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# Contributions to the study of the behavior of gas turbine propulsion systems at changes in environmental for all operating parameters

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**Abstract.** The paper encompasses the study of the evolution of the functional parameters (suction air mass flow rate, plant efficiency, etc.) of naval gas turbines propulsion systems at changes in environmental parameters. The operational parameters of a gas turbine propulsion system and their evolution in relation to the modification of the environmental status parameters have been highlighted by calculation. Another sensitive area in the operation of gas turbine installations is the transient operating modes (stopping, starting, accelerating and decelerating sequences of the installation), which were highlighted by determining of operating parameters on board the ship.

## 1. Introduction

In recent years power plants with gas turbines in shipping have developed complex both in terms of operational performance and in terms of complexity constructive in order to meet the demands of the marine environment by safe operation at high performance. For good knowledge of their operation and safe operation at the level of performance at which they were designed, the construction and functional parameters of the installations and, implicitly, of the gas turbines were constantly monitored and improved by various solutions. Gas turbines are more and more common in the shipbuilding industry both as a propulsion machine and as a drive for power generators in the turbo-generator energy groups.

In this paper is studied the evolution of functional parameters of gas turbines constituting the marine propulsion system by calculation, and by determination of the parameters on board, to changes in the marine environment and the transient operation of installations with gas turbines. Reference values for standard environmental conditions according to ISO 3977-2 for gas turbines were used as reference (detailed in Table I). The environmental factors with a direct impact on the functional parameters of the turbines are the changes in temperature, pressure and humidity of the suction air in the chambers.

## 2. Standard atmospheric conditions.

To compare the performance of gas turbines in marine propulsion systems facilities as close as possible to the marine environment, ISO establishes for gas turbines International Standard ISO 2977-2, developed by the TC 192 Technical Committee, Gas Turbines. This standard together with others cancels and replaces the revised ISO 3977: 1991 standard, consisting of the following parts:

- Part 1: General introduction and definitions;
- Part 2: Condiții standard de referință și puteri efective de exploatare;
- Part 3: Basic requirements for mechanical drive and electric drive;
- Part 4: Auxiliary equipment;
- Part 5: Controls and tools.

The standard conditions are shown in Table 1.

Table 1- Standard environmental conditions according to ISO 3977-2 for gas turbines and 3046-1: 2002 (E) and ISO 15550: 2002 (E) for thermal engines [8]

Parameter	Unit	Winter conditions	ISO conditions for gas turbines	ISO conditions for compression ignition engines	Summer conditions IACS M28(1978)
Atmospheric pressure $p_0$	[ bar]	1	1.01325	1	1.01325
The air temperature aspirated into the turbine, $t_0$	[ °C ]	10	15	25	45
Cooling air temperature (ISO) or sea water	[ °C ]	10	15	25	32
Relative humidity, $\varphi_0$	%	60	60	30	60

## 3. The standard conditions are shown in Table 1.

The gas turbine propulsion system shall be considered for a 35000 tdw vessel, according to the diagram in *Figure 1*.

## 4. Nominal parameters of gas turbine power plants.

The propulsion system consists of a gas turbine type **GT35C**. The main parameters are:

- effective nominal power required for propulsion to drive the axial line under ISO conditions 3977-2,  $P_{en} = 17000$  [kW];
- total effective power of the gas turbine power plant (calculated),  $P_{eGT} = 51910$  [kW];
- specific energy consumption for total effective power,  $q_e = 11180$  [ $\frac{kJ}{kWh}$ ];
- compressor pressure ratio  $\pi = \frac{p_s}{p_1} = 12.1$  ;
- air mass flow  $\dot{m}_a = 92$  [ $\frac{kg}{s}$ ] (for the other air temperature and humidity values, the values of air mass flow are in Tables 2 and 3) ;
- the exhaust gas temperature in GTPP (Gas Turbine Propulsion Plant) in the environment,  $t_{evGT} = 378$  [ °C ] ;
- nominal speed at rated power  $n_n = 3300$  [ $\frac{rot}{min}$ ];
- propeller speed  $n_p = 102$  [ $\frac{rot}{min}$ ];
- speed of the ship 17,1 [Nd].

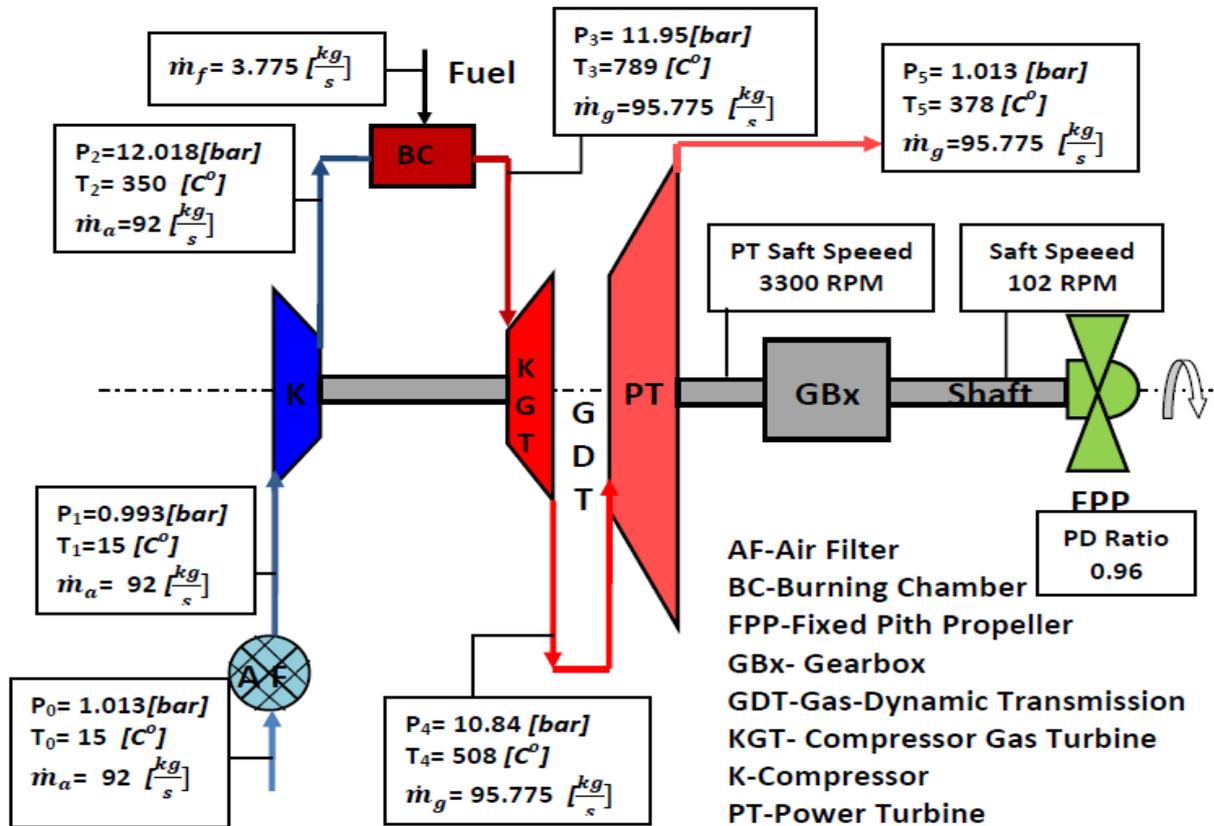


Fig. 1 – Schematic diagram of a ship propulsion system with gas turbine (Gas Turbine Propulsion Plant)

## 5. Nominal parameters of gas turbine power plants.

The propulsion system consists of a gas turbine type *GT35C*. The main parameters are:

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- total effective power of the gas turbine power plant (calculated),  $P_{eGT} = 51910 \text{ [kW]}$ ;
- specific energy consumption for total effective power,  $q_e = 11180 \text{ [} \frac{\text{kJ}}{\text{kWh}} \text{]}$ ;
- compressor pressure ratio  $\pi = \frac{p_s}{p_1} = 12.1$  ;
- air mass flow  $\dot{m}_a = 92 \text{ [} \frac{\text{kg}}{\text{s}} \text{]}$  (for the other air temperature and humidity values, the values of air mass flow are in Tables 2 and 3) ;
- the exhaust gas temperature in GTPP (Gas Turbine Propulsion Plant) in the environment,  $t_{evGT} = 378 \text{ [}^\circ\text{C]}$  ;
- nominal speed at rated power  $n_n = 3300 \text{ [} \frac{\text{rot}}{\text{min}} \text{]}$ ;
- propeller speed (propulsorului)  $n_p = 102 \text{ [} \frac{\text{rot}}{\text{min}} \text{]}$ ;
- speed of the ship 17,1 [Nd].

## 6. Choosing the main parameters for the calculation.

To calculate the functional parameters for the gas turbine selected under ISO conditions, we considered the following known sizes:

- adiabatic compression exponent,  $n_k = 1.4$  ;

- air-specific heat,  $c_a = 1.011 \left[ \frac{kJ}{kg \cdot K} \right]$ ;
- the polytropic yield of the compressor takes values between 0.85 and 0.94, and it was chose ,  
 $\eta_k = 0.893$ ;
- lower calorific power values of fuel,  $Q_i = 42704 \left[ \frac{kJ}{kg} \right]$ , and the fuel reference temperature we considered the value of  $[0^{\circ}C]$ ;
- the gas generator turbine effective yield takes values between 0.88 and 0.94 and it was chose,  $\eta_{TG} = 0.89$ , and for the power turbine we consider the value  $\eta_{TP} = 0.88$  ;
- specific heat of the gases,  $c_g = 1.2 \left[ \frac{kJ}{kg \cdot grad} \right]$ ;
- the mass of air required to burn one kilogram of fuel ,  
 $m_{aT} = 14.394 \left[ \frac{kg_a}{kg_f} \right]$  ;

In Table 2, the parameter values are expressed according to the environmental conditions for the gas turbines in Table 1.

TABLE 2 – Thermal calculation at nominal operating mode of the gas turbine propulsion plant according to the model in [8]

	Parameter		Unit	Mathematical computing relation	Envir. Condition ISO TG	Notes
<b>Point 0</b>	Temperature	$T_0$	[K]	$T_0 = t_0 + 273.15$	288.15	
	Air enthalpy	$i_0$	$\left[ \frac{kJ}{kg} \right]$	$i_0 = c_a \cdot T_0$	291.32	
	Pressure	$p_0$	[bar]		1.0132	
<b>Point 1</b>	Temperature	$T_1$	[K]	$T_1 = T_0$	288.15	
	Air enthalpy	$i_1$	$\left[ \frac{kJ}{kg} \right]$	$i_1 = i_0$	291.32	
	Pressure	$p_1$	[bar]	$p_1 = p_0 - \Delta_{p0-1}$	0.993	
<b>Point 2</b>	Temperature	$T_2$	[K]	$T_2 = \frac{i_2}{c_a}$	623.335	
	Temperature	$T_{2T}$	[K]	$T_{2T} = T_1 \cdot \pi^{\frac{n_k-1}{n_k}}$	587.962	
	Specific theoretical enthalpy	$i_{2T}$	$\left[ \frac{kJ}{kg} \right]$	$i_{2T} = c_a \cdot T_{2T}$	593.93	
	Air enthalpy	$i_2$	$\left[ \frac{kJ}{kg} \right]$	$i_2 = i_1 + \frac{i_{2T} + i_1}{\eta_k}$	630.192	
	Pressure	$p_2$	[bar]	$p_2 = p_1 \cdot \pi$	12.018	
<b>Burning Chamber</b>	Specific fuel flow	$d_f$	$\left[ \frac{kg_f}{kg_a} \right]$	$d_f = \frac{c_a \cdot (T_3 - T_2)}{\eta_{CA} \cdot Q_i - c_a \cdot (T_3 - T_{ref})}$	0.011	
	Excess air coefficient	$\alpha$		$\alpha = \frac{3600 \cdot \dot{m}_a}{C_h \cdot \dot{m}_{aT}} = \frac{\dot{m}_a}{\dot{m}_{aT} \cdot \dot{m}_f}$	1.693	
<b>Point 3</b>	The temperature calculated under standard	$T_3$	[K]	$T_3 = \Delta t_{g_{KGT}} + T_5$	1052	Consid. the max. value.

	<i>ISO conditions</i>					
	Enthalpy	$i_3$	$\left[\frac{kJ}{kg_{aer}}\right]$	$i_3 = c_g \cdot T_3$	1262	
	Pressure	$p_3$	[bar]	$p_3 = p_2 - \Delta p_{2-3}$	11.948	
<b>Point 4</b>	Temperature	$T_4$	[K]	$T_4 = T_3 - \Delta t_{gKGT}$	781.65	
	Enthalpy	$i_4$	$\left[\frac{kJ}{kg_{aer}}\right]$	$i_4 = T_4 \cdot c_g$	938	
	Enthalpy	$i_{4t}$	$\left[\frac{kJ}{kg_{aer}}\right]$	$i_{4t} = \left  \frac{(i_3 - i_4)}{\eta_{GT}} - i_3 \right $	898	
	Temperature	$T_{4t}$	[K]	$T_{4t} = \frac{i_{4t}}{c_g}$	836.67	
	Pressure	$p_4$	[bar]	$p_4 = \varepsilon_{KTG} \cdot p_3$	10.84	
<b>Point 5</b>	Exhaust gas temperature	$T_5$	[K]	$t_{evg} + 273.15$	651.15	
	Enthalpy of exhaust gases	$i_5$	$\left[\frac{kJ}{kg_{aer}}\right]$	$i_5 = T_5 \cdot c_g$	781.38	
	Pressure	$p_5$	[bar]	$p_5 = p_0$	1.0132	
	The specific mechanical work consumed by the compressor	$w_K$	$\left[\frac{kJ}{kg_{aer}}\right]$	$w_K = i_2 - i_1$	338.887	
	The specific mechanical work produced by gas turbine power plant	$w_{GT}$	$\left[\frac{kJ}{kg_{aer}}\right]$	$w_{GT} = [(1 + d_{ITG}) \cdot (i_3 - i_5) - (i_2 - i_1)]$	147	
	The specific thermal power taken from Burning Chamber	$Q_{BR}$	$\left[\frac{kJ}{kg_{aer}}\right]$	$Q_{BR} = d_f \cdot Q_i \cdot \eta_{BR}$	441.45	
	Specific heat energy	$q_e$	$\left[\frac{kJ}{kWh}\right]$	$q_e = \frac{3600 \cdot \dot{m}_f \cdot Q_i}{P_{eGT}}$	11180	
	Thermal efficiency	$\eta_t$	-	$\eta_t = \frac{L_{PT}}{Q_{CA}}$	0.332	
	Actual efficiency of the power turbine	$\eta_{PT}$	-	$\eta_{ec} = \frac{P_{eITG}}{\dot{m}_c \cdot Q_i}$	0.322	
	Effective propulsion efficiency	$\eta_{PP}$	-	$\eta_{PP} = \eta_{PT} \cdot \eta_G \cdot \eta_{LA}$	0.309	
	Air Intake mass flow	$\dot{m}_a$	$\left[\frac{kg_a}{s}\right]$		92	
	Fuel mass flow	$\dot{m}_f$	$\left[\frac{kg_c}{s}\right]$	$\dot{m}_f = \frac{c_h}{3600}$	3.775	

Mass flow of gas	$\dot{m}_g$	$\left[\frac{kg}{s}\right]$	$\dot{m}_g = \dot{m}_a + \dot{m}_f$	95.775	
Fuel consumption	$C_h$	$\left[\frac{kg_c}{h}\right]$	$C_h = \frac{q_e \cdot P_{eGT}}{Q_i}$	13590	
SFC	$c_e$	$\left[\frac{kg_c}{kWh}\right]$	$c_e = \frac{q_e}{Q_i}$	0.262	
Total effective power of the gas turbine power plant	$P_{eGT}$	[kW]	$P_{eGT} = P_{en} + P_K$	51910	
The specific mechanical work produced by GT Power Plant	$w_{GTTP}$	$\left[\frac{kJ}{kg}\right]$	$w_{GTTP} = w_{GT} - w_K$	148.662	
Power compressor drive	$P_K$	[kW]	$P_K = \frac{\dot{m}_{aer} \cdot c_a \cdot (T_2 - T_1)}{\eta_K}$	34910	
Energy flow of the air to the compressor	$\dot{Q}_a$	$\left[\frac{kJ}{s}\right]$	$\dot{Q}_a = \dot{m}_a \cdot c_a \cdot (T_2 - T_1)$	31180	
The power delivered by the gases in the turbine	$Q_{gKTG}$	[kW]	$Q_{gKTG} = \frac{P_K}{\eta_{KTG}}$	42580	
Temperature variation on the power turbine	$\Delta T_{gPT}$	[K]	$\Delta T_{gPT} = \frac{P_{en} \cdot \eta_{PT}}{\dot{m}_g \cdot c_g}$	130.17	
Temperature variation on the compressor Gas Turbine	$\Delta T_{gKTG}$	[K]	$\Delta T_{gKTG} = \frac{Q_{gKTG}}{\dot{m}_g \cdot c_g}$	270.35	
Decompression ratio in the compressor drive turbine	$\epsilon_{KTG}$	-	$\epsilon_{KTG} = \frac{p_3}{p_4} = \left(\frac{T_{4t}}{T_3}\right)^{\frac{n_k-1}{n_k}}$	0.907	

## 7. Verification of functional parameters (determination of functional parameters in the factory (determinations under existing environmental conditions))

In order to verify the operation in the operating parameters for which the gas turbines have been designed, it will be checked at all the load stages that characterize the propulsion system to which they will be part, but in the environmental conditions offered by the factory location on the globe.

### a. Evolution of functional parameters depending on temperature and humidity.

As the environmental parameters (temperature, relative humidity and pressure) are subject to continuous variations, in the case of INPTG depending on the area in which the ship is sailing, cold,

temperate or tropical, winter or summer will implicitly result in variations of the turbine parameters resulting in the increase or decrease of gas turbine performance and implicitly of the whole plant. Given that ship gas turbines operate at constant altitude at sea level, the greatest influence on their performance is the variation in atmospheric air temperature.

At sea level atmospheric pressure generally has small variations in relation to turbine performance, but if there were considerable variations, it would have effects on turbine power that drops as the atmospheric pressure drops. This will calculate parameters in environmental conditions involving variations in temperature and humidity of the air, and then be determined on board the ship in areas where it is navigating.

TABLE 3 - Evolution of the Functional Parameters of the Gas Turbine Propulsion Plant according to the air intake temperature.

Parameter	Symbol	Unit	The aspirated air temperature [0C] at relative humidity of 60%						
			5	10	15	20	25	30	35
Specific air weight	$\gamma$	$\frac{kg}{m^3}$	1,269	1,244	1.221	1.198	1.176	1.154	1.131
Air Intake mass flow	$\dot{m}_{aer}$	$\frac{kg}{s}$	95.620	93.733	92.000	90.267	88.610	86.950	85.220
Thermal yield	$\eta_t$	-	0.361	0.337	0.333	0.318	0.304	0.289	0.274
Total effective power of the GT	$P_{eGT}$	[kW]	52030	51950	51910	51850	51790	51710	51580
Gas temp. variation between BC and PT output	$\Delta T_{gGT}$	[K]	376.87	388.78	400.53	412.70	425.00	437.72	451.32

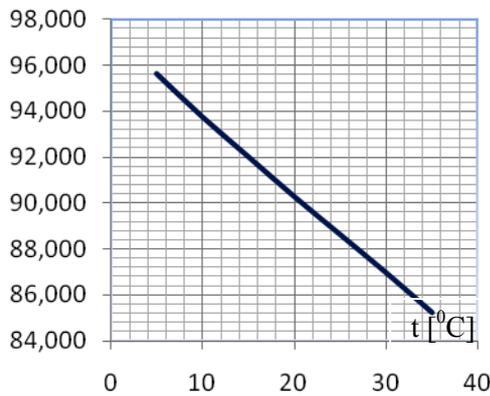


Fig.2-Evolution of  $\dot{m}_a$  [kg/s]  $\rightarrow$   $f(t_{am})$  [°C]

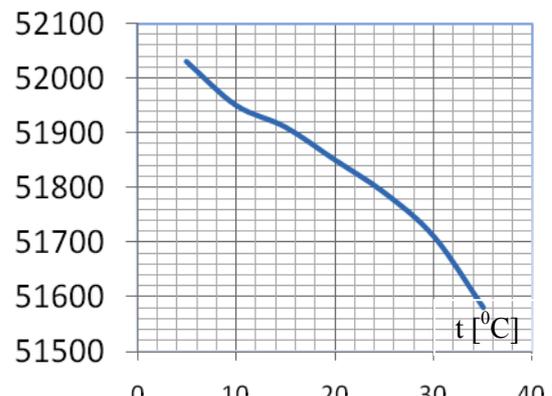
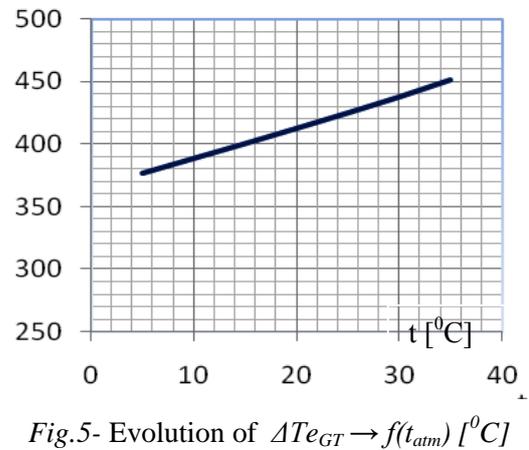
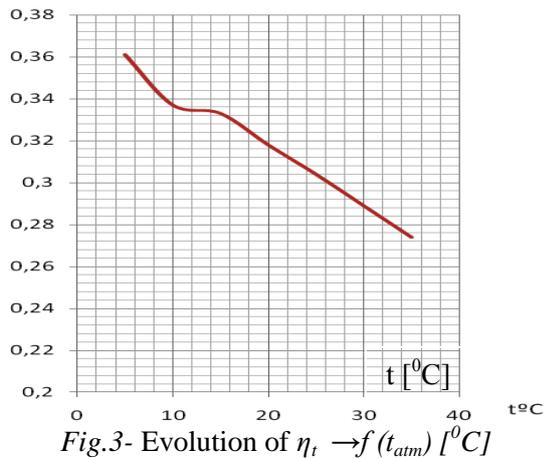


Fig.4 – Evolution of  $P_{eGT}$  [kW]  $\rightarrow$   $f(t_{am})$  [°C]



- In Figures 2, 3, 4 and 5 it can see the effect of increasing atmospheric air temperature:
- Increasing the temperature leads to lower air density resulting in a decrease in the air intake mass flow ;
  - by decreasing the air mass flow there is also a decrease in the turbine power;
  - gas turbine thermal yield decreases;
  - gases temperature rises.

According to the values calculated in Table 4, it is observed that the increase of the humidity of the atmospheric air brings about the decrease of the specific air weight and, implicitly, of the air mass flow, so that the turbine performance decreases. This can be seen in the graphs below, especially in the case of the actual power generated by the turbine.

TABLE 4 - Evolution of the Functional Parameters of the Gas Turbine Propulsion Plant according to the air intake humidity .

Parameter	Symbol	Unit	Air humidity in [%] at 15 [° C]						
			20	30	40	50	60	70	80
Specific air weight	$\gamma$	$\frac{kg}{m^3}$	1,225	1,224	1,223	1,222	1,221	1,220	1,219
Air Intake mass flow	$\dot{m}_{aer}$	$\frac{kg}{s}$	92.30	92.226	92.15	92.08	92.00	91.85	91.85
Thermal yield	$\eta_t$	-	0.334	0.333	0.333	0.333	0.332	0.332	0.332
Total effective power of the GT	$P_{eGT}$	[kW]	52030	52000	51970	51940	51910	51880	51850
Gas temp. variation between BC and PT output	$\Delta T_{gGT}$	[K]	399.27	399.55	399.87	400.19	400.84	400.84	401.17

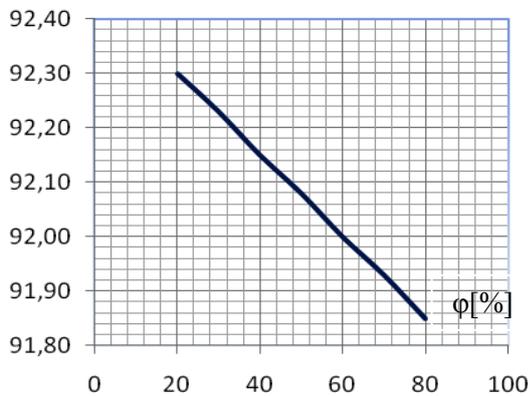


Fig. 6.- Evolution of  $\dot{m}_a$  [ $\frac{kg}{s}$ ]  $\rightarrow$   $f(\phi)$  [%]

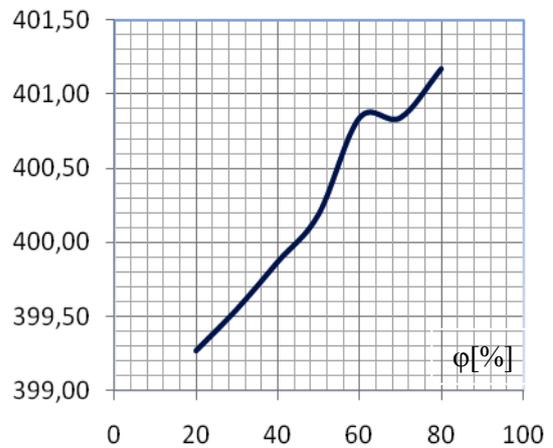


Fig. 7.- Evolution  $\Delta T_{e_{GT}}$  [K]  $\rightarrow$   $f(\phi)$  [%]

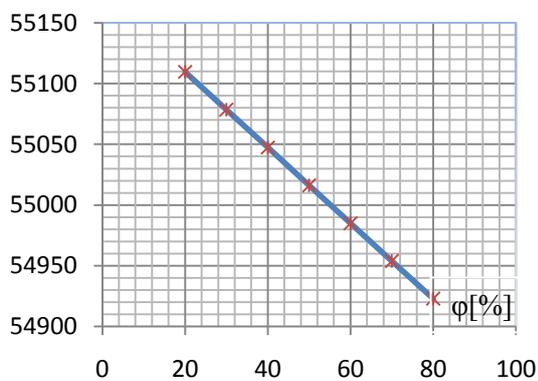


Fig. 8.- Evolution of  $P_e$  [kW]  $\rightarrow$   $f(\phi)$  [%]

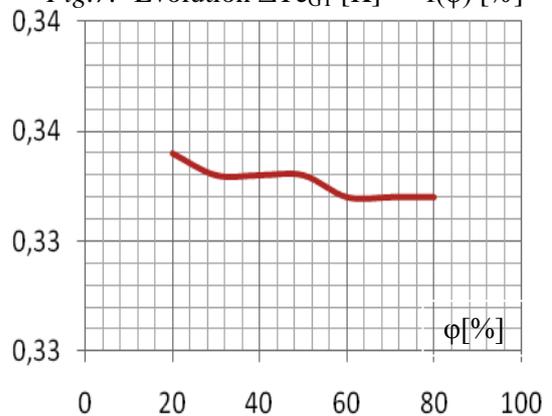


Fig. 9.- Evolution of  $\eta_t$   $\rightarrow$   $f(\phi)$  [%]

## 8. Functional parameters in transient conditions

Transient parameters occur in the start-stop operations of gas turbines and at load and speed fluctuations of the turbines.

### a. Functional start-up parameters (safe start)

The naval turbine start sequence is characterized by a rapid increase of its speed to idling speed and the temperature of the combustion gases at the inlet exhibits a speed-like increase with the difference that it has a peak rise higher than the normal value at idle speed after which it stabilizes to normal. Depending on the environmental conditions (air temperature and humidity) and fuel quality, it can reach higher values, producing the phenomenon called "Hot Start" (Figure 10a).

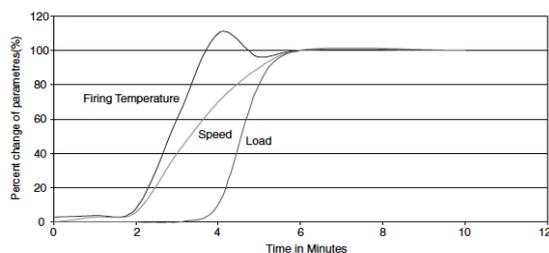


Fig. 10a.- Evolution of gas temperature, turbine speed, and charge load at start-up. [11, pg. 666]

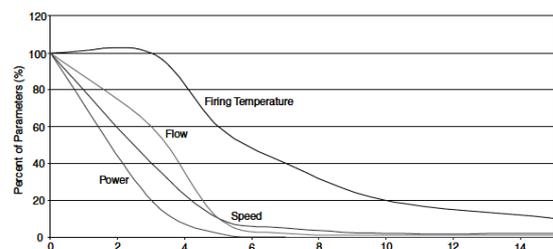


Fig. 10b.- Evolution of gas temperature, turbine speed and load at turbine shutdown. [11, pg. 671]

When the turbines are switched off in the first part of the stop sequence, a slight increase in the temperature of the combustion gases occurs as a result of the immediate decrease of the turbine speed and, implicitly, of the air compressor.

*b. Changing functional parameters; reaction time.*

In Figure 11 illustrates the evolution of the parameters measured during operation at a propulsion gas turbine at an ambient temperature of 24 [° C] and an atmospheric pressure of 1,017 bar at acceleration and deceleration relative to the load on the speed governor in percent during some sea trial we've done. The activity took place on a special ship.. It is noted that at the same percent load on the speed controller, the deceleration parameters have higher values than acceleration, highlighting the higher reaction velocity on the turbine acceleration.

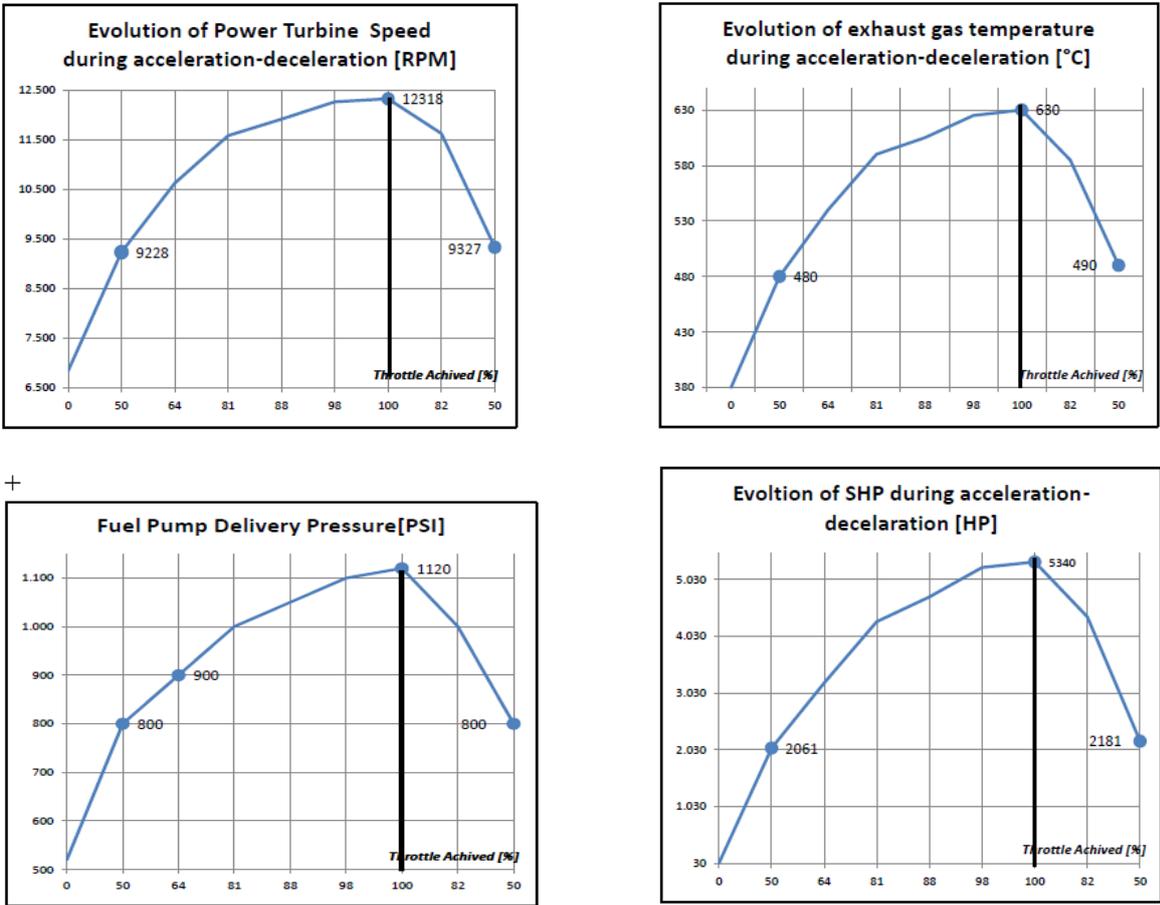


Fig.12.- Evolution of the GT functional parameters in the acceleration-deceleration propulsion system (the author<sup>1</sup> also participated in the measurement of the parameters as a crew member.)

A similar study vis-à-vis the hazardous emissions from combustion gases, according to the evolution of functional parameters of gas turbines in the naval power plants, was presented in the bibliography [13].

**Conclusions**

Shipping takes place throughout the year in all areas of navigation. The marine environment provides complex conditions for the operation of gas turbine installations.

Changes in water and air temperature, as well as its humidity, affect the performance of gas turbines as follows:

- increasing the air intake temperature reduces the suction flow, which leads to the increase of the exhaust gas temperature and the decrease of the turbine performance;
- the increase in air humidity leads to a decrease in the specific weight of the air.

In areas with hot climates and increased humidity, the starting sequence is considerably influenced by overheating of the combustion gases resulting in the so-called "hot start" phenomenon.

For the operational safety, the tendency of the variation of the functional parameters to the changes in the ambient conditions must be known.

From the experimental determinations presented in the paper was determined the tendency of variation of each main functional parameter.

From the calculation presented for a gas turbine propulsion system the same trend of variation of the main functional parameters was revealed.

The present study allows shipboard personnel to adjust the functional parameters to maintain the safety of the gas turbine propulsion system for all environmental conditions.

The study allows for the designing and realization of automation installations for monitoring, alarming and protection of the gas turbine propulsion system, as well as monitoring from at least two remote control stations (Ship Control Center and Command Deck of the Ship).

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