MODELLING GAS-DYNAMICAL PROCESSES WITHIN A TURBOCHARGING SYSTEM OF A MARINE FOUR-STROKE ENGINE

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Summary. There have been demonstrated main principles for elaboration of mathematical model describing gas-dynamical processes worked out within a turbocharging system of a marine four-stroke engine having a pulsatory power supply of the turbine. An analysis of theoretical basis of physical phenomena which occur in the modelled object during the engine’s work in unsteady states has been carried out as well. Additionally, a physical model of the system has been elaborated. This issue deals with a conventional division of the object into essential (from realised gas-dynamical processes point of view) functional modules as well as with a proper flow establishment of their input and output signals, which are indispensable to work out an energy balance.

NOMENCLATURE

Parameters:
- $H$ - enthalpy flux
- $M$ - torque
- $m$ - mass flow rate
- $n$ - rotational speed
- $p$ - pressure
- $R$ - reaction force
- $r$ - position of rotational speed governor
- $\dot{Q}$ - heat flow
- $V$ - volumetric flow rate
- $T[K], t[{^\circ}C] - absolute or Celsius temperature$
- $\delta$ - radial clearance
- $\varphi$ - relative air humidity
- $t$ - time
- $\omega$ - angular speed
- $\alpha$ - vane angle
- $R+PP$ - rotational speed governor along with fuel pomp
- OWK - crankshaft revolutions
- $S$ - compressor
- $T$ - turbine
- TSS - diesel engine
- ch - cooling
- d - inlet
- $h$ - hydraulic brake
- i - internal
- $k$ - passage
- m - mechanical loss
- o - surrounding, lube oil
- $p$ - air
- $pd$ - supercharging air
- pal - fuel
- $S$ - compressor’s
- $sp$ - exhaust
- $T$ - turbine’s
- TS - turbocharger’s
- $v$ - volumetric
- $w$ - outlet
- WZ - cooling water
- 0, 1, 2, 3, 4, 5, 6 - engine’s cylinder numbers, control intersection numbers of flow passages

Abbreviations and subscripts:
- $CH$ - cooler
- $KDP$ - air inlet passage to the compressor
- KDS1, KDS2 - exhaust connecting passage from load exchange system to the turbine
- KWP - air connecting passage to a load exchange system of the engine
- KWS - exhaust outlet passage
1. Introduction

Four-stroke engines supercharged by means of turbochargers are mainly applied for propelling contemporary naval vessels. A turbocharger viewed as an integral engine's part represents for it a source of feeding mass flow rate of air. A quantity of the feeding air in relation to quantity and quality of feeding fuel conceives a coefficient of excess air. Its value must be in the range guarantying the complete combustion of fuel in the engine cylinders [3,5]. In engine's unsteady processes like: start-up, rotational speed alterations, load alterations etc., because of time delays within the engine turbocharging system (considered together with an automatic control system) the boundary value of a coefficient of excess air may be exceeded. As a consequence of exceedingly rich (or poor) fuel-air mixture some disturbances of the combustion process may occur. It has a vital impact on mean indicated pressure, specific fuel consumption, mechanical and thermal load of construction elements, exhaust toxicity as well as loudness of the engine's work. In an extreme situation misfiring of cylinders or even an engine stopping may occur. Such incidents are clearly known from operation experiences of naval propulsion systems.

2. Issue of modelling gas-dynamical processes

The consideration of dynamical energetic processes, which are carried out in the engine turbocharging system, viewed as an object of experimental researches, deals (among the others) with the necessity of mathematical circumscribing gas-dynamical phenomena. They are connected with an unsteady flow of air and exhaust through the compressor and turbine, their passages, respectively: inflow and outflow as well as connecting passages to the engine's exchange system. During unsteady working states such an object is characterised with determined inertias, which results from accumulating features of respective functional modules. A character and velocity of the realisation of transient processes in the engine depend on the inertias.

On the grounds of theoretical basis of an undertaken issue it results [1,2,6] that within analytical circumscribing modelled processes there should be considered following accumulations:

- kinetic energy of whirling masses of the turbocharger's rotor,
- thermal energy in the structural components of the turbine together with exhaust passages storing heat generated as a result of fuel combustion inside engine's cylinder,
- substance of working medium stored at the moment in the flow elements of the turbocharging system's passage.

Modelling dynamic energetic processes in the engine's turbocharging system on constant pressure of power supply of the turbine (mainly two-stroke engines) may be worked out by well-known way described in accessible professional literature [4,5,6]. In general, zero-dimensional models of concentrated parameters are applied in order to identify dynamical features. By using mass conservation law and energy conservation law it is possible to formulate balance equations within gasdynamical feedback system between turbocharger and engine.

Nevertheless, more and more common applied pulsatory constructions, where the turbocharger is powered by exhaust of peak pressures from outlets (Buchi systems) put up determined particularities into calculating flowcharts of the element's of the considered flow system as well as their mutual connection. The phenomenon that you should be paid attention (during dynamics analysing this types of system) is alteration principle of the input magnitudes exciting unsteady processes in a turbocharger – energy flux (enthalpy) delivered
Fig. 1. Alteration courses of a disposed exhaust enthalpy flux while a quantity of exhaust in the inlet section of guide vanes of turbocharger's radial compressor is the same.  

\( P \) - pulsatory power supply system, \( S \) - stable-pressure power supply system

by impulses exhaust pressure waves from the engine's outlet. In figure 1 there is presented an objective comparison of the alterations of a disposed exhaust enthalpy flux in the inlet section of guide vanes of radial turbine \( H^*_{X,X} \), assuming the same quantity of exhaust flowing through the pulsatory (P) and stable-pressure (S) power supply system.

Because of pulsation of delivery exhaust flux of the turbine its efficiency is much lower than the efficiency of stable-pressure system. It results from a discontinuous supply. Nevertheless, exhaust kinetic energy discharging the engine is utilised. It is an especially vital virtue concerning low power engines at moderate degree of supercharging (1.2\( \pm \)1.4) and while the engine is operated in a wide range of load's alterations.

Additionally, thanks to appropriate course of pressure waves in the outlet exhaust pipe the course of cylinder rinsing process is much more effective (the course of pressure waves in the outlet pipe should be close to the course of pressure drops in the cylinders).

Other factor which have a vital impact on time delays of unsteady processes within the turbocharging system is applied solution of a rotational speed governor and its gasdynamical feedback to the supercharging system [3,5].

3. Examination's object

The modelling object represents the turbocharging system of the 6-cylinder Sulzer 6AL20/24 four-stroke engine equipped with pulsatory power supply of the turbine and cooling supercharging air – fig. 2. The system consists of sub-assemblies as follows: turbocharger's rotor with radial turbine (T) and radial compressor (S), flow passages of air and exhaust, cooler of the engine's supercharging air (CH). Measuring places for the engine control parameters are marked in the figure as well. The measurements are carried out by means of the computer measured-recording system, which has been designed and built at the Technical Institute of Ships' Maintenance, Polish Naval Academy. Table 1 includes a set of the measured engine parameters. A sampling frequency of the recording values' parameters is equal 10 Hz.

The singular supercharging system of the engine of firing sequence: 1-4-2-6-3-5 is equipped with a radial turbine having exhaust bipassage pulsatory power supply system.
Fig. 2. Schematic diagram of the Sulzer 6AL20/24 engine's turbocharging system

Tab. 1. Measured parameters of the Sulzer 6AL20/24 engine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measuring range</th>
<th>Accuracy (%)</th>
<th>Type of sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine's crankshaft rotational speed - ( n )</td>
<td>800 rev/min</td>
<td>0.1</td>
<td>inductive</td>
</tr>
<tr>
<td>Turbocharger rotor's rotational speed - ( \omega_T )</td>
<td>40000 rev/min</td>
<td>0.5</td>
<td>magnetoelectric</td>
</tr>
<tr>
<td>Exhaust temperature in cylinder outlets - ( T_{601}, T_{602} )</td>
<td>600 °C</td>
<td>0.3</td>
<td>thermocouple</td>
</tr>
<tr>
<td>Exhaust temperature in gathering passages before the turbine - ( T_{601}(1,2,3 \text{ cylinder}), T_{602}(4,5,6 \text{ cylinder}) )</td>
<td>600 °C</td>
<td>0.3</td>
<td>thermocouple</td>
</tr>
<tr>
<td>Exhaust temperature behind the turbine - ( T_{ext} )</td>
<td>600 °C</td>
<td>0.3</td>
<td>thermocouple</td>
</tr>
<tr>
<td>Volumetric flow rate of air before the compressor - ( V_p )</td>
<td>2600 m(^3)/h</td>
<td>1.5</td>
<td>strain gauge</td>
</tr>
<tr>
<td>Air temperature before compressor - ( T_{ca} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Air temperature behind compressor - ( T_{cd} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Supercharging air pressure - ( p_s )</td>
<td>0.25 MPa</td>
<td>1.0</td>
<td>strain gauge</td>
</tr>
<tr>
<td>Air temperature behind intercooler - ( T_{ol} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Air temperature before cylinders - ( T_{ol1}, T_{ol2} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Volumetric flow rate of water flowing through the air intercooler - ( V_{wash} )</td>
<td>15 m(^3)/h</td>
<td>1.0</td>
<td>flowmeter</td>
</tr>
<tr>
<td>Water temperature before the air intercooler - ( T_{wresh} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Water temperature behind the air intercooler - ( T_{wresh} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Volumetric flow rate of fuel flowing to the engine - ( V_{fuel} )</td>
<td>100 dm(^3)/h</td>
<td>0.5</td>
<td>flowmeter</td>
</tr>
<tr>
<td>Fuel temperature before the engine - ( T_{fuel} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Volumetric flow rate of lube oil before the engine - ( V_o )</td>
<td>25 m(^3)/h</td>
<td>0.5</td>
<td>flowmeter</td>
</tr>
<tr>
<td>Lube oil temperature before the engine - ( T_{ol} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Lube oil temperature behind the engine - ( T_{ol2} )</td>
<td>100 °C</td>
<td>0.5</td>
<td>resistive</td>
</tr>
<tr>
<td>Reaction force of the hydraulic brake - ( R_h )</td>
<td>1,2 kN</td>
<td>0.16</td>
<td>strain gauge</td>
</tr>
</tbody>
</table>
An alteration course of exhaust pressure in the pipes before the turbine wears a character similar to the one presented in figure 3. Such a solution, where the exhaust valve opening lasts $\alpha=340^\circ$ crankshaft revolutions, ensures positive interfering effect of pressure waves impulses from two cylinders by $\alpha=100^\circ$ OWK. Thanks to the phenomenon the lowest exhaust pressure in the outlet passages is higher than an outlet antpressure. This way, the improvement of turbine efficiency is obtained. Unfortunately, much more energy expenditures is needed to remove exhaust (an antpressure in the exhaust outlet passage is higher).

4. Physical modelling

As a result of the preliminary identification of dynamical features of the working medium flow process within gasdynamical feedback system between the turbocharger and the engine, after detailed analysing the construction structure of the SULZER 6AL20/24 engine, which has been taken to the examinations, a simplify physical model has been elaborated – fig. 4. There have been distinguished some dynamical modules, which should be considered in all their causes - consequences bearings for mathematical approach to the unsteady processes in the system. The input and output magnitudes have been determined for all the modules. State’s parameters of dynamical processes will be represented by magnitudes describing the alterations of substance quantity and quantity of internal energy of the working medium stored in the passages’ spaces as well as the alteration of quantity of kinetic energy stored in the turbocharger’s rotor.

Additionally, the demonstrated model takes into consideration the phenomenon of gasdynamic and kinematic interaction among the supercharging air passage, the engine and rotational speed governor. It is also considered the alterations of a turbine thermal state. Consequently, the alterations of radial rotor clearances and as a consequence the deformations of turbine flow capacity and efficiency characteristics are considered as well. Because during unsteady states a heating velocity of the turbine and exhaust passage metal components is considerably delayed (even by several minutes) in comparison to the alteration of the engine’s operating range, thus, it is especially complicated task and difficult for revising examinations to express analytically the correlations between heat exchange conditions and radial (axial) clearances’ values. But, having turbine characteristics done for different values of radial
clearances it is possible to introduce empirical correction coefficients improving the accuracy of the elaborated model.

5. Mathematical modelling

According to the elaborated physical model of the considered processes, on the basis of appropriate formulated equations:
- unsteady mass balance and energy balance of the flowing working medium,
- unsteady balance of an angular momentum in rotated motion of the rotor,
- algebraic, non-linear characterising the features of the flowing working medium, material features and structure's geometry of the modelled object.

it is possible to built a mathematical model describing a dynamics of the energetic processes which are carried out in the engine's supercharging system.
In order to simplify the mathematical model maximally the following assumption have been established in the first stage of its formulation:

- considered dynamical modules are modelled as absolute dynamical objects with concentrated parameters. Such an assumption its class determines:
  - time as an independent variable of the processes,
  - ideal mixing of forced through working medium,
  - the same temperature in each point of the considered gas spaces of the passages;
- air suction parameters are steady - standard, according to ambient ISA;
- flowing working medium is considered as a semi-ideal gas;
- fuel combustion process inside the engine’s cylinders is executed without delay resulting from fuel transportation between a fuel dosing element of the engine’s control system and combustion chamber injectors as well as delays caused by the time of fuel pulverising, evaporating and ignition (time constants are lower than 25-30 ms [3]);
- mathematical description of the working medium parameters concerns average, total values of pressures and temperatures in the marked out control intersections within the engine’s turbocharging system, considering the assumption that the alterations of pressure and density of the working medium flowing through the system are little in comparison to their average values;
- because time constants of dynamical processes of the working medium flow worked out inside the compressor and turbine have little values (1+10 ms range [4]) the working medium storage is negligible and dynamical phenomena are treated as sequence of instantaneous steady states. Hence, a quasi-continuum approach to flow process in the compressor and turbine will be put into practice. They are only treated as a substance and energy sources for the connecting passages to the engine’s load exchange system as well as the passages of the compressor’s inlet air and turbine’ outlet exhaust;
- termodynamical parameters in the outlet section of the storing spaces KDP, KWF, KDS1, KDS2 i KWS are determined with a delay to average parameters inside the spaces by a time of the working medium flow along the path between their inlet and outlet sections,
- alterations of radial and axial clearances in the turbocharger’s rotor caused by centrifugal forces and alterations of thermal states of the turbocharger’s component are not taken into consideration within modelled dynamical processes;
- it is omitted the influence of a working medium friction onto gas passages walls as well as heat exchange between the surroundings and the working medium flowing in the passages.

6. Conclusions

The presented physical model of the working medium flow process within the four stroke engine’s turbocharging system will be used for the elaboration of a mathematical model describing gasdynamical processes worked out in the system during engine operation in unsteady states. It is foreseen to apply the mathematical model for building a computer program simulating unsteady gasdynamical processes in the considered system. It gives possibilities to identify the processes qualitatively and quantitatively in the real an hypothetical operating condition as well as for diagnostic purposes (so called “simulation diagnostics” - according to the model).
Bibliography


Streszczenie. W opracowaniu przedstawiono podstawowe założenia dla budowy modelu matematycznego opisującego procesy gazodynamiczne w układzie turbodoładowania okrętowego silnika czterosuwowego przy pulsacyjnym zasilaniu turbiny spalinami. Przeprowadzono analizę podstaw teoretycznych zjawisk fizycznych występujących w modelowanym obiekcie w stanach nieustalonej pracy silnika. Opracowano model fizyczny układu, w którym dokonano jego umownego podziału na moduły funkcjonalne, istotne z punktu widzenia realizowanych procesów gazodynamicznych oraz ustalone dla nich przepływ sygnałów wejściowych i wyjściowych, niezbędnych do sporządzenia bilansu energetycznego.