200 rpm
Exhaust temperature	519°C
Air flow rate	7.128 kg/hr
Cycle efficiency	45.1 %
Specific fuel consumption	45.07 g/HP-hr

Table 4
Peripheral speeds and diameter of each rotating component

Component	Compressor	Compressor turbine	Power turbine
Peripheral speed (m/sec) [7]	500	300	400
Diameter (m)	0.9549	0.573	1.061

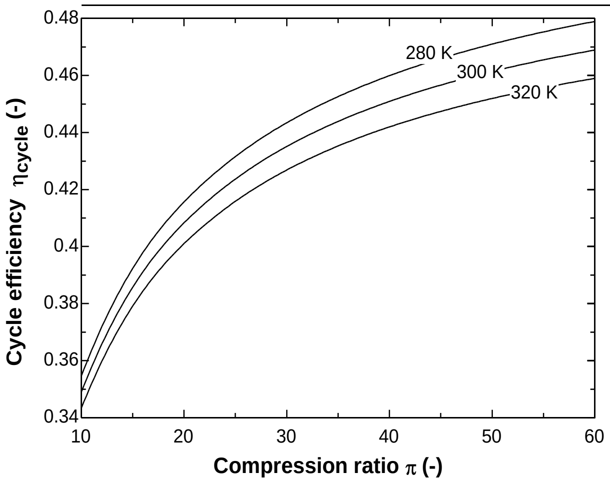

Fig. 3. Effect of compression ratio (π) on cycle efficiency at variable ambient temperature (@ λ = 4).

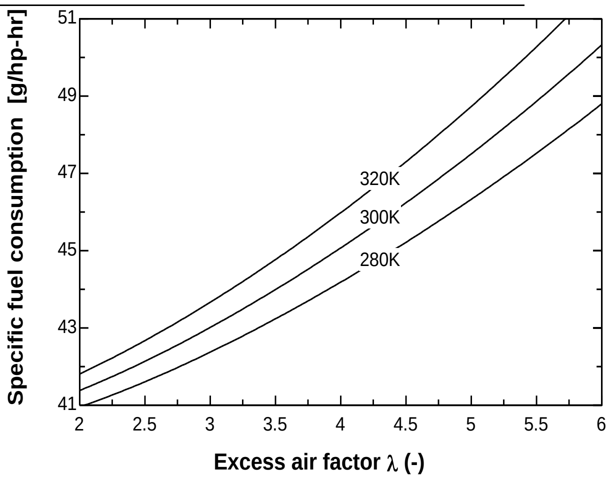

Fig. 5. Effect of excess air factor (λ) on specific fuel consumption at variable ambient temperature (@ π = 40).

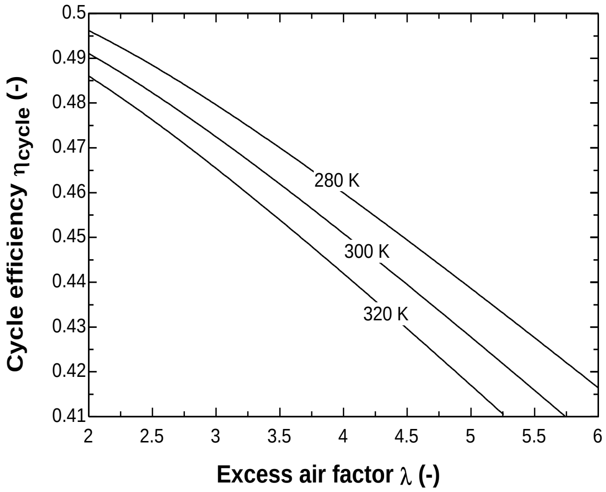

Fig. 4. Effect of excess air factor (λ) on cycle efficiency at variable ambient temperature (@ π = 40) .

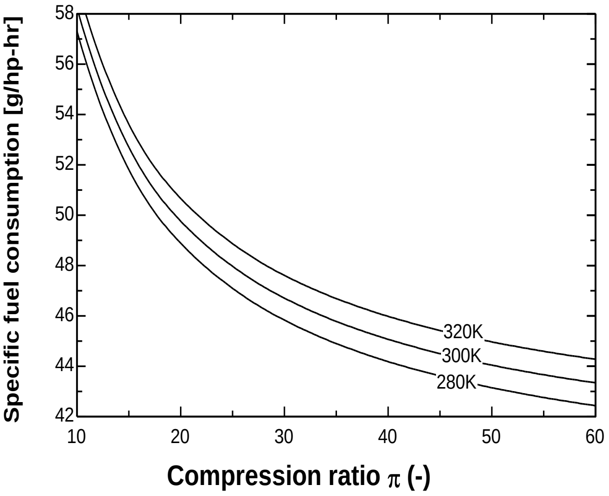

Fig. 6. Effect of compression ratio (π) on specific fuel consumption at variable ambient temperature (@ λ=4).

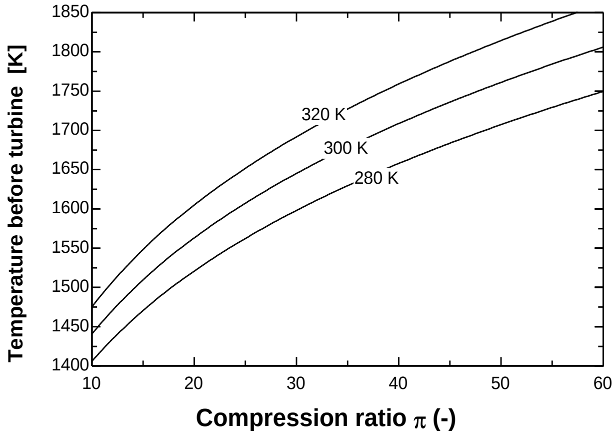

Fig. 7. Effect of compression ratio (π) on combustion temperature at variable ambient temperature (@ $\lambda=4$).

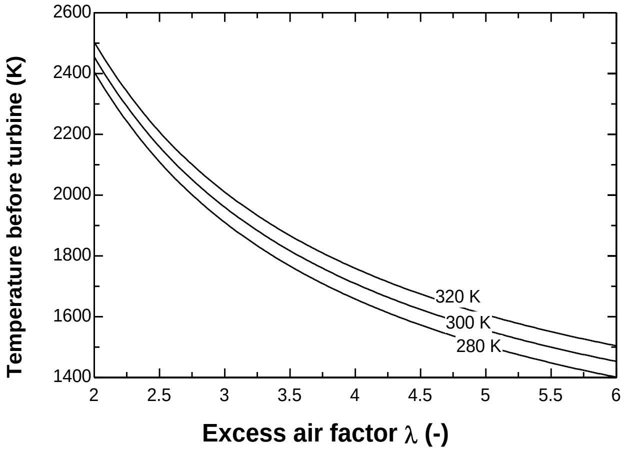

Fig. 8. Effect of excess air factor (λ) on combustion temperature at variable ambient temperature (@ $\pi=40$).

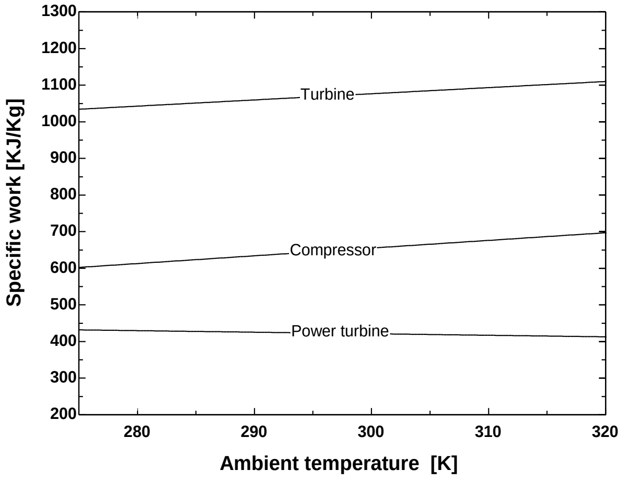

Fig. 9. Effect of ambient temperature on specific work of engine components (@ $\pi=40$, $\lambda=4$.

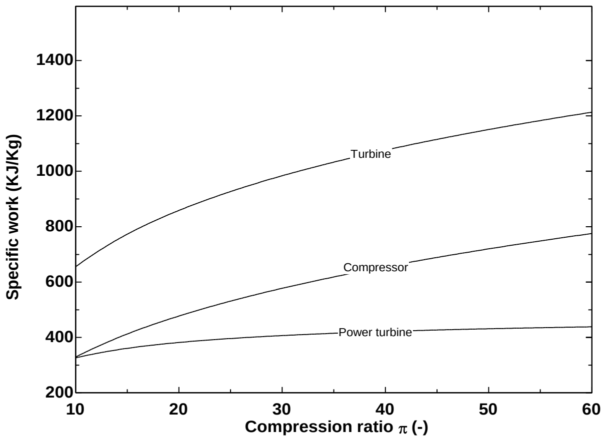

Fig. 10. Effect of compression ratio (π) on specific work of engine components @ $T_{amb}=300K$, $\lambda=4$).

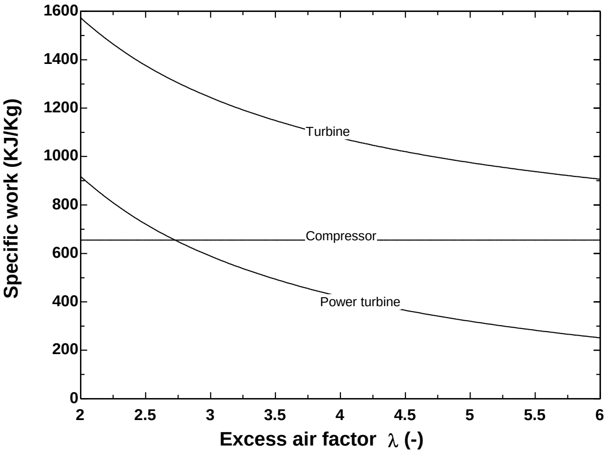

Fig. 11. Effect of excess air factor (λ) on specific work of engine components (@ $T_{amb}=300K$, $\pi=40$).

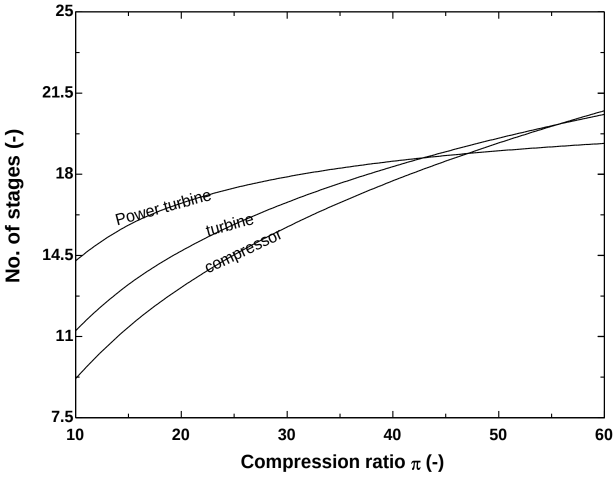

Fig.12. Effect of compression ratio (π) on the number of stages of different components (@ $T_{amb}=300K$, $\lambda=4$).

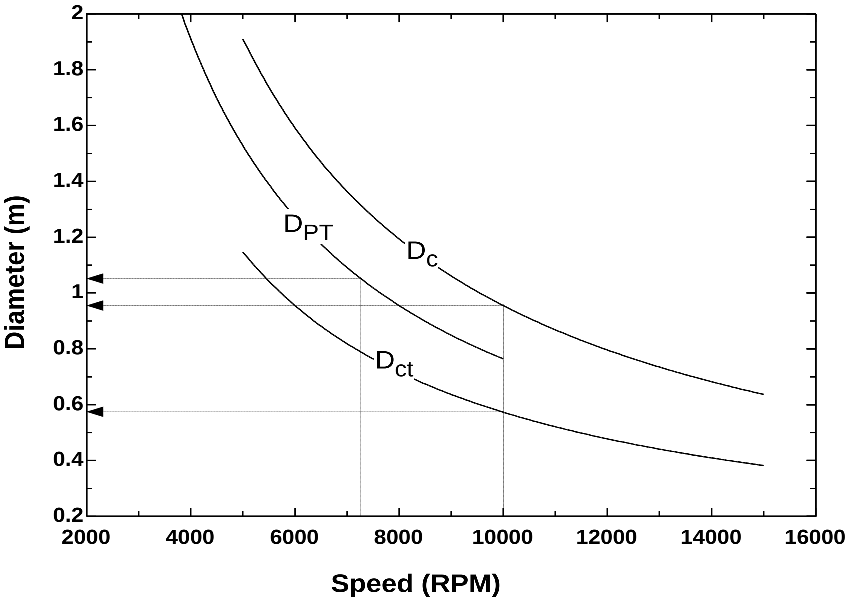

Fig. 13. Effect of shaft speed on the diameter of the different components.

Regarding the compression ratio fig. 3, its increase causes an improvement of efficiency, this increase is limited as high compression ratios result more in expensive and heavier engine. For the excess air factor, it is preferred to keep it at low level to have good efficiency fig. 4, but for hydrogen, it is preferred to use highs value to decrease the combustion temperature fig. 7. So a compensation between both factors (π and λ) must be made.

The effect on specific fuel consumption is the inverse of that on the cycle efficiency figs. 5, 6, this is logical as improved efficiency means lower cost through reduced fuel consumption.

The distribution of specific work generated inside the engine and that consumed in the compressor is affected by ambient temperature, but its variation is not large fig. 9, but both the compression ratio and the excess air factor affect to a large extent this distribution figs. 10, 11, at high compression ratios, the output of the power turbine approaches a near constant value while the compressor consumes the extra power generated by the turbine.

In what concerns the dimensions and size of the engine, it is clear that the higher the speed at which the various components rotate, the smaller the diameter is needed to be fig. 13. The number of stages of the various components is proportional to the energy contained in the gas flow for the turbine and with the energy needed to be added to this flow for the compressor, so by increasing the compression ratio, i.e. increasing the energy content, more stages are needed for the compressor and turbines as the energy variation is kept constant between stages fig. 12.

3. Conclusions

The basic design of hydrogen gas turbine follows the same simple steps as the ordinary gas turbines. It has been demonstrated in this paper that a marine gas turbine running on gaseous hydrogen can introduce a good alternative for ordinary marine power plants as no special technologies are needed and good performance can be achieved.

For this type of engines, the challenge is in the adoption of the new type of fuel for waterborne vehicles and also the difference between the properties of hydrogen and those of other types of fuels. One of these properties includes the combustion characteristics which are widely different than those of ordinary fuels. This may be overcome by using a mixture of hydrogen with other types of fuels like natural gas. This method is used nowadays in different applications [9-10].

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