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SYMPTOMS OF STATES INCLUDED IN THE PERFORMANCE OF CON-ROD-PISTON COMBUSTION ENGINES SYSTEMS

Jan Rosłanowski, Adam Charchalis

Gdynia Maritime University
Morska Street 83-87, 81-225 Gdynia
e-mail:rosa@am.gdynia.pl, achar@am.gdynia.pl

Abstract

The following article describes energetic states symptoms, included in correct and incorrect performance of crank-piston combustion engines systems. Special attention has been paid to accompanying processes of such performance, with regard to, heat generation effect in combustion chamber and friction in joined frictional movements. Combustion chamber is a moving space formed by connection of the piston through piston rings with the cylinder liner and the engine head. Heat generation process takes place above the piston, generated by burning of fuel. It causes an increase of gas pressure in the combustion space, which results in the movement of the piston tightened by the rings, followed by an increase of the space volume. In this way energy is emitted from fuel burning, influencing the elements of piston-con-rod system in the form of heat and work. The ability of such thermodynamical system to convert energy into an effective one is limited. Internal energy of exhaust gases can be divided into the part which cannot be converted into work. The process of heat generation in engine cylinder is of irreversible character which results in the loss of energy. In piston combustion engines, work is performed by heat generated in cylinders. Energetic performance in piston-crank system results from internal exchange of exhaust gases in combustion chamber with the engine surroundings. Analysis of such energetic performances allows us to isolate symptoms of correct operation of piston con-rod combustion engine systems. Such symptoms include: exhaust gases temperature, temperature of piston surface, momentary values of torque and the speed of pressure increase during combustion. Piston-con-rod system is a component part of the engine. Evaluation of its performance allows to identify the present technical condition of the engine. Diagnostic advantages of some, above mentioned symptoms of piston-con-rod combustion engine operation, have been verified by means of adequate laboratory testing and during engine operation on the ship.

***Keywords**: energetic operation of piston crank system, frequency of momentary values of the torque on the crankshaft*

1. Introduction

To identify energetic states of crank-piston systems, taking place in the course of their operation, it is necessary to get acquainted with their accompanying processes which include evolution of heat in combustion chamber and friction in frictional associations. The process of heat evolution in the cylinder of combustion engine takes place when the cylinder is being filled with a fresh charge, injection, also burning fuel, as well as, exchange of heat between working medium and the walls of cylinder during motion of the piston (volume changes).

Effective work of the engine is connected with the torque on the shaft, of which momentary measured values during steady motion of the ship, can be used as symptom of the energetic state of piston-con-rod system of correct or incorrect operating [6, 7].

Correctness control of piston-crank system can be carried out according to other diagnostic symptoms. They include: temperature and pressure in the points defining particular changes that take place in the engine.

2. Energetic operation of piston-con-rod system of diesel engine

Energetic operation of piston-crank engine results from inner energy exchange of exhaust gases that form in the cylinder during transformation into mechanical energy of the piston. The piston is connected with the crankshaft of the engine by means of connecting rod and performs plane motion [1]. Because of the above fact, mechanical energy of piston-con-rod system can be presented as the following formula:

$$E_m(t)=\frac{1}{2}\cdot I\cdot\omega^2+\frac{1}{2}\cdot I_k\cdot\left(\frac{d\beta}{dt}\right)^2+\frac{1}{2}\cdot m_k\cdot\left[\left(\frac{dx_s}{dt}\right)^2+\left(\frac{dy_s}{dt}\right)^2\right]+\frac{1}{2}\cdot m\cdot\left(\frac{dx}{dt}\right)^2, \tag{1}$$

where:

I – mass moment of inertia of engine crankshaft and flywheel,
I_k – moment of inertia of connecting-rod,
m_k – mass of connecting-rod,
m – mass of piston,
x_s, y_s – vertical and horizontal coordinate of connecting-rod mass mid-point,
$\boldsymbol{\beta}$ – deflection angle of engine crankshaft,
$\boldsymbol{\omega}$ – angular velocity of engine crankshaft.

The first constituent of the formula (1) represents energy of engine crankshaft together with the flywheel. The second-energy of connecting-rod rotational motion. The third-energy of its translator motion. And the fourth-energy of piston translator motion. The expression (1) can be written down in a simpler form, taking advantage of trigonometrical dependences compulsory in piston-crank system:

$$E_m=\frac{1}{2}\left[I+F(\alpha)\right]\cdot\omega^2, \tag{2}$$

where:

$F(\boldsymbol{\alpha})$ – characteristic function of the piston-con-rod system is defined in the following way:

$$F(\alpha)=I_k\cdot\left(\frac{d\beta}{d\alpha}\right)^2+m_k\left[\left(r\cdot\sin\alpha+\lambda\cdot a\cdot\sin\beta\cdot\frac{\cos\alpha}{\cos\beta}\right)^2+(r-\lambda\cdot a)^2\cdot\cos^2\alpha\right]+m\cdot r^2\cdot\frac{\sin^2(\alpha+\beta)}{\cos^2\beta}$$

where:

r – radius of crank throw,
$\boldsymbol{\alpha}$ – rotation angle of crankshaft,
a – distance of connecting-rod mass from the mid-point of connecting rod big end mass of engine crankshaft,
$\lambda=\frac{r}{l}$ – ratio of crank throw to the length of connecting rod,
- remaining designations as in the formula (1).

Operation of forces operating on piston-con-rod system and complying with the growth of its kinematic energy is defined by the following expression:

$$L(\alpha)=\int_0^{\alpha}\left(S_{G+M}-R_A\right)\cdot r\cdot d\alpha=P\cdot r\cdot(1-\cos\alpha)+\frac{r}{2\cdot\lambda}\cdot\arcsin\left(\lambda^2\cdot\sin^2\alpha\right)+R_A\cdot r\cdot\alpha, \tag{3}$$

where:

S_{G+M} – resultant tangent force derived from mass forces S_M and gas S_G operating on cranked crankshaft of the engine,
R_A – useful resistance of the engine,
P – gas force.

Expression (3) shows that operation of piston-con-rod system is an angle function of crankshaft rotation $\boldsymbol{\alpha}$, and causes the change of its kinetic energy.

Angle of ignition and angle of combustion duration are constant and known for a given cylinder engine, which allows to compare work performed by respective cylinders. In case when one of the cylinders performs work of a different value than the remaining ones, there follows the change of combustion pressure course, and the change of friction moment. With a known useful moment, it is possible to determine the friction moment on the basis of angular acceleration measurement of the crankshaft and the course of combustion pressure in cylinder [1, 4, 8, 9].

Connection of kinetic energy and work is expressed by:

$$\frac{1}{2}\left[I + F(\alpha)\right]\cdot \omega^2 + \int_0^{\alpha}\left(S - R_A\right)\cdot r \cdot d\alpha = E_{mo}, \qquad (4)$$

where:

E_{mo} – mechanical energy of piston-crank system in dead centres of its motion,

- remaining designations as in formulas above.

From formula (4) it is evident that kinetic energy obtained from internal energy of exhaust gases is used up during piston operation. Additionally, potential energy of the piston takes part in this transformation. Exchange of energy between the piston and gases takes part in the form of work and heat. The size of such exchange can be determined on the basis of energetic balance open system, like, for example, combustion chamber, during established state [1]. From this balance it appears that the heat taken over by gases during fuel combustion, induces the change of its internal energy and work performance transformation by means of the piston. From the power balance one can obtain the following equation of moments [4]:

$$I \cdot \frac{d^2\alpha}{dt} = M_g - M_u - M_T - \frac{1}{2}\frac{dI}{dt}\cdot\left(\frac{d\alpha}{dt}\right)^2, \qquad (5)$$

where :

M_u – useful moment,

M_g – moment of gas forces,

M_T – moment of friction,

I – mass moment of inertia,

t – rotation time of engine crankshaft.

Equation (5) can take the form of particular case, where the engine performs its work under steady load. Then the equation of moments looks like this:

$$\frac{r}{\alpha_2 - \alpha_1}\cdot\int_{\alpha_1}^{\alpha_2} S_{G+M}\cdot d\alpha - M_{S(\alpha_2 - \alpha_{11})} - M_{u(\alpha_2 - \alpha_1)} = I_{s+m}\cdot\frac{1}{\alpha_2 - \alpha_1}\cdot\int_{\alpha_1}^{\alpha_2}\varepsilon\cdot d\alpha, \qquad (6)$$

where:

$\boldsymbol{\alpha}_1;\boldsymbol{\alpha}_2$ – angles of crankshaft rotation,

$\boldsymbol{\varepsilon}$ – angular acceleration of the crankshaft,

I_{s+m} – mass moment of inertia of engine movable elements,

$M_u;M_T$ – useful moment of the engine and a frictional one.

Energy transfer of gases to the piston crown in the form of heat takes place by way of convection Q_k, flame radiation Q_F, and gases radiation Q_G. It changes in the cycle of engine performance. During filling stroke and compression, taking up the heat by the piston head takes place by way of convection. Whereas during combustion and expansion, taking up of the heat by the piston head takes place by way of convection, as well as radiation, in the presence of high temperature and pressure. In those periods, taking up of the heat is the most intensive. Thermal action of the piston is caused by receiving heat from gases and taken over by the piston head. Then there is also friction heat resulting from close contact of the liner and rings with the remaining surfaces [2, 9].

Density of heat flux q taken over and conducted by the unit of the crown area can be determined on the basis of Newton and Fourier's laws. Its averaging value q_{av} for the whole cycle of engine performance repeated in the period of time τ_0 is expressed by the formula:

$$q_{av} = \frac{1}{\tau_0}\int_0^{\tau_0}\alpha_g\cdot\left(T_g - T_t\right)d\tau - \lambda\cdot\frac{dT}{ds}, \qquad (7)$$

where:

τ – time of heat take over,

α_g – coefficient of heat take over,

T_g – momentary gas temperature,
T_t – momentary temperature of piston head,
λ – coefficient of heat conduction,
dT – temperature rise on the surface of friction,
ds – rise of the piston stroke.

In formula (7) an integral defines heat flux taken over by the piston and a differential defines heat flux conducted half-way to piston and cylinder liner.

Temperature of gases in engine combustion chamber is one of the engines diagnostic parameters of thermal operation correctness. In case of piston seizure, the temperature of its area rises excessively. The piston as a movable closure of the engine cylinder, conveys force of gas pressure from combustion chamber to connecting rod. Forces generate mechanical variables of piston operation, whose dynamics depends on pressure in cylinder, especially on speed of its escalation. This speed determines load conditions of the shaft bearings and crank mechanism. It is also connected with dynamics of heat generation during combustion and depends on mass intensity of combustion reaction. Speed operation of the piston can be described by means of speed escalation pressure during burning. To assume that during combustion the exchange of heat between the walls of combustion chamber and exhaust gases does not occur, then the speed of gas pressure escalation can be expressed by means of the following dependence:

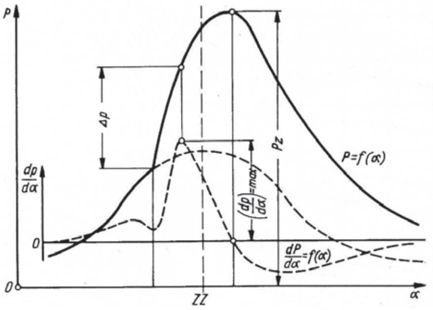

Fig. 1. Parameters characterizing dynamics of combustion process. Designations as in text [2]

$$\frac{dp}{d\alpha} = \frac{\chi - 1}{V} \cdot W_d \cdot m_p \cdot \frac{dw}{d\alpha} - \chi \cdot \frac{p}{V} \cdot \frac{dV}{d\alpha}, \tag{8}$$

where:
W_d – - heating value of fuel,
m_p – fuel dose,
χ – adiabatic exponent,
V – volume of combustion chamber,
p – pressure in combustion chamber,
α – angle of crank rotation,
$\frac{dV}{d\alpha}$ – speed of change of combustion chamber,
$\frac{dw}{d\alpha}$ – relative mass speed of reacting substance mass burning (to be subject to reaction in time unit),
$\frac{dp}{d\alpha}$ – speed of pressure escalation during combustion.

First part of the equation expresses the influence of heat generation and second-volume change of combustion chamber. Fig. 1 according to paper [2], presents dependence between speed of pressure escalation in engine cylinder and rotation angle of crankshaft. Attention should be paid to the fact that mechanical operation of the piston caused by gas pressure in cylinder is of dynamic character.

3. Characteristic of symptoms defining correctness of piston-con-rod system operation

In order to characterize symptoms of energetic states of combustion engine and its piston-crank system, special research was carried out in combustion engines laboratory of Engine Department in the Gdynia Maritime Academy.

To achieve this purpose, they took advantage of experimental combustion engine L 22 produced by the Warsaw Institute of Technology and four-stroke combustion engine Sulzer 3 AL 25/30 by the Cegielski Plant.

The engine L 22 is equipped with devices for smooth change of injection advance angle, which, allows to determine the impact of such angle on the symptom of speed change of pressure escalation in cylinder. Speed measurement results of pressure escalation in engine cylinder of different load and different advance injection angles, are shown in Fig. 2. Research results reveal that the change of maximal speed of pressure escalation cause deviations from the proper angle of injection advance, which in turn, causes improper piston operation. Too big angle is the reason why maximal speed of pressure escalation will be too early [3-5]. As a result of too quickly growing pressure speed, one can observe overloading of piston-crank system. On the other hand, too small angle is the reason why maximal speed of pressure escalation moves in the direction of expansion stroke and thus decreases engine efficiency.

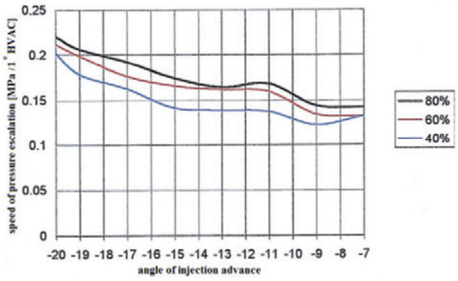

Fig. 2. Dependence of maximal speed of pressure escalation on the angle of advance injection with L 22 engine load of 40%, 60% and 80%

The influence of choked injector sprayer on symptom of energetic state in piston-crank system, in other words, on maximal speed of pressure escalation in cylinder, was tested on the engine 3 AL 25/30. Measurements results of maximal speed of pressure escalation in engine cylinder N^0 2 was shown in Fig. 3 under different loads (Fig. 4). Fig. 3 shows that such inefficiency of the injector decreases maximal speed of pressure escalation and therefore decreases power of the engine with the same index load. Deterioration of engine performance is caused by worse spraying of fuel in the combustion chamber, and this, in turn, causes ignition delay. Decrease of fuel dose injected into cylinder is the reason of exhaust gases temperature drop. Together with speed of pressure escalation, temperature of gases increases. Medium indicated pressure and maximal

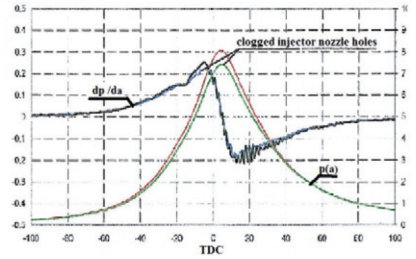

Fig. 3. The course of maximal speed escalation pressure in the cylinder N0 of the 3 AL 25/30 engine with choked injector holes and the load of 220 kW in function of crankshaft rotation

combustion pressure increase too.

The speed of pressure escalation changes its value depending on the quality of engine operation in the cylinder. Fig. 4 shows maximal speeds of pressure escalation in engine cylinder 3 AL 25/30 of its different loads and incorrectness operation of fuel apparatus in second cylinder, as well as, the leakage of its combustion chamber simulated by a deflection of indicator cock on the head of the engine.

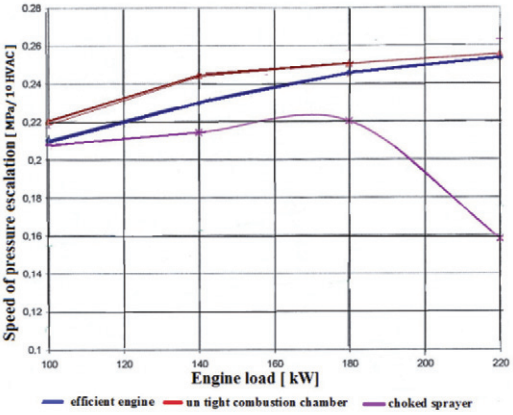

Fig. 4. Dependences of speed escalation pressure in cylinder N02 of the engine 3 AL 25/30 of its different loads: 100 kW, 140 k, 180 kW and 220 kW

Operating testing was carried out on a two-stroke, five cylinder engine-Sulzer type 5 RD 68 of five successive ignitions: 1-4-3-2-5, which was the propulsion engine of general cargo vessel with a displacement of 5500 DWT during its voyage. Correctness of piston-crank systems of this engine was controlled by means of momentary measurements of the torque's value at time intervals every 0.02 [s]. The above values of the engine's turning moment are a symptom of the energetic state of its piston-crank systems. They are of sinusoidal signals character, distorted by random disturbances [6, 7]. Frequency of these signals is fixed by the frequency of ignitions taking part in engine cylinders. Therefore information about energetic state of piston-crank systems, included in the signal of momentary values of the torque, can be recognized directly from its temporal realization. Measurements results of engine's turning moment, during ship's voyage are shown in Fig. 5. They allow us to state that the analysis of frequency band of signal moment up to 50 Hz and distributive ability up to 0.5 Hz, make it possible to isolate and to determine precisely harmonic components connected with the process of heat generation in the cylinders during established engine operation. During one rotation of engine crankshaft, one can observe distinctly,

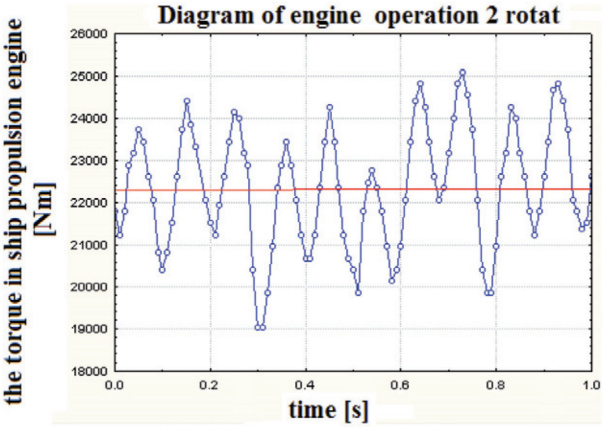

Fig. 5. Changes of momentary values of the torque in ship propulsion engine Sulzer 5 RD 68, measured during two rotations of fixed performance of the engine

five forced actions coming from particular cylinders. Having known exactly the sequence of ignitions and on which cylinder pressure is measured, we can identify which cylinder this forced action is coming from. Irregularity of curve moment course, measured on the shaft during one turning of the crankshaft is caused by non-repetition of the injection, in other words, by random process causing different combustion pressures in the engine cylinders. To state the influence of any disturbance of the heat generation process in the cylinder, on the torque values of the engine, measured in short time intervals, they dropped fuel from the injector through gradual opening of the injector air value. Such disturbances were carried out during ship's motion on the sea.

The above experiment allows us to state that by dropping 14.3% of fuel delivered to cylinder, there follows a distinct change of momentary values of the engine torque [6, 7]. Fig. 6 shows such changes of momentary values of engine turning moment during two rotations of the crankshaft, while being operated and with a decreased fuel dose delivered to the third cylinder. Periodically changeable course of torque momentary values is caused by the change of dominating forces operating in its piston-crank system. When the heat generation process happens to be disturbed, then mass forces begin to prevail in cylinder and together with gas forces disturb considerably the engine operation.

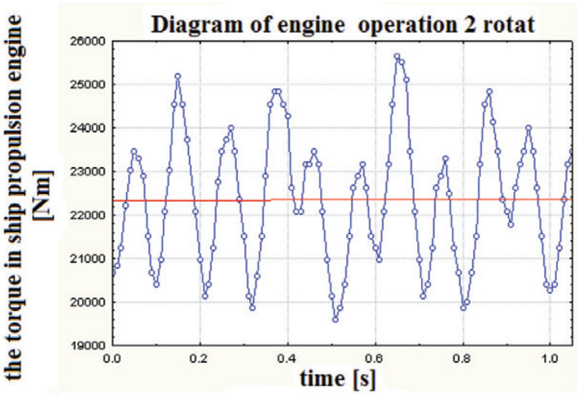

Fig. 6. Measured at the time of 0.02 [s] engine 5 RD 68 torque for two revolutions of the crankshaft when the dose reduced by 14.3% fuel supplied to the third cylinder, while ship's sailing on a calm sea

Operation of speed governor may be the cause of some disturbance to the engine when in case of faulty operation of one or even more cylinders, the remaining ones have to work harder to supply bigger torque and to keep up the required rotational speed, as well as the moment assigned to these rotations, required by the propeller.

It causes an excessive increase of thermal and mechanical load in cylinders, which leads to their overloading and consequences connected with it.

4. Summary

To rely only on the basis of speed escalation pressure in engine cylinder or on momentary changes of the torque values, it is possible to make a diagnosis of only some incorrectness of piston-crank system.

For unmistakable identification it is necessary to use other diagnostic symptoms.

The course of speed escalation pressure in the engine cylinder can be also affected by: engine load, rotational speed and the type of fuel.

Frequency of momentary values of the torque is established by frequency of ignitions in engine cylinders and does not depend on external conditions of sailing, which cause an increase of amplitude at unchanged frequency.

The analysis of operation changes of the whole engine can be difficult during its normal functioning because faulty performance of one of the cylinders can be unnoticeable.

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