Analysis of piston applications due to fuel burning

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Abstract. The paper aims to analyze the demands of four-stroke naval pistons. To begin with, a brief analysis of the evolution of shipbuilding was made. Mechanical requests are produced by the gas pressure force and inertial force of the alternate moving masses. Under its action, the piston suffers an axial deformation. The thermal demands appearing in the engine are all the more important as the engine power is higher. The possibility of calculating them is more difficult due to the complexity of the thermogazodinamic phenomena in the engine cylinder. Thus, in the piston head, which comes in contact with both the hot gases and the fresh (much cooler) load, a non-stationary heat flow is installed which leads to a certain thermal regime of the engine. Considering the demands outlined in the last chapter, they lead to the conclusion that although the most unfavourable loading situation was considered as the maximum pressure during the processes and even exaggerated in establishing the working conditions, the piston is still close to the elastic limit. This demonstrates that the way of calculating the dimensions of the piston is correct and safe, as long as its constructive dimensions are not oversized.

1. Introduction

A piston is a machine member, which has an alternating rectilinear motion in a cylinder and serves to close a variable volume space of the cylinder, filled with air, fuel mixture or a pressure fluid. The piston is used to convert the internal energy into mechanical work on the motor cars, or vice versa, on the generating machines. In the first case, the piston is driven by internal energy, and in the second it acts on air or fluid (compressor, hydraulic motor). Usually, the piston is coupled to a crank-crankshaft mechanism, which transforms the rectilinear movement into circular motion (to engines) and vice versa (to pumps). The piston is used as a constructive element also in the production of piston pumps, which resembles the principle of operation with compressors. The pistons are made mainly of cast iron or light metal alloys, which have stable heating properties. In thermal machines where the distribution is made through windows, the piston also has the function to open or close them. To draw the indicated diagram of the operating cycle, it is necessary to determine the compression and release curves. [1] To perform the simulation of the piston is performed in the Ansys simulation program the following steps:

• realization of the piston geometry
• realization of the discretized structure of the piston
• simulation of forces on the piston.

2. Engine characteristics

Principle characteristics of 20000 dwt tanker ship are described in table 1.
3. Thermal calculation

Thermal calculation of naval diesel engines aims at determining the state of the motor fluid state in its evolution during the operating cycle. With the help of these parameters, one can draw the indicated operating cycle diagram, as shown in figure 2, which can be used to determine the main engine dimensions: the indicated and effective parameters, the main engine dimensions, the power and economy of the engine, and the forces acting on the engine parts. According to the calculation method, analytical methods and graphical methods are based on thermodynamic diagrams. Thermal calculation results are shown in table 2 [2].
### Table 2. Thermal calculation results.

| Parameter                  | Note | Unite | Formulas                                                                 | Result          |
|----------------------------|------|-------|---------------------------------------------------------------------------|-----------------|
| Mechanical work            |      |       | $L'_i = p_d \cdot (V_{Z_i} - V_{V_i}) + (p_z \cdot V_z - p_b \cdot V_b)/(n_a - 1) + (p_z \cdot V_z - p_i \cdot V_i)/(n_i - 1)$ | $1.80476 \cdot 10^7$ |
| Medium indicated pressure  | $p_i$ | Pa    | $p_i = \varphi_i \cdot L'_i/(V_a - V_e) + p_a - p_e$                      | $1.8425 \cdot 10^6$ |
| Indicated efficiency       | $\eta_i$ | -     | $\eta_i = 9R \cdot L \cdot T_s \cdot p_e$                              | $0.4282$        |
| Specific fuel cons         | $c_i$ | Kg/KW·h | $c_i = 3600/\eta_i \cdot Q_i$                                            | $0.19689$       |
| Effective medium pressure  | $p_c$ | Pa    | $p_c = \eta_m \cdot p_i$                                                | $1.63988 \cdot 10^6$ |
| Effective efficiency       | $\eta_e$ | -     | $\eta_e = \eta_m \cdot \eta_i$                                          | $0.38515$       |
| Effective fuel cons        | $c_c$ | Kg/KW·h | $c_c = c_i/\eta_a$                                                       | $0.22123$       |
| Indicated work             | $L_{ic}$ | J     | $L_{ic} = 30000 \cdot p_{ic} \cdot \tau/\eta_a \cdot n_i$               | $0.12359 \cdot 10^6$ |
| Bore                       | $D$  | mm    | $D = 10^3 \cdot \sqrt[4]{4 \cdot (V_a' - V_e')} / \pi \cdot \Psi_d$       | $191.79582$     |
| Stroke                     | $S$  | mm    | $S = \Psi_d \cdot D$                                                    | $232.17389$     |
| Rod radius                 | $R$  | mm    | $R = S/2$                                                                | $116.08$        |
| Rod length                 | $L_b$ | mm    | $L_b = R/\lambda_d$                                                     | $464.34778$     |

**Figure 2.** Indicate diagram.
4. Calculation of forces acting upon the piston
In contrast to the kinematic calculation, in the dynamic calculation, it is necessary to use a range of variation of the rotation angle \( \alpha \), which represents a sub-multiple of the angular offset \( \Delta \alpha \) between the crankshaft cranks. Kinematic calculation graphs are shown in figures 3, 4 and 5 representing piston move, speed and acceleration. Also, for dynamic calculation, the values of pressure force, inertial force and total force are shown in table 3 and its graph in figures 6, 7 and 8. [3, 4]
Figure 5. Piston acceleration [m/s²].

Pressure force:

\[ F_p = \frac{\pi D^2}{4} (p - p_{\text{新媒体}}) \] [N] \hspace{1cm} (1)

| Nrc. | [°RC] | \(V_j\) [m³] | \(p\) [MPa] | \(F_p\) [kN] | \(F_{\text{fit}}\) [kN] | \(F\) [kN] |
|------|-------|--------------|-------------|-------------|----------------|-------------|
| 1    | 0     | 1.252000     | 0.1000      | 0.000       | -152.802       | -152.800    |
| 2    | 20    | 1.853788     | 0.1000      | 0.000       | -138.278       | -138.278    |
| 3    | 40    | 3.545781     | 0.1000      | 0.000       | -98.9481       | -98.948     |
| 4    | 60    | 6.020629     | 0.1000      | 0.000       | -45.8401       | -45.840     |
| 5    | 80    | 8.862391     | 0.1000      | 0.000       | 7.4903         | 7.490       |
| 6    | 100   | 11.651659    | 0.1000      | 0.000       | 49.9438        | 49.944      |
| 7    | 120   | 14.052004    | 0.1000      | 0.000       | 76.4001        | 76.400      |
| 8    | 140   | 15.850562    | 0.1000      | 0.000       | 88.3347        | 88.335      |
| 9    | 160   | 16.947835    | 0.1000      | 0.000       | 91.4578        | 91.458      |
| 10   | 180   | 17.314750    | 0.1000      | 0.000       | 91.6801        | 91.680      |
| 11   | 200   | 16.947835    | 0.1695507   | 0.637       | 91.4578        | 92.095      |
| 12   | 220   | 15.850562    | 0.1857717   | 0.786       | 88.3347        | 89.120      |
| 13   | 240   | 14.052004    | 0.2189666   | 1.090       | 76.4001        | 77.490      |
| 14   | 260   | 11.651659    | 0.2827622   | 1.674       | 49.9438        | 51.618      |
| 15   | 280   | 8.862391     | 0.4108030   | 2.847       | 7.4903         | 10.337      |
| 16   | 300   | 6.020629     | 0.6963530   | 5.463       | -45.8401       | -40.377     |
| 17   | 320   | 3.545781     | 1.4344446   | 12.225      | -98.9481       | -86.723     |
| 18   | 340   | 1.853788     | 3.4764714   | 30.931      | -138.2785      | -107.347    |
|    |     |           |           |           |           |
|----|-----|-----------|-----------|-----------|-----------|
| 19 | 360 | 1.252000  | 5.9403311 | 53.503    | -152.8002 | -99.298   |
| 20 | 380 | 1.853788  | 9.1470340 | 82.879    | -138.2785 | -55.400   |
| 21 | 400 | 3.545781  | 3.9648884 | 35.406    | -98.9481  | -63.542   |
| 22 | 420 | 6.020629  | 2.0037857 | 17.440    | -45.8401  | -28.400   |
| 23 | 440 | 8.862391  | 1.2173529 | 10.236    | 7.4903    | 17.726    |
| 24 | 460 | 11.651659 | 0.8555312 | 6.921     | 49.9438   | 56.865    |
| 25 | 480 | 14.052004 | 0.6720089 | 5.240     | 76.4001   | 81.640    |
| 26 | 500 | 15.850562 | 0.5753764 | 4.355     | 88.3347   | 92.690    |
| 27 | 520 | 16.947835 | 0.5278146 | 3.919     | 91.4578   | 95.377    |
| 28 | 540 | 17.314750 | 0.5134417 | 3.787     | 91.6801   | 95.468    |
| 29 | 560 | 16.947835 | 0.1000000 | 0.000     | 91.4578   | 91.458    |
| 30 | 580 | 15.850562 | 0.1000000 | 0.000     | 88.3347   | 88.335    |
| 31 | 600 | 14.052004 | 0.1000000 | 0.000     | 76.4001   | 76.400    |
| 32 | 620 | 11.651659 | 0.1000000 | 0.000     | 49.9438   | 49.944    |
| 33 | 640 | 8.862391  | 0.1000000 | 0.000     | 7.4903    | 7.490     |
| 34 | 660 | 6.020629  | 0.1000000 | 0.000     | -45.8401  | -45.840   |
| 35 | 680 | 3.545781  | 0.1000000 | 0.000     | -98.9481  | -98.948   |
| 36 | 700 | 1.853788  | 0.1000000 | 0.000     | -138.2785 | -138.278  |
| 37 | 720 | 1.252000  | 0.1000000 | 0.000     | -152.8002 | -152.800  |

**Figure 6.** Forces diagram.
5. Ansys simulation

With the Ansys software, simulation of operation under the conditions of gas discharge will be made to facilitate calculation. Enhancement with finite elements has to go through the following steps:

- defining the structure, its geometrical and elastic characteristics, the applied loads and the bearing conditions;
- schematic how the structure takes over the applied loads: membrane, beam slab, etc.
individualization of local deviations of the structure, such as additional stiffening, cutting and consolidation of the area;

- the choice of finite element types, from the program library, for modelling the structure, taking into account the deformation modes or the stresses that arise in the elements;

- meshing the structure into finite elements, taking into account: the geometrical dimensions of the structure, the elastic characteristics of the material, the edge conditions, the loads and the displacements imposed on the materials;

- checking input data for compatibility and accuracy;

- running the calculation program;

- verification of the obtained results [5, 6]

Figure 9. Mesh.

Realization of the section of the model in real size by drawing the figure below taking into account the dimensions calculated in the previous chapter. Special attention should be paid to closing the contour between points. Making the model using the function revolvers, and then validating with generated the model will be realized.

Figure 10. Cylindrical support.

Realization of the discretized structure of the model using the mesh generated function as shown in figure 9. For a surface finish, the refinement function will be used on several surfaces of the valve for
a finer division of the body. To simulate the forces acting on the piston as best as possible, in the Ansys program I attached cylindrical support to the piston, shown in figure 10 and the gas pressure force normally presses on it, shown in figure 11 and calculated in equation (1).

![Figure 11. Pressure.](image)

![Figure 12. Deformations.](image)

![Figure 13. Equivalent elastic stain.](image)
6. Conclusions
Following the analysis of the calculation and the demands of the engine mechanism for the Daihatsu naval engine, we obtained the following results with the Ansys simulation program as follows:

- maximum total deformations: \(3.9 \times 10^{-5}\) mm, shown in figure 12;
- maximum elastic equivalent stain: 0.00039 mm/mm, shown in figure 13. [7]

All the above, lead to the conclusion that, although it was considered the most unfavourable loading situation, even exaggerated in establishing the forces and moments, the piston is still close to the elasticity limit. This shows that the calculation model of the piston is a correct one, and safe, as long as the dimensions of the piston are not oversized. The piston head is required both mechanically due to the pressure of the motor fluid and thermal due to the temperature differences between the regions of the piston head. In order to determine the mechanical demands, the piston head is considered a continuous circular plate embedded on the contour in the connection region (segment port). As a result of the action of the pressure of the motor fluid in the head of the piston unitary efforts appear that act both on the radial and tangential directions. These values vary continuously in the piston head, the extreme values being recorded either in the centre of the piston head or at its extremities both in the upper and lower.

7. References
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