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OPTIMIZATION OF MECHANICAL LOSSES IN RECIPROCATING AIR COMPRESSOR WITH CYLINDER CONSISTING OF ALUMINUM ALLOY

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Abstract: *Transport is largely dependent on oil because the majority of transport vehicles are propelled by engines combusting petroleum products-hydrocarbon fuels. This particularly relates to road, air and water transport. Power losses in the internal combustion engines and other reciprocating machines are mainly engaged to overcome friction. If using aluminum alloys for producing of piston and cylinders in engines and compressors, the results are lower fuel consumption and exhaust emission, firstly because of lower weight and mechanical losses, too. The problems are poor tribological characteristics and lower strength of unprotected aluminum comparing with gray cast iron. For research purposes, the inner surface of cylinder which was produced of aluminum was reinforced by integrating tribological inserts. In this paper, the tribological properties of ferrous based reinforcements were analyzed and compared with aluminum alloy as a base material for cylinder liner and piston skirt in air brake compressor. The ball-on-plate CSM tribometer was used to carry out these tests under dry sliding conditions. In addition to tribological, have carried out and testing of experimental reciprocating compressor on the bench, in the laboratory for engines and compressors in Faculty of Engineering in Kragujevac.*

Keywords: *Aluminum, cylinder liner, friction, mechanical losses, reciprocating compressors, transport.*

1. INTRODUCTION

In the transport process, the input energy is converted into the movement of transport vehicles which provide the required spatial relocation of goods and persons. Therefore, transport is dependent on energy supply. Existing main energy resources are non-renewable and their stocks are constantly decreasing. Transport is the only major sector in the EU where greenhouse gas (GHG) emissions are still raising. Given to the mentioned facts there is the effort to make transport more efficient in the field of energy dependence [1-3].

The European Commission (EC) is working on the measures to reduction of GHG emissions from all sources and specific emission of carbon dioxide (CO_2) has limited proportional to fuel consumption.

Heavy-duty (HD) vehicles, trucks and buses are responsible for about a quarter of (CO_2) emissions from road transport in the EU and for about 6% of total EU emissions. There was not much progress in reduction of fuel consumption and thus exhaust emission starting from vehicle model EURO I (1992-1996) to EURO VI (since 2013) [4].

Because of the fact that all vehicles must give to reduction of fuel consumption and emission, the EU formed regulation for certification of all new registered HD vehicles. The main idea is to determinate which components of HD vehicles contributing to lowering mechanical efficiency and fuel consumption [4, 5].

As a contribution, we researched reduction of power demand of auxiliary devices on the engine, specifically in air compressor [6,7,8].

The air compressor in brake system of trucks and buses is two-stroke reciprocating machine which delivering air into pressure cylinders to feed the consumers as pneumatic brakes, clutch, gearbox and drivetrain, suspension system, actuators at engine, AdBlue injector, if exists inside of the exhaust system etc.

According to above facts, simplified model of pneumatic system for simulation of cylinder pressure, as well as the compressor power and measurement of the air consumption was given in Fig. 1.

In every moment of time, the air mass inside the pneumatic system we will determined by application of the ideal gas law, Eq. 1 and Eq. 2. Air temperature, air pressure and the cylinder volumes were main input values [8].

$$(p \cdot V)_R = R_{s,air} \cdot (m \cdot T_{avr})_{R,air} \quad (1)$$

$$V_{air,tot,std} = \frac{m_{air,tot}}{\rho_{air,tot}} \quad (2)$$

where is:

- $(p \cdot V)_R$ -Volume of air cylinder and pressure in cylinder;
- $(m \cdot T_{avr})_{R,air}$ -Air mass and average temperature in cylinder;
- $m_{air,tot}$ - Total air mass, cylinders brake front, brake rear, air suspension system, auxiliaries;
- $R_{s,air}$ - Specific gas constant for dry air, $287.1\, J \cdot (kg \cdot K)^{-1}$;
- $\rho_{air,std}$ - Density of dry air at standard conditions:
  $(20℃, 1.013\, bar); 1.204\, kg \cdot m^{-3}$
- $V_{air,tot,std}$- Total air content, mass unit of standard litres air; one litre of dry air at $(1\, bar, 20\, ℃)$; $[sl] = 0.001204\, kg$.

The air mass in reservoir is calculated in steps of one second, by applying the ideal gas law for dry air.

As example, when the reservoir pressure falls under the lower limit, e.g. $6\, bar$ the compressor is turned on, the reservoir pressure increases, and when the upper limit, e.g. $10\, bar$ is reached, the compressor is turned off. Then, compressed air is only taken off the reservoir, its pressure decreases until the lower limit, and the cycle restarts.

The $1\, Hz$ time course of the reservoir pressure can be calculated via Eq. 3.

$$p_R(t) = p_R(t - 1s) + \Delta p_R(t) \quad (3)$$

where is:

- $p_R(t)$ -reservoir pressure at current time step (t);
- $p_R(t - 1s)$ -reservoir pressure at last time step $(t - 1s)$; and
- $\Delta p_R(t)$ -pressure change in actual time step.

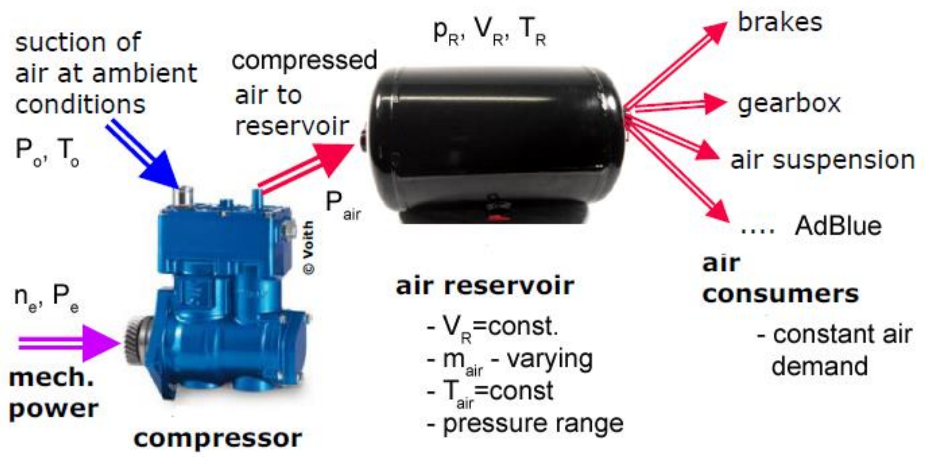

Figure 1. Simplified model for simulation of pneumatic system of a delivery truck (category N2)

2. TRIBOLOGICAL RESEARCHES AND RESULTS

With the aim to achieving strength as well as tribological characteristics similarly as in case of the application grey cast iron, we patented the cylinder of composite material for reciprocating air compressor with the reinforcements consisting of tribological materials.

For the purposes of the experiment, internal surface of the aluminum cylinder as base material–matrix, (alloy EN AlSi10Mg), was modified by putting tribological reinforcements of cast iron that are arranged in the form of continuous pads, the plates or like discrete tribological plugs in the form of spheres (nodule), or particles spherical shape, as reinforcement [9].

Tribological tests were carried out at CSM tribometer with ball-on-plate contact pair for different normal loads and sliding speeds in dry conditions. Tribological tests are based on variation of three different normal loads $(0.3, 0.6\ and\ 0.9)\ N$ and sliding speeds, $(3, 9\ and\ 15)\ mm \cdot s^{-1}$. Duration of each test was $500\ cycles$ (distance of $1\ m$) acquisition rate $100\ Hz$ [10].

2.1 Optical microscopy analysis

Experiments were carried out with the base material for cylinders (aluminum alloy) and with the material for reinforcements made of cast iron [11,12].

More detail analysis of prepared samples, both of aluminum alloy and cast iron inclusions were performed using Phenom ProX Energy–Dispersive Spectroscopy (EDS). EDS analysis results are presented on the Fig. 2 and 3 for base aluminum alloy and on the Fig. 4 and 5 for cast iron inserts.

Figure 2 presents EDS analysis of aluminum alloy and it noticeable that are present three phases, white one iron particles trapped in aluminum alloy as a result of grinding process. Lighter grey zones represent eutectic silicone, which is constituent element of the aluminum alloy, while dark grey represent pure aluminum, Fig. 3.

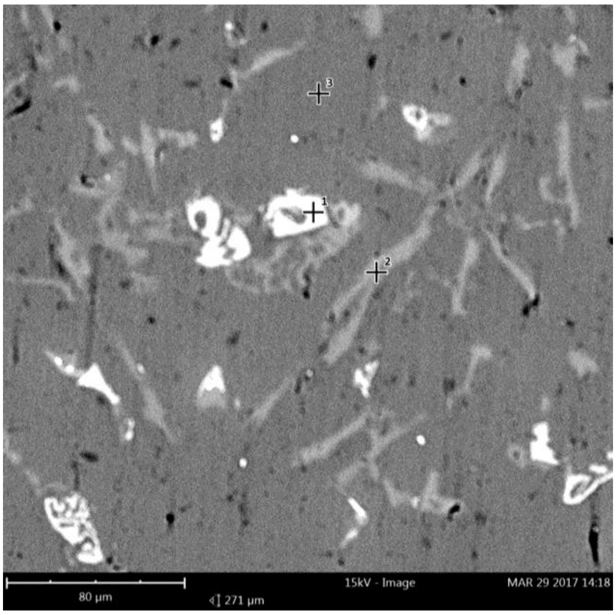

Figure 2. Prepared sample for EDS analysis of base aluminum alloy

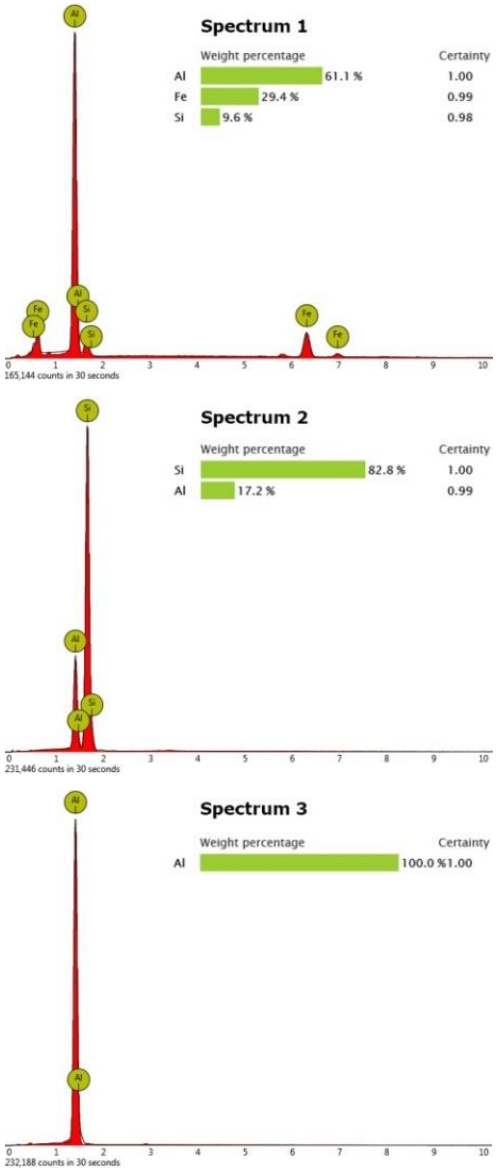

Figure 3. EDS analysis of base aluminum alloy

Fig. 4 and 5 represents EDS analysis of cast iron inserts, and it is noticeable that only two phases exist. Black phase represent graphite inclusions as is it is previously assumed based on optical microscopy. White phase represents pure iron, although graphite is present, which can be seen on spectrum 2.

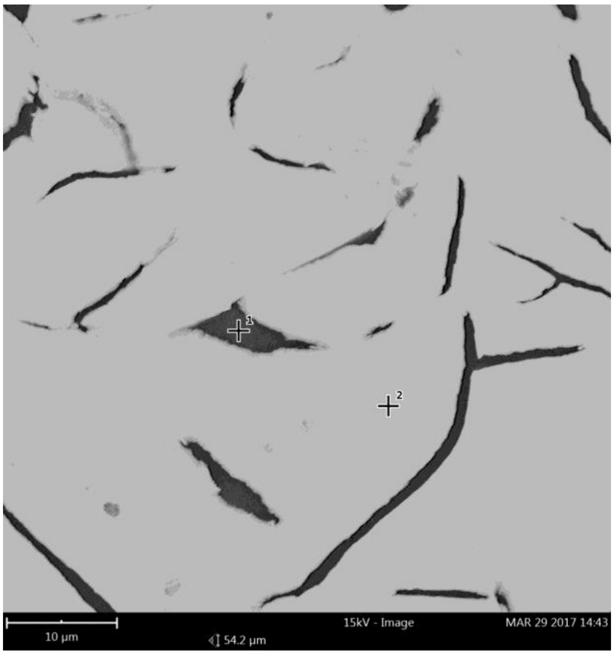

Figure 4. Prepared sample for EDS analysis of cast iron inserts

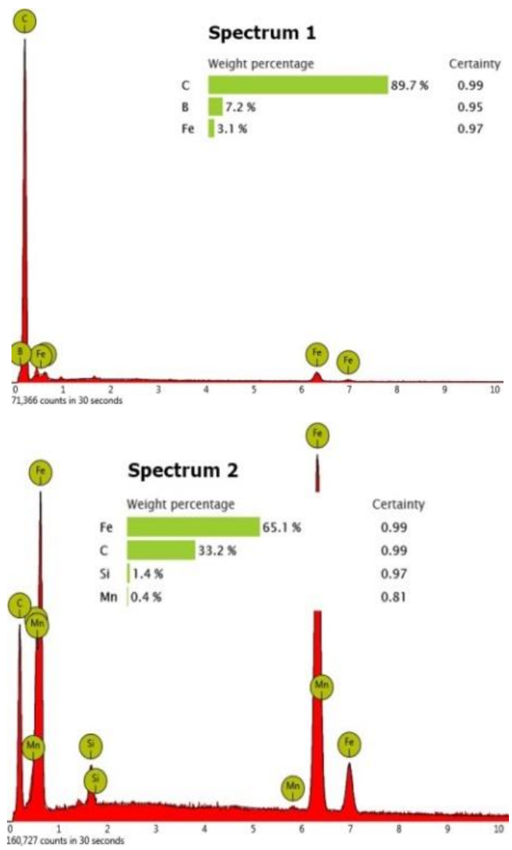

Figure 5. EDS analysis of cast iron inserts

Higher percentage of graphite in this phase is, also, result of grinding and polishing process that smears graphite inclusions all over the surface.

2.2 Coefficient of friction and penetration depth

Changes of COF and PD (ordinate) during sliding under low load conditions, depending on time, distance and numbers of cycles (abscissa) are shown in Fig. 6 for basic material (aluminum) and in Fig. 7 for tribological reinforcement. Due to the reciprocating motion of the needle of CSM tribometer between two end positions, the friction force was also changing direction during the test.

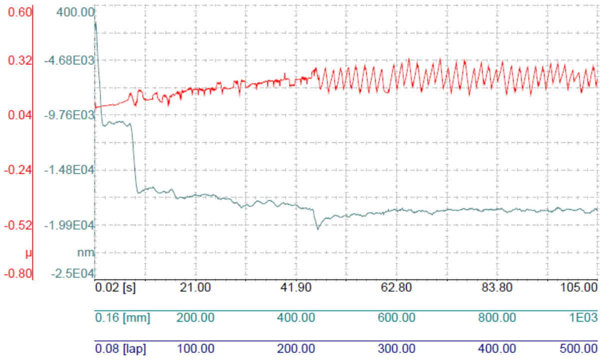

Figure 6. COF and PD for base material under $(F_N = 0.9\ N;\ V = 15\ mm \cdot s^{-1})$

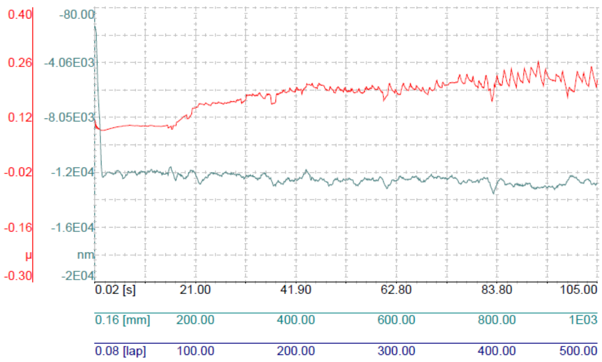

Figure 7. COF and PD for reinforcements under $(F_N = 0.9\ N;\ V = 15\ mm \cdot s^{-1})$

Under higher load conditions and same sliding speed, a lower maximum value of COF of the reinforcement was recorded, Fig. 8. The obtained COF values is in the range (0.087-0.262) for the reinforcements, and (0.076-0.327) for the base material. The mean value of COF of the reinforcements is lower (0.176) than the value for base material (0.202).

It is noticeable that during wear testing of base material (aluminum alloy) COF sharply rises after a certain period of sliding as result of material transfer on counter body steel ball. After the material was transferred on the steel ball contact between transferred aluminum and aluminum as a base material was achieved, which result in increase of COF value. This process happens regardless the applied load, and it has cyclic nature, which indicates that transferred material on the counter body surface accumulates until it reaches critical size, that cannot bear tangential loads.

Penetration depth plot (Fig. 6 and Fig. 7) confirms this assumption. After reaching critical size, transferred material will fall off and process of transferring starts from the beginning.

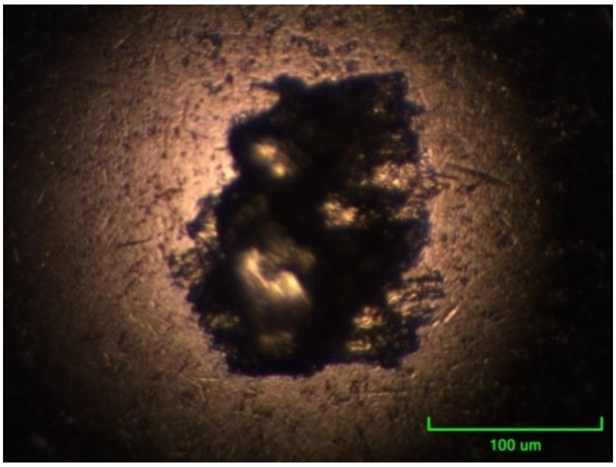

Figure 8. Optical microscopy of the counter body steel ball profile after sliding test with aluminum

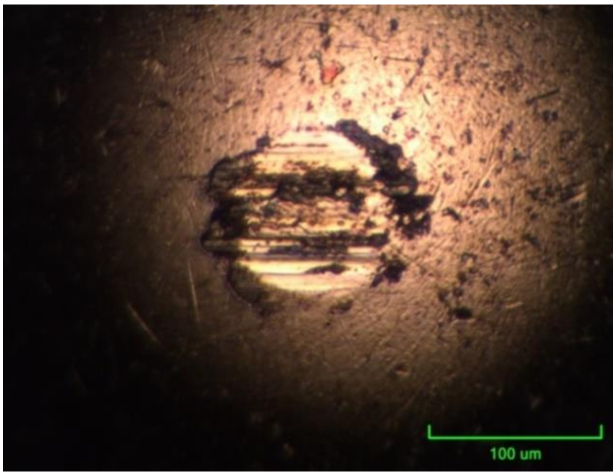

Figure 9. Optical microscopy of the counter body steel ball profile after sliding test with reinforcement (cast iron inserts)

In case of wear testing of cast iron inserts (reinforcements) no transfer material was observed, which is also confirmed by COF and penetration depth curves regarding applied load value. Both measured values, COF and penetration depth has almost constant averaged value during wear testing.

In addition to this conclusion, Fig. 8 clearly indicates accumulated transferred material on the counter body steel ball surface after sliding tests of base material (aluminum alloy) and no transferred material on counter bod surface after sliding test of reinforcement (cast iron), Fig. 9.

2.3 Wear analysis

Wear mechanisms based on examinations of worn surfaces by optical microscopy, were analyzed in comparison with trends of PD curves. Figure 10 and 11 present surface micrographs of base material and reinforcements after test under dry sliding, obtained for the same conditions of applied load and speed. It is noticeable that wear of aluminum is higher than cast iron sample due to transfer material and increase of COF which occurs for aluminum.

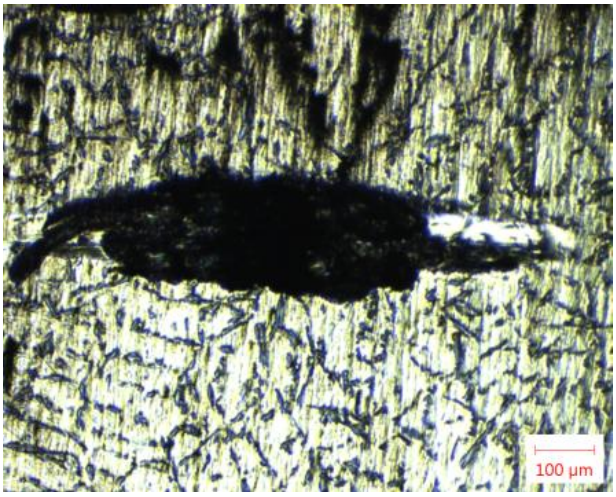

Figure 10. Surface micrographs of base material after dry sliding test under ($F_N = 0.9\ N;\ and\ V = 15\ mm \cdot s^{-1}$)

Prior wear tests, mechanical characterization of the prepared samples have been performed. Hardness tests were performed using CSM NHT2 nanoindenter, using Berkowich three sided diamond tip. Nine measurements for each tested material were done and averaged hardness values for base material and for reinforcement are 90 and 318 Vickers, respectively. Divergence in hardness values of tested materials indicates in better wear resistance of reinforcement in comparison to the base material.

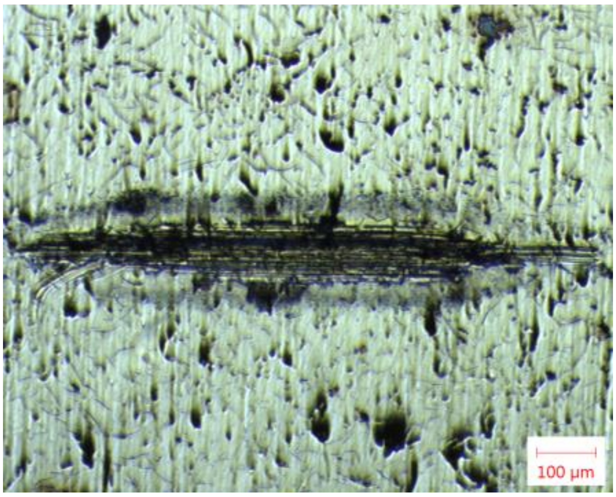

Figure 11. Surface micrographs of reinforcement after dry sliding test under ($F_N = 0.9\ N;\ and\ V = 15\ mm \cdot s^{-1}$)

Deep grooves in analyzed surfaces, indicates that the abrasive wear is the most dominant mechanism of wear for both tested materials, although transfer material on the counter body should not be neglected, especially for aluminum alloy.

Similar conclusions can also be made when testing materials at lower load and at the same sliding speed ($\mathrm{F_N} = 0{,}3\ \mathrm{N};\ \mathrm{V} = 15\ \mathrm{mm} \cdot \mathrm{s}^{-1}$) [11].

3. TEST RIG FOR MEASUREMENT OF LOSSES RELATED TO FRICTION IN AIR COMPRESSOR

Investigated reciprocating compressor, as an auxiliary device on the vehicle, drives the IC engine or an electric motor during its laboratory testing. When determining power (kW) of friction losses (P_m) using the indicator method, the indicated mean effective pressure (W_i) is determined with the help of pressure sensor which mounted in cylinder head, Fig. 12. The pressure inside the cylinder is captured by piezo-electric pressure transducer and the data is stored using data acquisition system. Effective compressor power (at the flywheel), (P_e) is analogous to it, the driving power, contrary to the IC engines. Indicated power (P_i) is less than the effective power for friction losses, that demanded to overcome mechanical losses in the compressor (friction in the cylinder, bearings, etc.), Eq. 4.

Figure 12. Photography of the experimental reciprocating air compressor

Use of the indicator method requires very high reproduction accuracies of the operating conditions, and thus of the friction conditions. For the most precise control and reproducibility of the boundary conditions, therefore, the oil and coolant pumps are replaced with external cooling system. The compressor is cooled by a fan. The detailed test rig setup for small air compressors is shown in Fig. 13 [13]. The compressor is connected with air reservoir and the pressure is maintained by using the automatic servo valve.

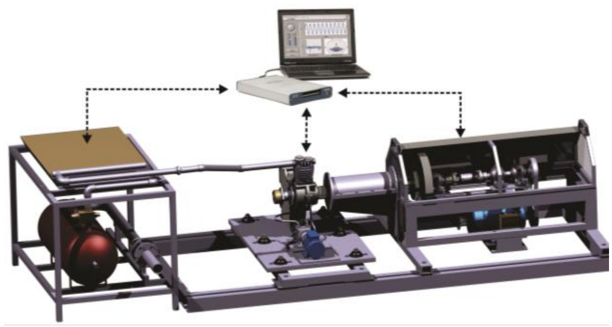

Figure 13. Test rig for small air compressors

Generally, over a period of time, performances of compressor reduce drastically. The causes are mainly such as wear and poor maintenance. Because of a periodic performance assessment is essential to minimize the cost of compressed air. To test performance of the compressor proposed the use of ACACA Protocol™ 2000 of the

Australian Commercial Air Compressor Association. Protocol defines standard test procedure for measuring of Free Air Delivery (FAD) of air compressor package.

FAD ($l \cdot min^{-1}$) is the volume flow rate of air (measured at ambient pressure and temperature and humidity) which has been compressed and delivered to the terminal discharge point of the air compressor package. It is a measure of the volume of air available for use at the exit point of the air compressor package.

The air flow is measured by pump up test method. The pump up test consists of operating the compressor at a constant speed and observing the time required to increase the pressure in the air receiver (cylinder of measured volume) from $6-8\ bar$ ie when the compressor is operating under load. The approximate air output of the compressor or FAD can then be calculated with application of the Eq. 4:

$$FAD = \frac{V_R \cdot (p_1 - p_2)}{p_o \cdot t} = \frac{2 \cdot V_R}{t} \quad (4)$$

where is:

- p_1, p_2 -Air cylinder pressure at start and at and of test, respectively;
- t -Pump up time taken to increase the pressure in the air cylinder from $p_1\ to\ p_2$, min; and
- p_o -Atmospheric pressure $p_0 = 100\ kPa\ (1\ bar)$.

Testing must need to be completed within twenty minutes after the compressor has reached normal operating temperature. After the results of 3 tests have been recorded, take the average and calculate FAD of compressor package in accordance with Protocol.

However the pump up test is a useful comparative measure and has been selected as being suitable to rate commercial air compressors for pump displacements, up to $600\ l \cdot min^{-1}$. Large compressors must be rated in accordance with standard ISO 1217.

Pump displacement ($\dot{V}_h, l \cdot min^{-1}$) is the theoretical volume of air that can be pumped by a reciprocating air compressor, if it was 100% efficient, Eq. 5:

$$\dot{V}_h = \frac{\pi d^2}{4} s N \chi n_e 10^{-6} \quad (5)$$

where is:

- d, s -Cylinder diameter and stroke, mm;
- N -Number of cylinders;
- χ -1 for single acting and 2 for double acting cylinders; and
- n_e -Compressor speed, rpm.

4. CONCLUSIONS

The European Commission is working on the measures to reduction of greenhouse gases emissions from all sources. Because of the fact that all vehicles must give to reduction of fuel consumption and emission, the EU formed regulation for certification of all new registered HD vehicles. We researched reduction of power demand in air compressor as auxiliary device on the engine, by tribological optimization of their piston and cylinder.

The use of aluminum alloys for making parts of propulsion and mobile systems is important from the aspect of weight reduction, which directly affects the reduction of fuel consumption. On the other hand, the problems in application are lower strength and poor tribological characteristics of aluminum as well as aluminum constructions.

The problems of lower strength as well as the poor tribological characteristics of the cylinder for application in reciprocating air compressor for brake system of bus have solved by application aluminum matrix composite material. One of the constituents is aluminum alloy (EN AlSi10Mg) as the base material or matrix. Second constituent is being inserted into base material and serves as reinforcement which is made of cast iron in the form of particles of a spherical shape.

Presented results obtained during tests of materials from which consisting cylinder, shows that by transferring the contact between the piston rings and cylinder made of aluminum on the reinforcements, it is possible to reduce the friction and wear.

To test performance of the experimental compressor on test rig proposed the use of ACACA Protocol™ 2000. Protocol defines standard test procedure for measuring of free air delivery and pump displacement.

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REFERENCES

[1] T. Skrucany, S. Milojević, Š. Semanová, T. Čechovič, T. Figlus, F. Synák: The Energy Efficiency of Electric Energy as a Traction Used in Transport, Transport technic and technology, Vol. XIV, No. 2, pp. 9-14, 2018.

[2] S. Milojević, R. Pešić: CNG buses for clean and economical city transport, Int. J. Mobility and Vehicle Mechanics (MVM), Vol. 37, No. 4, pp. 57-71, 2011.

[3] S. Milojević, T. Skrucany, H. Milošević, D. Stanojević, M. Pantić, B. Stojanović: Alternative Drive Systems and Environmentally Friendly Public Passengers Transport, Applied Engineering Letters, Vol. 3, No. 3, pp. 105-113, 2018.

[4] European Commission. Climate Action, from *https://ec.europa.eu/clima/policies/transport/vehicles/heavy_en*, accessed on 13.04.2019.

[5] S. Milojević: Reconstruction of existing city buses on diesel fuel for drive on Hydrogen, Applied Engineering Letters, Vol. 1, No. 1, pp. 16-23, 2016.

[6] Pesic, S. Milojevic: Efficiency and Ecological Characteristics of a VCR Diesel Engine, Int. J. Automotive Technology, Vol. 14, No. 5, pp. 675-681, 2013.

[7] S. Milojević: Sustainable application of natural gas as engine fuel in city buses - Benefit and restrictions, Journal of Applied Engineering Science, Vol. 15, No. 1, pp. 81-88, 2017.

[8] D. Ninković, D. Taranović, S. Milojević, R. Pešić: *Modelling* Valve Dynamics and Flow in Reciprocating Compressors, Mobility & Vehicle Mechanics (MVM), Vol. 39, No. 3, pp. 47-63, 2013.

[9] S. Milojević, R. Pešić, D. Taranović: Tribological Principles of Constructing the Reciprocating Machines, Tribology in Industry, Vol. 37, No. 1, pp. 13-19, 2015.

[10] S. Milojevic, R. Pesic, D. Taranovic: Tribological optimization of reciprocating machines according to improving performance, Journal Balkan Tribological Association, Vol. 21, No. 3, pp. 690-699, 2015.

[11] S. Milojević, D. Džunić, D. Taranović, R. Pešić, S. Mitrović: Tribological Reinforcements for Cylinder Liner of Aluminum - Example Compressors for Brake Systems of Trucks and Buses, in: *15th International Conference on Tribology SERBIATRIB '17*, Kragujevac, 17 – 19 05. 2017, pp. 251-257, 2017.

[12] S. Milojević, D. Džunić, D. Taranović, R. Pešić, S. Mitrović: Experimental Determination of Tribological Characteristics of Composite Materials in use for Parts in Aluminum Air Compressor (Piston and Cylinder), in: *VII International Congress, Motor Vehicles & Motors 2018, Ecology - Vehicle and Road Safety - Efficiency*, Serbia, Kragujevac, 04-05 10.2018, pp. 383-392, 2018.

[13] D. Taranović, D. Ninković, A. Davinić, R. Pešić, J. Glišović, S. Milojević: Valve dynamics in reciprocating compressors for motor vehicles, Tehnički Vjesnik, Vol. 24, No. 2, pp. 314-319, 2017.