The naval main engines parameters variation, due different external factors

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Abstract: In this paper, we carried out a real and simulated study, regarding the naval main engines parameters variation on different external factors. The ships, was in normal operation mode, at various around the globe points, so different environmental external conditions. It is worth mentioning that such studies help us to better understand the operating processes of naval propulsion engines, under different environmental conditions. We can also draw conclusions on how to improve the operating mode of these types of engines. Such tests cannot be carried out in the factory condition, only in operation mode with the ship under way. In particular, the studied parameters of the engines were: average effective pressure, average effective power and maximum combustion pressure. As external factors that have been taken into account I mention: ambient temperature, sea water temperature, supercharger pressure.

The study was conducted on two known types of naval propulsion engines. The first most common is the MAN B&W 6S35MC-MK7, in this case being a propulsion engine for a tanker. The second type of naval propulsion engine is in a reefer container ship, the engine being a Sultzer 9RND-90M. The experimental or simulated determinations carried out on board the ships, were made using the existing specific reading devices. Using data obtained by direct reading or performed countless thermal calculations for each engine. There followed the interpretation of the final data obtained, many being presented graphically. The final conclusions were followed, which led to a more efficient operation by regulating certain operating parameters, such as the temperature of the supercharger air under different atmospheric weather conditions.

1. Introduction

Propulsion of the vast majority of modern merchant ships, are utilize as propeller prime mover the Marine Diesel Engines. This propulsion plants, include usually a single slow speed, long stroke and large cylinder diameter, large power engines. Engines are characterized by a good operational reliability due to its conceptual simplicity. Today the Diesel engines dominate the marine propulsion systems. The major reasons are: the good thermal efficiency, can use heavy fuel oil because of the supplementary cylinder alkaline oil lubrication system, slow revolution (RPM) engines what can directly connected to the propeller. This slow speed - two stroke diesel engines can burn very low quality fuel whit low price, more easily than medium-speed diesel engines. The powerful two stroke main engines are built in arrangements whit 5 to 16 cylinders according whit ship power wanted. Always the engines are turbocharged, usually a constant pressure system. Engine control system should act in a manner to give a safe propulsion operation near to (MCR) Maximum Continuous Rating under different conditions what can induce significant propeller load fluctuation. Such
situations can occur under a variety of ship operating conditions, but most common are: heavy weather, rough sea, and other critical condition of the environment. For good results the engine propulsion control system must be improved with new created additional equipment, but for that is need more and more research, observation on real ship operating condition. How much more collected data are available for builders and researchers, much better the systems will be improved. All of works give as benefits regarding efficiency, installation viability and design, capabilities of control system, design the new robust controllers, safety operation and new rules, and so on. [1, 2]

We have followed in this paper, conducting a research either through experiments or through simulations, so that we can collect as much data about the behaviour of the propulsion engine in different conditions. For example: environments, sea cooling water temperature, influence of supercharge pressure.

Also we have considered, based on the data obtained, the highlighting, improvement and application in the operation of the supercharged naval engines, of some qualitative analysis procedures in the various operating conditions existing on board the ships.

Our desire was to design and realize some operating variants that would ensure an improvement of the technical and economic performances, as well as highlighting the possibilities of optimizing the activity of the operating personnel, in order to adapt the engine's operation to the concrete operating conditions.

2. Thermal and parameters calculation of the two engines used in experiments

In order to simulate the behavior of the engines used in experiment, we performed the thermal and parameters calculation of main engines used in our ships determinations – the one is the SULZER 9RND 90M and other is MAN B&W 6S35MC-MK7 engines.

To establish concrete solutions to improve the functioning of the engine, I initially performed the thermal calculations for the two engines, which allowed me to determine by calculation the values of the main parameters indicated, effective and constructive of the engines.

These values are extremely close to those obtained by the measurements made. The engine type SULZER 9RND90M on reefer container ship world-wide, and MAN B&W 6S35MC-MK7 type on world-wide chemical tanker ship.

Thermal and parameters calculations were performed according to the data included in the calculation algorithm from references [3-7]. Thermal calculations were performed under an average ambient temperature (300 K), corresponding to most voyages conducted during the series of experimental determinations. Also, as all determinations were made during voyages, under the conditions of heavy fuel oil consumption, the calculations of the two engines are performed for operation with this type of fuel. In order to perform the calculations, according to the data included we adopted and used the initial calculation parameters included in table 1. [7-9]

| Parameter                              | MANB & W 6S35MC-MK7 | SULZER 9RND90M | Symbol | M.U |
|----------------------------------------|---------------------|----------------|--------|-----|
| Effective power (required to be insured) | 4440               | 19197          | \( P_e \) | kW  |
| Number of operating cycle times        | 2                   | 2              | \( \tau \) | -   |
| speed                                  | 173                 | 122            | \( N \) | rot/min |
| Number of cylinders                    | 6                   | 9              | \( I \) | -   |
| Percent composition of fuel:           |                     |                |        |     |
| • carbon                               | 87.9                | 87.9           | \( C \) | %   |
| • hydrogen                             | 7                   | 7              | \( H \) | %   |
| • sulfur                               | 3                   | 3              | \( S \) | %   |
| • oxygen                               | 0.6                 | 0.6            | \( O \) | %   |
| • water                                | 0.85                | 0.85           | \( W \) | %   |
Lower calorific power of fuel 37142 kg
Environmental pressure 101325 101325 Pa
Ambient temperature 300 300 K
Supply pressure 310000 250000 Pa
The intake pressure drop coefficient 0.92 0.92
Waste gas temperature (estimated value) 879 795 K
Air heating in contact with the engine 5 7.5 ∆T K
Intermediate cooling of overfill air 100 60 ∆T inc K
Coefficient of excess air 1.7 2 α -
Coefficient of residual flue gases 0.02 0.02 γl -
Coefficients of heat use:
• at constant volume
  0.87 0.8  εo -
• at constant pressure
  0.75 0.7  εp -
The coefficient of rounding of the indicated diagram 0.98 0.98 φ -
Useful stroke coefficient 0.84 0.84 ψu -
Mechanical yield 0.917 0.852 ηm -
Compression ratio 13 12.5 ε -
Coefficient of Compactness (R / L ratio) 0.25 0.25 λd -
Race / bore ratio 4 1.7222222 ψd -
Injection feed angle 11 12 β ⁰RAC
Correction angle for combustion duration 0 0 ⁰RAC
The poly tropic exponent of the 1.6 1.65 ns -

On the basis of these data, the thermal calculation was performed in the sequence presented in the mentioned bibliographic works:
• Calculation of the intake process;
• Calculating the compression process;
• Calculation of the burning process;
• Calculation of the iso-burning process;
• Calculation of the detente process;
• Determination of the indicated, effective and constructive parameters.

The calculation relationship and results obtained are presented centrally in Table 2.

Table 2. Thermal calculation for our main engines type. [7]

| Parameter | MANB&W 6S35MC-MK7 | SULZER 9RND90M | M.U. | Calculation relationship |
|-----------|-------------------|----------------|------|--------------------------|
| The amount of oxygen required to burn one kilogram of fuel, \( O_2 \) | 0.0915 | 0.0915 | kmoli | \( O_2 = \left( \frac{c}{12} + \frac{h}{4} + \frac{2 - a}{32} \right) \times \frac{1}{100} \) |
| The amount of air required to burn one kilogram of fuel, \( L_1 \) | 0.4357143 | 0.4357143 | kmoli | \( L_1 \frac{O_2}{0.21} \) |
Gas quantities resulting from burning one kilogram of fuel, L

- carbon dioxide, $v_{CO_2}$
  
  - water vapors, $v_{H_2O}$
  
  - sulfur dioxide, $v_{SO_2}$
  
  - oxygen, $v_{O_2}$
  
  - nitrogen, $v_{N_2}$
  
  - total quantity, $v_{g.a}$

Flue gas quantities:

- carbon dioxide, $v_{rCO_2}$
  
  - water vapors, $v_{rH_2O}$
  
  - sulfur dioxide, $v_{rSO_2}$
  
  - oxygen, $v_{rO_2}$
  
  - nitrogen, $v_{rN_2}$
  
  - total quantity, $v_{rN_2}$

Engine fluid mass at the end of intake, $m_{int’a}$:

- enthalpy, $l_{int’a}$
- pressure, $p_a$
- volume, $V_a$
- temperature, $T_a$

The characteristic constant of the engine fluid at the end of the intake, $R_{int’a}$:

Air temperature at the outlet of the blower, $T_s$

Intake air temperature, $T_a$

The fill coefficient, $\lambda_v$

Engine Fluid Parameters at Inlet End:

- enthalpy, $l_{int’a}$
- pressure, $p_a$
- volume, $V_a$
- temperature, $T_a$

Compression process
Coefficients of specific molar average heat of the engine fluid
\( a_{am}\Delta h_{am} \)

\[
\begin{align*}
20.08144 & \quad 20.07853 \\
2.58447 \times 10^{-3} & \quad 2.582198 \times 10^{-3}
\end{align*}
\]

The mean polytrophic exponent of compression, \( n_c \)

\[
1.3613849 & \quad 1.3603698 \\
2.58447 \times 10^{-3} & \quad 2.582198 \times 10^{-3}
\]

Motor fluid parameters at the end of compression:

- Pressure, \( p_c \)
  
  \[
  9.368179 \times 10^6 & \quad 7.14383 \times 10^6 \\
  0.6296239 & \quad 0.9872504 \\
  938.53179 & \quad 953.9408
\]

- Temperature, \( T_c \)

\[
895.8248 & \quad 905.18167
\]

Engine Fluid Parameters at Start of Injection:

- Pressure, \( p_{inj} \)
  
  \[
  7.860705 \times 10^5 & \quad 5.860259 \times 10^6 \\
  0.7162242 & \quad 1.1419732 \\
  895.8248 & \quad 905.18167
\]

- Temperature, \( T_{inj} \)

\[
2.746557 \times 10^{-3} & \quad 3.007868 \times 10^{-3} \\
2.850926 & \quad 2.2017597 \\
0.2627358 & \quad 0.1550343
\]

- Angle of rotation corresponding to the self-ignition delay, \( \theta_s \)
  
  \[
  10.850926 & \quad 14.2017597 \\
  0.2627358 & \quad 0.1550343
\]

- Angle of rotation corresponding to the total duration of combustion, \( \theta \)

\[
\frac{\theta_s}{\theta} = \frac{\theta_s + \beta + \zeta_0}{\theta}
\]

- Fumes of combustion gases:

- Carbon dioxide, \( v_{vCO_2} \)
  
  \[
  1.924523 \times 10^{-2} & \quad 1.13563 \times 10^{-2} \\
  0.2627358 & \quad 0.1550343
\]

- Water vapors, \( v_{vH_2O} \)
  
  \[
  9.319739 \times 10^{-3} & \quad 5.49909 \times 10^{-3} \\
  0.2627358 & \quad 0.1550343
\]
• Sulf dioxide, \( v_{SO_2} \)
  \[ 2.463126 \times 10^{-4} \] \[ 1.45345 \times 10^{-4} \] kmoli

• Oxygen, \( v_{O_2} \)
  \[ 0.1315099 \] \[ 0.1688144 \] kmoli

• Nitrogen, \( v_{N_2} \)
  \[ 0.5851643 \] \[ 0.6884286 \] kmoli

• Total quantity, \( v_{g.a.} \)
  \[ 0.7454855 \] \[ 0.874244 \] kmoli

Quantities of fired gases at the end of the isocorous combustion:

• Carbon dioxide, \( v'_{CO_2} \)
  \[ 2.071023 \times 10^{-2} \] \[ 1.28213 \times 10^{-2} \] kmoli

Water vapors, \( v'_{H_2O} \)
  \[ 1.002918 \times 10^{-2} \] \[ 6.20885 \times 10^{-3} \] kmoli

• Sulf dioxide, \( v'_{SO_2} \)
  \[ 2.650626 \times 10^{-4} \] \[ 1.64095 \times 10^{-4} \] kmoli

• Oxygen, \( v'_{O_2} \)
  \[ 0.1327909 \] \[ 0.1706444 \] kmoli

• Nitrogen, \( v'_{N_2} \)
  \[ 0.5968676 \] \[ 0.7021971 \] kmoli

• Total quantity, \( v'_{g.a.} \)
  \[ 0.760663 \] \[ 0.8920358 \] kmoli

The mass of the engine fluid at the end of the isocorous combustion,
  \[ 22.07855 \] \[ 25.81797 \] kg

The characteristic constant of the engine fluid at the end of the isoceoral combustion,
  \[ 286.4491 \] \[ 287.2671 \] J/kg.grd

The internal energy of the engine fluid at the end of the compression,
  \[ 15879.9 \] \[ 18819.11 \] kJ

The internal energy of the engine fluid at the end of the isocorous combustion,
  \[ 24369.75 \] \[ 23425.74 \] kJ

Engine fluid parameters at the end of isochroous combustion:

• Pressure, \( p_y \)
  \[ 1.370049 \times 10^7 \] \[ 8.686893 \times 10^6 \] Pa

• Volume, \( V_y \)
  \[ 0.629624 \] \[ 0.9872504 \] m³

• Temperature, \( T_y \)
  \[ 1363.953 \] \[ 1156.336 \] K

The pressure increase ratio, \( \lambda_p \)
  \[ 1.46243 \] \[ 1.215999 \] –

Isobar burning process

The amount of isobar burn (for one kilogram of fuel per cycle), \( g_p \)
  \[ 0.7372642 \] \[ 0.8449657 \] kg
Fumes of gas burned at the end of the burning of isobar:

- carbon dioxide, $v_{CO_2}$: $7.4715 \cdot 10^{-2}$ kmoli
- Water vapors, $v_{H_2O}$: $3.61817 \cdot 10^{-2}$ kmoli
- Sulfur dioxide, $v_{SO_2}$: $9.5625 \cdot 10^{-4}$ kmoli
- oxygen, $v_{O_2}$: $0.065331$ kmoli
- nitrogen, $v_{N_2}$: $0.5968676$ kmoli
- total quantity, $v_{g.a.}$: $0.7740515$ kmoli

The mass of the engine fluid at the end of the burning isobar, $z$amm: $22.812058$ kg

The characteristic constant of the engine fluid at the end of the burning isobar, $z$amR: $282.11954$ J/kg

The enthalpy of the engine fluid at the end of the isochoric combustion, $z$amI: $34796.63$ kJ

The motor fluid enthalpy at the end of the flame, $z$amI: $55334.3$ kJ

Engine Fluid Parameters at End of Flame Harvest:

- Pressure, $p_z$: $1.370049 \cdot 10^7$ Pa
- volume, $V_z$: $0.9650249$ m$^3$
- temperature, $T_z$: $2054.362$ K

The pre-release report, $\rho$: $1.5327$ kg/m$^3$

Coefficients of specific molar average heat of the engine fluid ($a_{am}$, $b_{am}$):

- $a_{am}$: $23.267379$ kJ/(kmol·K)
- $b_{am}$: $2.047901 \cdot 10^{-3}$ kJ/(kmol·K$^2$)

Motor Fluid Parameters at the End of Delay:

- Pressure, $p_b$: $8.866532 \cdot 10^5$ Pa
- volume, $V_b$: $8.185111$ m$^3$
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\[ T_b = T_i \left( \frac{V_i}{V_z} \right)^{n_z-1} \]

\[ \delta = \frac{V_i}{V_z} \]

\[ \sigma = \frac{p_i}{p_a} \]

\[ T' = T_i \left( \frac{p_a}{p_v} \right)^{n_z-1} \]

\[ \Delta T' = \frac{V_i - V_z}{T_i} \]

**Determination of indicated, effective and constructive parameters:**

- The indicated mechanical work developed in a cylinder in the operating cycle with one kilogram of fuel, \( L_i \):
  \[ L_i = p_i (V_z - V_y) + \frac{p_i V_y - p_i V_v}{n_d-1} + \frac{p_i V_d - p_i V_z}{n_e-1} \]

- The average pressure indicated, \( p_i \):
  \[ p_i = \frac{\psi L_i}{V_y} \]

- The indicated yield, \( \eta_i \):
  \[ \eta_i = \frac{\delta T_i}{p_i} \]

- The specific consumption indicated by the fuel, \( c_i \):
  \[ c_i = \frac{3600}{\eta_i} \]

- Average effective pressure, \( p_e \):
  \[ p_e = \frac{\eta_m \cdot p_i}{p_i} \]

- The actual yield, \( \eta_e \):
  \[ \eta_e = \frac{c_i}{\eta_m} \]

- Specific fuel consumption, \( c_e \):
  \[ c_e = \frac{c_i}{\eta_m} \]

- The required mechanical work required to develop the required power, \( L_{ic} \):
  \[ L_{ic} = \frac{279877.21 \cdot 123124 \cdot 10^{-6}}{(28539.59) \cdot (1.25552 \cdot 10^{3})} \text{ (kgf} \cdot \text{m)} \]

- The coefficient of similarity, \( K \):
  \[ K = \frac{L_{ic}}{q_e \cdot L_i} \]

- The actual volumes occupied by the engine fluid at the characteristic points:
  - points "a" and "b":
    \[ V_a = V_b = k \cdot V_z \]
  - points "c" and "y":
    \[ V_c = V_y = k \cdot V_z \]
  - the "z":
    \[ V_z = k \cdot V_z \]

- The indicated mechanical work developed in a cylinder, \( L_i \):
  \[ L_i = \frac{p_i V_z - p_i V_y}{n_d-1} + \frac{p_i V_d - p_i V_z}{n_e-1} \]
The diameter of the cylinder, \( D \)

\[
D = 10^{3.3} \sqrt{\frac{4 (V_a - V_c)}{\pi \cdot \psi_d}}
\]

\[
\Delta D = \left| \frac{D_{(calculated)} - D}{D} \right| \times 100
\]

The cylinder diameter, \( \Delta D \)

\[
\Delta D = 6.1 \cdot 10^{-2} \quad 8.1 \cdot 10^{-3} \quad \%
\]

The piston stroke, \( S \)

\[
S = \psi_d \cdot D
\]

The useful stroke of the piston, \( S_u \)

\[
S_u = \psi_u \cdot S
\]

Crank Radius, \( R \)

\[
R = \frac{S}{2}
\]

The length of the whip, \( L \)

\[
L = R \cdot \psi_d
\]

Average piston speed, \( v_{mp} \)

\[
v_{mp} = 10^{-3} \cdot \frac{S \cdot n}{30}
\]

Angular rotation speed of the crankshaft, \( \omega \)

\[
\omega = \frac{\pi \cdot n}{30}
\]

The unitary cylinder, \( V_v \)

\[
V_v = 10^{-6} \cdot \frac{\pi D^2 S}{4}
\]

Total Cylinder, \( V_t \)

\[
V_t = i \cdot V_v
\]

Effective power, \( P_e \)

\[
P_e = \frac{p_c \cdot \pi \cdot D^3 \cdot S \cdot i \cdot n}{12 \cdot 10^{13} \cdot \gamma}
\]

Actual Power Determination Error

\[
\Delta P_e = \frac{|P_e - P_1|}{P_\infty} \times 100
\]

Power on the cylinder, \( P_{cil} \)

\[
P_{cil} = P_{cil} \cdot i
\]

Taking advantage of these calculations, we analyzed further the influences exerted on the operation of the engines by the following two categories of parameters:

- the temperature of the environment and the temperature of the sea water;
- ambient temperature and supercharge pressure.

Following the same calculation algorithm, and using the on-board measuring devices, we were able to follow the real evolution of the main operating parameters. We were also able to perform various series of experiments and trials. Some of these are included in this paper.

3. Simulation

3.1 Simulation of influences by environmental and sea water temperatures

In order to highlight the influences exerted by the ambient temperature and the sea water temperature on the operation of the two propulsion engines, we have performed several times their thermal calculation, using the same algorithm presented. For this purpose, we considered several values of the ambient temperature, located in the range \( T_0 = 290 \ldots 330^\circ K \), which corresponds to most situations in which the experimental determinations were performed. In terms of seawater temperature, it primarily influences the intermediate cooling of the supercharging air, considering the range \( \Delta T_{sec} = 20 \ldots 100^\circ K \).

The purpose of the calculations performed was to determine the average effective pressure of the operating cycle, the obtained values being included in tables 3 and 4. Based on them, in the figures 1 and 2 the graphs of variation of this parameter have been drawn for our two engines used in the experimental determinations.
Table 3. Effective average pressure values based on ambient temperature and intermediate cooling of the supercharger air at the SULZER9RND90M engine.[7]

| Ambient temperature $T_a$ [K] | Effective average pressure $p_e$ [Pa] | $\Delta T_{Trac} = 20$ K | $\Delta T_{Trac} = 40$ K | $\Delta T_{Trac} = 60$ K | $\Delta T_{Trac} = 80$ K | $\Delta T_{Trac} = 100$ K |
|-------------------------------|--------------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 290                           | 0.996865·10^6                       | 1.047845·10^6           | 1.105636·10^6           | 1.171742·10^6           | 1.247745·10^6           |
| 300                           | 0.9639271·10^6                      | 1.010746·10^6           | 1.06358·10^6            | 1.123522·10^6           | 1.192375·10^6           |
| 310                           | 0.936782·10^6                       | 0.9768166·10^6          | 1.025278·10^6           | 1.079974·10^6           | 1.142235·10^6           |
| 320                           | 0.9053203·10^6                      | 0.9455378·10^6          | 0.9901553·10^6          | 1.040295·10^6           | 1.097035·10^6           |
| 330                           | 0.880189·10^6                       | 0.916683·10^6           | 0.957677·10^6           | 1.00383·10^6            | 1.055722·10^6           |

Table 4. Effective average pressure values based on ambient temperature and intermediate cooling of the supercharger air at the MAN B&W 6S35MC-MK7 engine.[7]

| Ambient temperature $T_a$ [K] | Average effective pressure $p_e$ [Pa] | $\Delta T_{Trac} = 20$ K | $\Delta T_{Trac} = 40$ K | $\Delta T_{Trac} = 60$ K | $\Delta T_{Trac} = 80$ K | $\Delta T_{Trac} = 100$ K |
|-------------------------------|--------------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 290                           | 1.620888·10^6                       | 1.69543·10^6            | 1.780244·10^6           | 1.876548·10^6           | 1.987159-10^6           |
| 300                           | 1.569897·10^6                       | 1.637679·10^6           | 1.714861·10^6           | 1.802412·10^6           | 1.901902·10^6           |
| 310                           | 1.526845·10^6                       | 1.586053·10^6           | 1.655281·10^6           | 1.734848·10^6           | 1.824987·10^6           |
| 320                           | 1.50329·10^6                        | 1.548723·10^6           | 1.604956·10^6           | 1.673419·10^6           | 1.755334·10^6           |
| 330                           | 1.467008·10^6                       | 1.508091·10^6           | 1.558474·10^6           | 1.619307·10^6           | 1.69219·10^6            |

Figure 1. Variations of the effective average pressure depending on the ambient temperature and the intermediate cooling of the supercharger air at the SULZER 9RND90M engine.
Figure 2. Variations of the effective average pressure depending on the ambient temperature and the intermediate cooling of the supercharger air at the MAN B&W 6S35MC- MK7 engine.

Confirming those found during the operation of the two propulsion engines, the increase of the two temperatures leads to a severe decrease of the average effective pressure, including the power developed by the engine. Thus, for example, at the maximum value $T_o = 330 \text{ K}$ and at the lowest cooling degree $\Delta T_{\text{Trac}} = 20 \text{ K}$, the average effective pressure decreases by about 17.4% for the SULZER 9RND90M engine and, respectively, about 22.9% at MAN B&W 6S35MC- MK7 engine.

The values of these percentage variations are included in tables 5 and 6, and in the figures 3 and 4 the variations calculated in each case are illustrated graphically.

### Table 5. Percentage variations of the average effective pressure ($p_e$) depending on the ambient temperature and the intermediate cooling of the supercharger air on the SULZER 9RND90M engine.

| Temperature environment $T_o$ [K] | Percentage variation of effective average pressure $\Delta p_e$ [%] |
|----------------------------------|---------------------------------------------------------------|
|                                  | $\Delta T_{\text{Trac}} = 20$ K | $\Delta T_{\text{Trac}} = 40$ K | $\Delta T_{\text{Trac}} = 60$ K | $\Delta T_{\text{Trac}} = 80$ K | $\Delta T_{\text{Trac}} = 100$ K |
| 290                              | $-6.4292821$ | $-1.6440452$ | $+3.7805061$ | $+9.9855448$ | $+17.119565$ |
| 300                              | $-9.5209976$ | $-5.1263423$ | $0$ | $+5.4593752$ | $+11.922261$ |
| 310                              | $-12.36031$ | $-8.3111249$ | $-4.0082$ | $+1.3717429$ | $+7.2158707$ |
| 320                              | $-15.022124$ | $-11.247109$ | $-7.059088$ | $-2.3527258$ | $+2.9731734$ |
| 330                              | $-17.381073$ | $-13.955564$ | $-10.107663$ | $-5.7755125$ | $-0.9046707$ |
Figure 3. Percentage variations of the average effective pressure depending on the ambient temperature and the intermediate cooling of the supercharger air at the SULZER 9RND90M engine.

Table 6. Percentage variations of the average effective pressure depending on the temperature of the environment and the intermediate cooling of the supercharger air at MAN B&W 6S35MC- MK7 engine.

| Temperature environment $T_e$ [K] | Percentage variation of effective average pressure $\Delta p_e$ [%] | $\Delta T_{nv} = 20$ K | $\Delta T_{nv} = 40$ K | $\Delta T_{nv} = 60$ K | $\Delta T_{nv} = 80$ K | $\Delta T_{nv} = 100$ K |
|-----------------------------------|---------------------------------------------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 290                               | $-14.75542$                                                  | $-10.85608$            | $-6.3966492$           | $-1.3330866$           | $+4.4827231$           |
| 300                               | $-17.456473$                                                 | $-13.892566$           | $-9.8344184$           | $-5.2310792$           | $0$                    |
| 310                               | $-19.720101$                                                 | $-16.607007$           | $-12.967072$           | $-8.783523$            | $-4.0441095$           |
| 320                               | $-20.958598$                                                 | $-18.569779$           | $-15.613107$           | $-12.013395$           | $-7.7063908$           |
| 330                               | $-22.866268$                                                 | $-20.706167$           | $-18.057082$           | $-14.858547$           | $-11.026436$           |

Figure 4. Percentage variations of the average effective pressure depending on the temperature of the environment and the intermediate cooling of the supercharger air at MAN B&W 6S35MC- MK7 engine.
3.2 Simulation of influences exerted by the environmental temperature and supercharger air pressure

In the second set of experimental determinations, we also had the opportunity to act on the supercharger. Therefore, for the MAN B&W 6S35MC-MK7 engine, we performed a new series of thermal calculations, for the same range \(T_o = 290 \ldots 330 \text{ K}\) of the ambient temperature and with several values of the supercharger pressure, located in the range \(p_s = 0.2 \ldots 0.31 \text{ MPa}\).

The obtained results are included in table 7, and in figure 5 are plotted the graphs of variation of the average effective pressure for the various supercharged pressure \(p_s\) values taken into consideration.

**Table 7.** Average effective pressure values based on ambient temperature and supercharged pressure on MAN B&W 6S35MC-MK7 engine.

| Supercharged pressure \(p_s\) [Pa] | \(T_o = 290 \text{ K}\) | \(T_o = 300 \text{ K}\) | \(T_o = 310 \text{ K}\) | \(T_o = 320 \text{ K}\) | \(T_o = 330 \text{ K}\) |
|-----------------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| 2.0 \times 10^5                  | 1.625973 \times 10^6| 1.547314 \times 10^6| 1.476236 \times 10^6| 1.411921 \times 10^6| 1.353558 \times 10^6|
| 2.1 \times 10^5                  | 1.66058 \times 10^6  | 1.580913 \times 10^6| 1.509147 \times 10^6| 1.444256 \times 10^6| 1.385381 \times 10^6|
| 2.2 \times 10^5                  | 1.694579 \times 10^6 | 1.614214 \times 10^6| 1.541733 \times 10^6| 1.476303 \times 10^6| 1.416953 \times 10^6|
| 2.3 \times 10^5                  | 1.728045 \times 10^6 | 1.647111 \times 10^6| 1.574067 \times 10^6| 1.508093 \times 10^6| 1.448428 \times 10^6|
| 2.4 \times 10^5                  | 1.761449 \times 10^6 | 1.679618 \times 10^6| 1.606141 \times 10^6| 1.539695 \times 10^6| 1.47947 \times 10^6|
| 2.5 \times 10^5                  | 1.794469 \times 10^6 | 1.712033 \times 10^6| 1.637901 \times 10^6| 1.571128 \times 10^6| 1.510338 \times 10^6|
| 2.6 \times 10^5                  | 1.826985 \times 10^6 | 1.744125 \times 10^6| 1.669553 \times 10^6| 1.602227 \times 10^6| 1.541154 \times 10^6|
| 2.7 \times 10^5                  | 1.859388 \times 10^6 | 1.776003 \times 10^6| 1.700991 \times 10^6| 1.633145 \times 10^6| 1.57168 \times 10^6|
| 2.8 \times 10^5                  | 1.891768 \times 10^6 | 1.807632 \times 10^6| 1.732256 \times 10^6| 1.663987 \times 10^6| 1.602024 \times 10^6|
| 2.9 \times 10^5                  | 1.923736 \times 10^6 | 1.839323 \times 10^6| 1.763208 \times 10^6| 1.694675 \times 10^6| 1.632198 \times 10^6|
| 3.0 \times 10^5                  | 1.955596 \times 10^6 | 1.870710 \times 10^6| 1.794127 \times 10^6| 1.725063 \times 10^6| 1.662265 \times 10^6|
| 3.1 \times 10^5                  | 1.987159 \times 10^6 | 1.901902 \times 10^6| 1.824987 \times 10^6| 1.755334 \times 10^6| 1.69219 \times 10^6|

**Figure 5.** Variations of effective average pressure depending on the ambient temperature and the supercharged pressure at the MAN B&W 6S35MC-MK7 engine.
As in the previous case, we also determined the percentage variations of the average effective pressure, the results being presented in Table 8 and graphically illustrated in Figure 6.

**Table 8.** Percentage variations of the average effective pressure depending on the ambient temperature and the supercharged pressure \( p_s \) at the MAN B&W 6S35MC-MK7 engine. [7]

| Supercharged pressure \( p_s \) [Pa] | Percentage variation of the average effective pressure \( \Delta p_e \) [%] |
|-----------------------------------|----------------------------------|
| \( T_o = 290 \text{ K} \)           | \( T_o = 300 \text{ K} \)           | \( T_o = 310 \text{ K} \)           | \( T_o = 320 \text{ K} \)           | \( T_o = 330 \text{ K} \)           |
| 2.0 \times 10^5                   | -14.508056                        | -18.643863                        | -22.381069                        | -25.762684                        | -28.831349                        |
| 2.1 \times 10^5                   | -12.688456                        | -16.877263                        | -20.650643                        | -24.062544                        | -27.158129                        |
| 2.2 \times 10^5                   | -10.900825                        | -15.126331                        | -18.937306                        | -22.377546                        | -25.498107                        |
| 2.3 \times 10^5                   | -9.1412176                        | -13.396694                        | -17.237218                        | -20.706062                        | -23.843184                        |
| 2.4 \times 10^5                   | -7.3848705                        | -11.687458                        | -15.550801                        | -19.044462                        | -22.211029                        |
| 2.5 \times 10^5                   | -5.6487138                        | -9.9831116                        | -13.880894                        | -17.391748                        | -20.588022                        |
| 2.6 \times 10^5                   | -3.9390568                        | -8.2957482                        | -12.216665                        | -15.756595                        | -18.967749                        |
| 2.7 \times 10^5                   | -2.2353413                        | -6.6196366                        | -10.563688                        | -14.130959                        | -17.362724                        |
| 2.8 \times 10^5                   | -0.532835                         | -4.9566171                        | -8.9198076                        | -12.50932                         | -15.767269                        |
| 2.9 \times 10^5                   | +1.1480087                        | -3.2903378                        | -7.2923842                        | -10.895777                        | -14.180752                        |
| 3.0 \times 10^5                   | +2.8231739                        | -1.6405682                        | -5.666958                         | -9.298008                         | -12.599861                        |
| 3.1 \times 10^5                   | +4.4827231                        | 0                                | -4.0441095                        | -7.7063908                        | -11.026436                        |

**Figure 6.** Percentage variations of the average effective pressure depending on the ambient temperature and the supercharged pressure at the MAN B & W6S35MC-MK7 engine.

Usually, for a higher air temperature at the inlet of the turbocharger, a lower boost air pressure results and vice versa: the reduced temperature leads to an increase in pressure. For example, a 5ºC increase in air temperature in the standard tropical zone, from 45ºC to 50ºC, will lead to a slight decrease in the
booster air pressure. However, this pressure drop can be compensated by the corresponding increase in the boost pressure specific to the turbocharger under ISO ambient conditions. This implies that when designing the turbocharger, the temperature of $25 + 5 = 30^\circ C$ should be taken into account when entering the supercharger, instead of the ISO temperature of $25^\circ C$.

4. Conclusions

Engines must be capable of operating normally, without restrictions, under special conditions of maximum or minimum ambient temperatures. According to IACS (International Association of Classification Societies), there is rule M28 that provides for this.

The main engines and the auxiliary engines, according to the IACS M28 rule, must operate without restrictions in these environmental conditions. Engine builders sometimes do not have the opportunity to simultaneously create these conditions at the test bench. [2, 10]

In certain situations, the ship-owners may require the manufacturer to operate the engines without restriction on conditions that are considered to be outside the standards.

Usually, for a higher air temperature when entering the turbocharger, a lower air pressure of the supercharger air results and vice versa: the reduced temperature leads to increased pressure. For example, a 5ºC rise in air temperature in the standard tropical area, from $45^\circ C$ to $50^\circ C$, will lead to some drop in the overhead air pressure.

However, this pressure drop can be compensated by the corresponding increase of the turbocharger pressure, specific to the turbocharger under ISO ambient conditions. This implies that, when designing the turbocharger, the temperature of $25 + 5 = 30^\circ C$ is taken into account when entering the supercharger, instead of the ISO temperature of $25^\circ C$.

For long-term operation in the tropical area, with high seawater temperature, a number of observations must be made. An increase in seawater temperature and, automatically, the temperature of the supercharger air cooler, implies an increase of the supercharger air temperature, which has a negative impact on the temperature in the combustion chamber.

When the ship is operating in arctic conditions, the air density will be very high and also the temperature at the turbocharger intake is quite low. This results in increased air pressure, compression pressure and maximum combustion pressure. In such conditions, to prevent these excessive pressures, the air temperature at the turbocharger inlet must somehow be maintained at a higher value than that of the environment, possibly by preheating it, if this is possible. Furthermore, the temperature of the supercharger air coolant should be kept as low as possible to reduce the pressure of the supercharger air. The power of the running engine must also be reduced. For an atmospheric air temperature below about -10° C, the recommended precautions depend very much on the current operating profile of the ship. [11-15]

The complexity of the thematic approach, as well as the relatively small possibilities of carrying out the experimental determinations and the verification of the optimization solutions proposed, mean that the present paper does not completely cover the thematic approach, offering to the specialists in the field new directions of research, such as:

- studying the thermal regime of the naval propulsion engines under various operating conditions and determining the characteristic parameters;
- studying the influences exerted by other external operating conditions, such as wind force and direction, sea state, ship loading degree, etc.;
- creation of a database and generalization of the positive experience gained in the operation of supercharged naval diesel engines. [7]

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