THERMODYNAMIC CHARACTERISTICS OF RECIPROCATING COMPRESSORS FOR MOTOR VEHICLES

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Summary: *Validation of thermodynamic characteristics of reciprocating compressors for motor vehicles is performed on test bench which allows measurement of cylinder pressure of compressor depending on the angular position of the compressor crankshaft. This paper presents the characteristics of the test bench and measurement results of compressor's indicator diagram. The measurement results are compared to simulation results and results obtained by other authors from measurement on similar compressors. Good agreement between the results of measurements and the results of simulation and literature data are obtained.*
Keywords: *Test bench, Reciprocating compressor, Indicator diagram*

1. INTRODUCTION

Reciprocating compressors are well-known and have vast application. The production of energy-efficient reciprocating compressors with good environmental and economic characteristics is a goal for every manufacturer of motor vehicles. In order to achieve that, motor vehicle manufacturers invest great funds in the development of reciprocating compressors and research with the goal to improve the characteristics of reciprocating compressors, which can be seen in many publications in this field. The reciprocating compressors in motor vehicles have relatively small power, but operate in variable modes, so it is necessary to examine and optimize the compressor's work processes. The research done in the process is very long and expensive. Part of it can be replaced with mathematical modelling if there is an adequate, verified mathematical model.

The formation of the mathematical model is a complicated problem that can be solved in many ways with the application of various mathematical methods. The complexity of the mathematical modelling has been indicated by Rasmussen and

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Jakobsen with the analysis of publications from the period from 1990 to 2000 year that had been presented at the International engineering conference on compressors at the Purdue University. They established that the researchers had dealt with the mathematical modelling of various compressors in more than 100 publications [1]. Subramanian and his associates presented mathematical models of compressors used in reference works. [2].

Mathematical modelling of the reciprocating compressor is complicated since it is necessary to use relations from different fields of science to describe the processes involved. The process of air intake and compressed air discharge are described with the equations from the fluid dynamic. The process of air compressing is described with the equations of thermodynamics based on the first and second law of thermodynamics and the equations for mass and heat transfer. Movement of the piston and valve is described with mechanical equations. One must also be aware of the energy relations that are necessary for compressor to work. In addition, care must be taken, and the power relations that are necessary for the operation of the compressor. The majority of reference books on mathematical modelling deal with a few aspects of the compressor operation in order to study certain phenomenon.

The verification of the mathematical modelling is conducted by comparing the results of mathematical modelling to the results of measuring compressor's characteristics on an experimental measuring installation.

At the Faculty of engineering, University of Kragujevac, on the department of Laboratory for internal combustion engines, a measuring installation that provides non-standard research of compressors as well as other machines, apparatus and devices with similar method of operation was made. The results of the research can be used for verifying mathematical models of compressor.

2. MATHEMATICAL MODEL OF RECIPROCATING COMPRESSOR

Determining thermodynamic characteristics of reciprocating compressors in motor vehicles according to the mathematical model requires knowing all the characteristics of the compressors. This is the reason we chose single-stage, low pressure reciprocating compressor for compressing air up to 1 MPa, to model and verify the modelling.

The compressor model is constructed of three connected pieces: compressor cylinder with suction and exhaustion valve, suction chambers with suction pipes and exhaustion chambers with exhaustion pipes. If we regard the volume of the suction and exhaustion chamber to be bigger than the volume of the compressor cylinder ("infinitely" bigger), we do not have to take into consideration air pulsing during suction and exhaustion while modelling the compressor.

Mathematical modelling of the compressor's working mode includes analysis and modelling of various connected physical phenomena, which are:

- thermodynamic processes in the compressor,
- kinematical relations among parts of the compressor,
- valve dynamics,
- air flow through valves, the produced amount of comprised air,
- heat transfer between air and the compressor, as well as the compressor and the environment,

- forces and torque on the piston and compressor drive shaft.

Analysis and modelling of thermodynamic processes in the compressor are performed using zero-dimensional**,** general model with certain suppositions:

- working body is air that is considered to have characteristics of an ideal gas,
- gas flow is isentropic and quasi stationary,
- gas in the cylinder is always balanced,
- we do not take into consideration kinetic and potential gas energy.

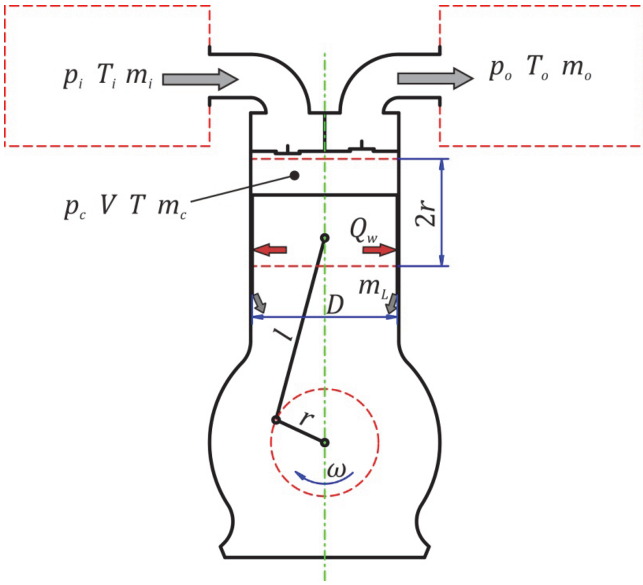


Fig. 1 *Model of reciprocating compressor*

When we apply the first law of thermodynamics on the compressor model on Figure 1, after the transformation presented in literature [3], we get the following equation describing the thermodynamic processes in the compressor:

$$c_v m_c \frac{dT}{dt} + \frac{m_c R_v T}{V}\frac{dV}{dt} + c_v T \frac{dm_c}{dt} + c_v \kappa T_o \frac{dm_o}{dt} + c_v \kappa T \frac{dm_L}{dt} - c_v \kappa T_i \frac{dm_i}{dt} - \frac{dQ}{dt} = 0,$$

where are:

Q – heat that the compressor releases into the environment,
m_c – air mass in the compressor cylinder,
m_i – air mass that enters the cylinder through the suction valve,
m_o – air mass that leaves the cylinder through the exhaustion valve,
m_L – air loss mass through the gap between the piston and cylinder wall,
p_c – pressure in the compressor cylinder,
p_i – pressure on the suction valve,
p_o – pressure on the exhaust valve,
c_p – specific heat of air at constant pressure,
c_v – specific heat of air at constant volume,
κ – isentropic exponent of the air,
T – absolute temperature of the air in the cylinder,

T_i - absolute temperature of air on the suction valve,
T_o - absolute temperature of air on the exhaust valve,
R_v – the gas constant of air,
V – air volume in the cylinder.

Processes in the reciprocating compressor are cyclic, and they all include the following phases: suction of gas in the cylinder, compression of gas, exhaustion of gas from the cylinder, and expansion of gas. Depending on the phase, some parts of the equation are omitted, so for each phase, one can obtain a simpler equation. By connecting the relations that describe kinetic relations, forces and torque in the compressor, as well as the heat transfer through the compressor wall, a complex model, that is used for modelling the compressor with the program package MATLAB® and its module Simulink®, has been created [3].

3. MEASURE INSTALLATION

Pressure flow measurement in the compressor cylinder is conducted depending on the angular position of the crankshaft. Pressure is measured with Piezoelectric pressure sensors, and angular position with the optic encoder. Diagram of the measuring system is shown in Figure 2. Similar principle of measuring characteristics of pressure flow in an SI engine is in the reference. [4].

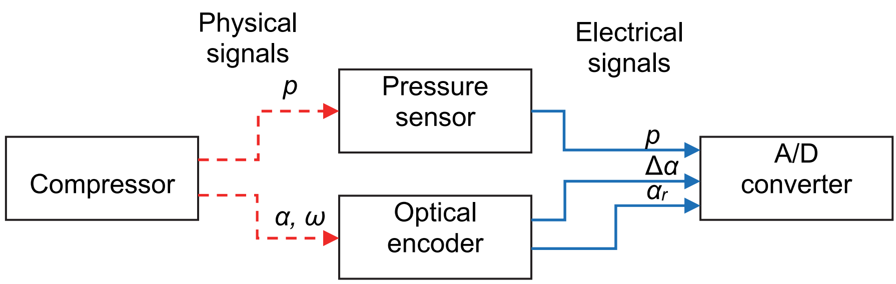
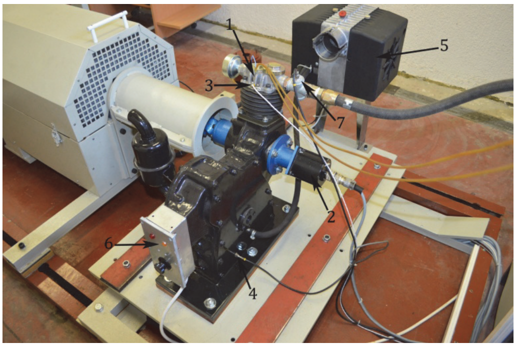


Fig. 2 *Diagram of the measuring system*

Every degree of the crankshaft receives impulses from the optical encoder. Those impulses, with an extra impulse for the top dead centre (TDC) position of the crankshaft, enable to determine the exact position of the compressor crankshaft with the resolution of 1 degree. Pressure measurement is synchronized with the impulses from the optical encoder. By measuring the time between two impulses, one can establish the change in angular speed of the crankshaft during the working cycle of the compressor.

In Figure 3, we can see a part of the measuring installation – a reciprocating compressor with sensors that enable measurement of the thermodynamic characteristics of the compressor. Parts of the measuring installation that enable working conditions similar to those on a motor vehicle, are also shown.



1 – Pressure sensor in the compressor cylinder,
2 – Optical encoder
3 – Temperature sensor of the compressor head,
4 – Oil temperature sensor,
5 – Ventilator for cooling the compressor and oil pump,
6 – Oil temperature regulator
7 – Air temperature sensor at the cylinder exit

Fig. 3 *Position of the sensor on the compressor*

4. RESULTS OF MEASUREMENT

Results of measurement and results of simulations according to the developed mathematical model are shown as closed - pV indicator diagrams of the compressor in Figure 4.

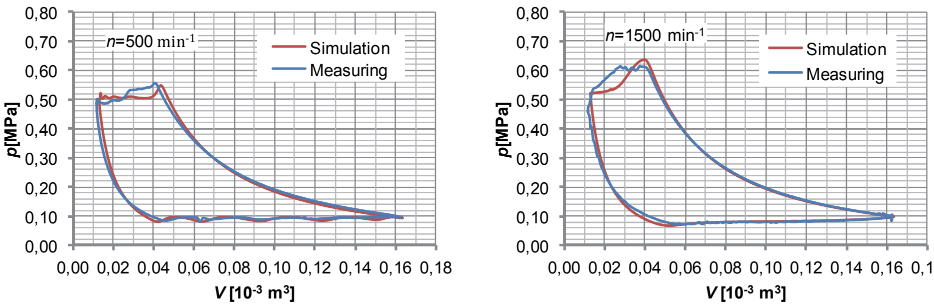


Fig. 5 *Closed – pV indicator diagrams of the compressor*

When the indicator diagrams in the Figure 4 are compared, one can see a good agreement between the results of the measurement with the results of simulations according to the developed mathematical model of the reciprocating compressor. The biggest discrepancies in the results of measurement and simulation are in the phase of exhaustion of air, since the modelling of this phase of the working process of the compressor is done with simpler relations. With the analysis of the diagram, one can see oscillations of pressure in the suction and exhaustion phase, when the number of rotations is small, and these oscillations are a result of adequate valve dynamics. Insufficient speed of opening the exhaustion valve is manifested as greater difference between the pressure in the cylinder and the reservoir when the number of rotations is bigger. Other researchers received similar results [5].

5. CONCLUSION

By comparing the indicator diagrams, one can establish a good agreement with the results of simulations gained by the developed model of the reciprocating compressor. The biggest discrepancies between the result of measurement and simulation occur in the exhausting phase, because the modelling of that phase of the working process has been modelled with relatively simple relations. Still, even the simple model as that, enables the correct modelling of the reciprocating compressor as a whole. With the small number of rotations of the crankshaft, especially in the suction phase, oscillations in the indicator diagrams can be seen, and are the result of valve dynamics, as well as air flow through the valves, and are expected based on the simulations on the compressor model.

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REFERENCES

[1] Rasmussen B. D., Jakobsen A., (2000). Review of Compressor Models and Performance Characterizing Variables, *Fifteenth International Compressor Engineering Conference at Purdue University*, West Lafayette, p. 515-522.
[2] Subramanian K., Subramanian L. R. G., Joseph B., Jayaraman, (2010). Mathematical Modeling and Simulation of Reciprocating Compressors – A Review of Literature, *Mathematics Modelling and Applied Computing*, vol. 1, no.1 p.81–96.
[3] Taranović, D. (2013). *The test bench for non-standard testing of reciprocating compressors for motor vehicles*. Ph.D. Dissertation, Faculty of Engineering, University of Kragujevac, Kragujevac.
[4] Radonjić, D., Pešić, R., Taranović, D., Davinić, A. (2012). Possibilities for use of simulation models in research of angular speed variations of IC engine's crank shaft, *International Congress Motor Vehicles & Motors 2012,* p. 76-86.
[5] Venkatesan J., Nagarajan G., Seeniraj R. V., Murugan R. (2010). Experimental validation of a mathematical model of a reed-valve reciprocating air compressor from an automotive braking system, *International journal of automotive technology*, vol. 11, no. 3, p. 317-322.