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Tests of a New Construction of Pneumatic Engine

***Abstract**. The aim of this thesis is to describe a new, Polish pneumatic engine invention according to patent no. PL 214371. The construction, principals of functionality, the inspection facility, were described in the thesis. Initial measurement results and main directions of further research were also provided.*

***Streszczenie.** Celem pracy jest opisanie nowego polskiego wynalazku silnika pneumatycznego według patentu PL 214371. W pracy przedstawiono budowę oraz zasadę działania, opisano stanowisko badawcze, wstępne wyniki pomiarów oraz wyznaczono podstawowe kierunki dalszych prac badawczych. **Stanowisko do badania silnika pneumatycznego**.*

Keywords: pneumatic engine, test stand, rotary piston, rotary sealants.
Słowa kluczowe: silnik pneumatyczny, stanowisko badawcze, obrotowy tłok, obrotowe uszczelniacze.

Introduction

Pneumatic engines have considerably wide range of use as far as powering of heavy machinery is concerned. The main advantage of air engines is their reduced weight in relation to produced power as well as their capacity to work at high rotational speed. Decompression of the air in the pistons causes the temperature to drop, decreasing the overall efficiency. This phenomenon often adds an additional requirement of engine preheating, so that the efficiency could improved. The history of pneumatic engine design dates back to seventeenth century. In 1678, the world’s first pneumatic railway was invented. The most advanced development of said engines started with the invention of a Polish engineer Ludwik Mękarski. In 1870, he created a pneumatic piston engine, which had been used in the mine railway system as well as in the trams of French cities such as Vichy, Nantes and Saint Quentin [1]. Its principle was to use a check valve, which was actuated by the movement of the piston. The invention of fuel pumping system which was activated during the braking process was also an important discovery in the history of pneumatic engines [2]. Robert Hardy had invented the system in 1892. The idea was to use the engine as a pumping device during the braking process, which allowed some of the decompressed air to be compressed back during the deceleration of the vehicle. One of the latest pre-war achievements in this field of science was Johannes Wardenier’s project, which, according to sources, was the first engine not to be fueled by any liquid medium. In 1991, Guy Negre had invented the dual power supply engine [3]. That engine consisted of two cylinders of different diameters and a completely different rod design.

This thesis proposes a solution based on the principle of a rotating piston, similar to the flow engines [4]. The method of sealing the rotor and the cylinder surface is, however, an innovative solution and has been patented with the number PL 214371 [5]. Sealing procedure is based on a solution similar to that used in the vane motors, but the system does not use the centrifugal force to seal itself [6].

The schematics of the new type of pneumatic engine

Schematics of the new type of engine are shown on the figure 1. It consists of a cylinder (1), inside of which there are two air inlets (5) and two air outlets (4).

The operating element in this case is a rotary piston (2) in a shape of a barrel with three apexes arranged symmetrically on its periphery. Inside of the housing, there are also two rotating sealants shaped cylindrically (3), so that they fit with the piston. The sealants are fixed coaxially in the housing, and their rotations are synchronized with those of the piston through the external gearing system, so that the angular velocity’s ratio of the sealants in relation to the piston equals 1/3.

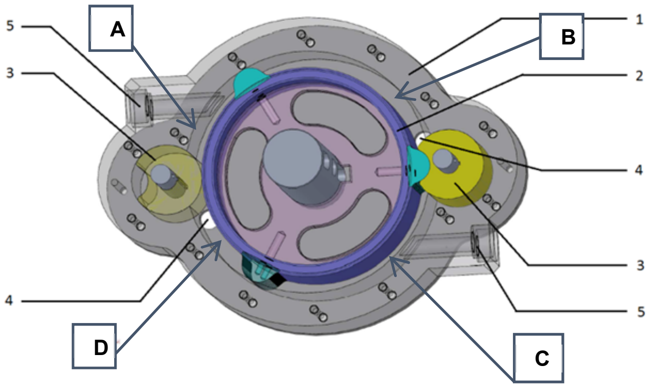

Fig.1 The schematics of pneumatic engine

During the operation time, four/five changing chambers can be distinguished, formed by the housing, the piston and its apexes and the sealants. By providing the compressed air to chamber A, a force causes the piston to rotate. In the chamber B, a decompression occurs through the outlet nozzle (4). A similar phenomenon take place in chambers C and D. The work performed by the whole system is hence being done by both chambers A and C.

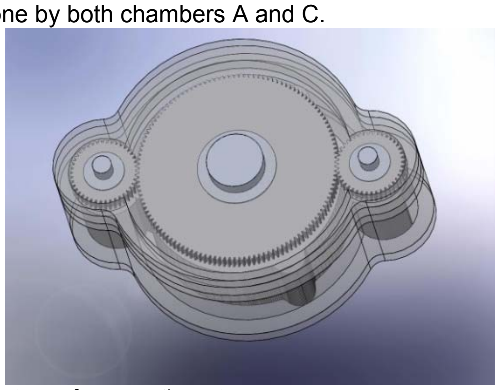

Fig.2 Prototype of pneumatic motor

The analyzed pneumatic motor is a novel design, which is confirmed by the patent no. PL214371 from 2013. It is assumed that the motor will be able to operate with the maximum rotational speed of 1000 rpm. This classifies it into the category of low speed machines.

Research lab description

In order to validate the design assumptions, an engine has been built in accordance to the described structure (fig.

2). The external dimensions of that engine equal 250x186x70 [mm]. In order to determine the efficiency of the engine, a lab station was assembled (fig. 3). The station is supplied with compressed air by the pneumatic network *1*, and constant pressure of 6 [bar] is ensured. The air is then directed onto the particle filters *2* and an air lubricator. The operating pressure is being adjusted by the pressure reducer *3*. In order to avoid the influence of pressure pulsation onto the measurements, an equalizing tank *4* is used. Air from the equalizing tank is directed to the prototype engine *7*. The air flow is measured with airflow meter *5*. The air outlet is directed to the equalizing tank, equipped with the choke valve, enabling the adjustment of air flow that passes through the engine.

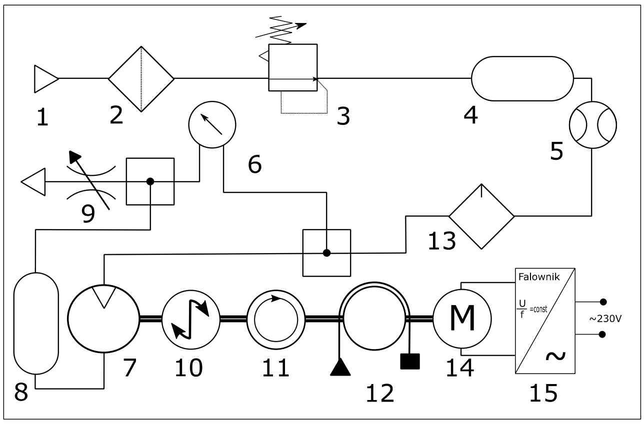

Fig. 3 Research lab description.

Behind the equalizing tank, a measurement channel is placed, connected to a pressure drop sensor *6*. The load of the motor shaft is adjusted by the belt brake *12*, which was mounted on one shaft, together with the engine, torque sensor *10* and rotational speed *11*. In order to determine the resistance to motion, the experimental setup will be equipped with an electric motor *14* used to drive the tested pneumatic motor. For the fully unsealed pneumatic system, it will be possible to measure the torque on the shaft, which corresponds the resistance to motion of the pneumatic motor. For the measurements of the resistance to motion for various rotational speeds, the motor rpm will be controlled by an inverter *15*. The setup will be capable of determining the power consumption of the motor. The input power will be calculated on the basis of the measurement of the gas flow and pressure drop measured on the motor.

The power on the shaft was derived on the basis of the input of rotational speed and load torque

(1) $$\mathrm{P_M} = \frac{2\pi}{60} n \cdot M$$

where: M – torque [Nm]; n – rotational speed [rpm]

On this equation is calculated motor efficiency:

(2) $$\mathrm{H} = \frac{\mathrm{P_M}}{\mathrm{P_{IN}}} \cdot 100\% = \frac{P_M}{Q \cdot \Delta p} \cdot 100\%$$

where: Δp – pressure drop on the engine [Pa]; Q – airflow [m^3/s]

The input power is composed of power on the motor shaft and value of losses. The major reason for the occurrence of the losses is associated with the resistance to motion, losses relating to leaks and the ones relating to the gas phase shifts.

The measurement data will be registered using a computer with LabJack U12 measurement card and LabVIEW 2015. For this purpose, it will be necessary to develop an application – an example of the measurement panel in which is found in fig. 4.

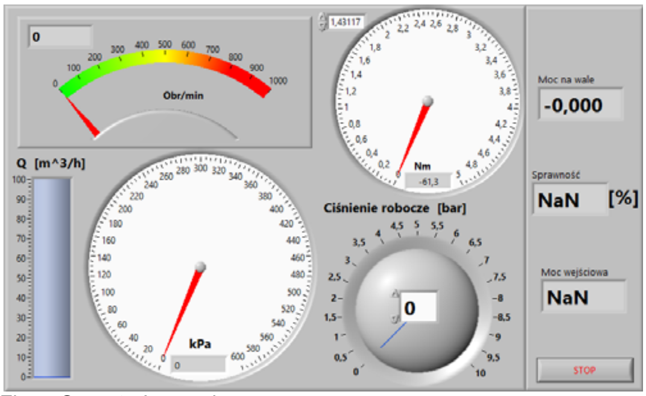

Fig. 4 Operator's panel.

During standard operation, the user will be able to control the principal measured parameters, such as pressure drop on the motor, rotational speed, shaft torque and flow rate of gas.

The correct measurement of the input power requires the knowledge of gas flow rate for the working pressure. Since flowmeters are calibrated to measure using normal litters per hour, it is necessary to adequately convert the results of the flowmeter with the purpose of rescaling it.

The following formula will be used for this purpose:

(3) $$Q = Q_m \sqrt{\frac{\rho_n}{\rho}} = Q_m \sqrt{\frac{p_n}{p}}$$

where: Q_m – measured flow rate; ρ_n – gas velocity for normal conditions; ρ – gas velocity; p_n – normal pressure; p – working pressure.

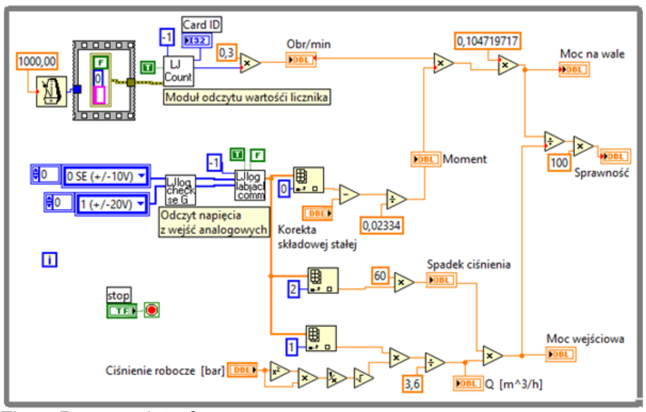

Fig. 4 Program interface.

Fig. 5 presents an example screen of the user interface. The rotational speed is calculated on the basis of the counter reading, which determines the impulses transmitted from the encoder by producing 2000 impulses per rotation. The registration of the counter is performed every second. The remaining values are measured by means of analog inputs. The torque sensor is coupled with the neutral input. The amplification factor of the sensor is equal to 23.34 mV/Nm for the measurement range of -75 to 75 Nm. Due to the fact that for the torque is equal to zero, and the value of the input voltage is around 2.5V, it was necessary to apply the possibility of correcting the constant component of the expression. It was performed by entering the adequate value in the field named “correction of the constant”. On the basis of basis of these two values, it was possible to calculate the value of the power output of the motor shaft. In this application, the value is expressed in watts.

The second part of the software involves the measurement of the input power. For this purpose, it was necessary to calculate the value of the differential pressure. The applied sensor had a voltage output in the range 0-10V for the pressure range of 0-6 bar; hence, the value of the amplification factor was 60 kPa/V. The value of the flow rate was measured by a rotameter, which included a correction accounting for the value of the working pressure in accordance with the relation in (5). The value of the working pressure was adjusted by a reducing valve with a manometer and the value from the manometer in the program was regulated by providing referencing unit with the „working pressure [bar]”. The input power was calculated as the product of the corrected value of the air flow rate and pressure drop on the motor. In consideration of the law of conservation of flow rate mass:

$$Q_N \cdot \rho_n = Q_\rho \tag{4}$$

Hence, accounting for the relations in (3) and (4), we obtain the formula for the input power:

$$P_{IN} = \frac{\rho_n}{\rho} \cdot Q_N \cdot \Delta p = \left(\frac{p_n}{p}\right)^{\frac{2}{3}} \cdot Q_m \cdot \Delta p \tag{5}$$

On the basis of the calculation of power on the motor shaft and input power, it was possible to obtain the efficiency, which was displayed in the field „Efficiency”.

Results preliminary research

The laboratory tests of the pneumatic engine has been conducted and described in detail in paper [7]. The results are provided on the figure 5.

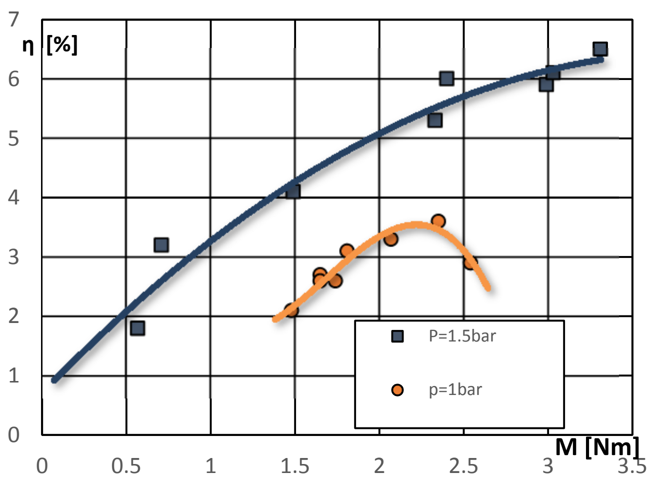

Fig.5 Characteristic of efficiency relative to the torque on motor shaft

An experiment was performed with the aim of determining the total power losses resulting from leaks in the motor. For this purpose, the outlet from the motor was led into the atmosphere and; therefore, the atmospheric pressure was gained on the air exhaust from the motor. The shaft was blocked to eliminate the impact of the motor’s resistance to motion so that it would not rotate. For a system developed in this way, the value of the working pressure was modified, which was accompanied by the concurrent measurement of the air flow rate.

Fig. 6 shows the power losses resulting from leaks in the motor. Considering the fact that the power input of the motor for the working pressure of p = 1.5 bar and flow rate of 24 m^3/h was around 545W, the losses resulting from the leaks are equal to 498W, which corresponds to 90% of energy input to the motor. On this basis, we can say that the principle area deciding on the motor efficiency is associated with the leaks occurring in it.

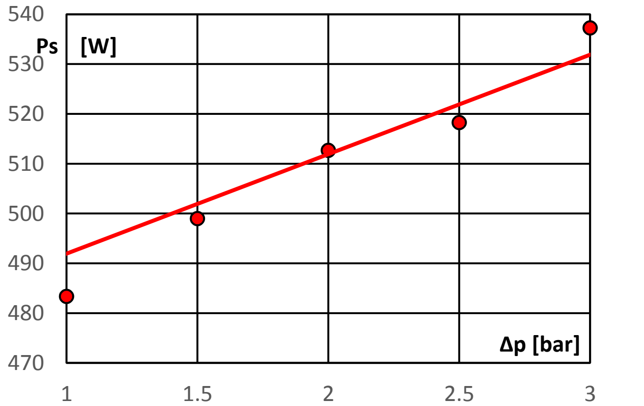

Fig.6 Power of the motor shaft

Detailed inspection of the motor was subsequently performed with the purpose of identifying the areas with the greatest leaks. On the basis of this, it was observed that such leaks occur on the motor bearings and a large portion of the air passes through the leaks between the piston and the sealant and the area between the piston and the housing.

The decrease in the tightness between the piston and the housing is achieved as a result of reducing the clearance. This will also lead to a considerable increase in the resistance to motion. Therefore we should develop adequate sealants for this motor, which can form the direction for the further development of the design.

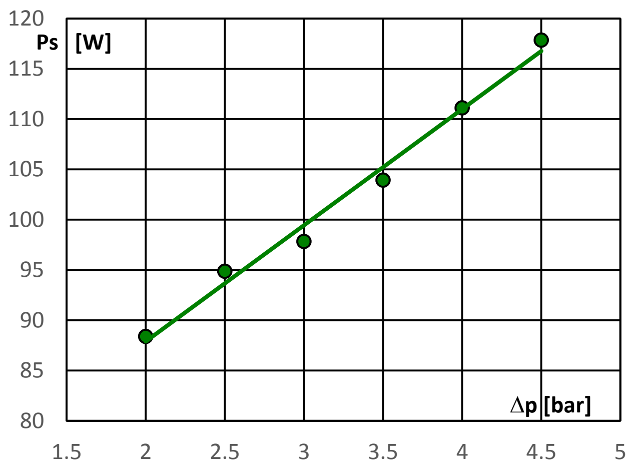

Fig.7 Power of losses

In order to determine the power loss resulting from the leaks in the motor bearings, a test was carried out involving the closing of the air exhaust from the motor. As a consequence, this led to the lack of gas flow through the motor causing its rotating. Additionally to show a stationary motor, the motor shaft was blocked. Fig. 7 illustrates the power losses depending on the working pressure. These losses increase linearly along with the increase in the working pressure. As illustrated by the above chart, such losses account for around 20% of the total power input to the motor; and so, this area forms an important design component, which can improve the motor efficiency.

The prototype was developed by the application of slide bearings. Due to the fact that the lubrication of pneumatic motors is performed by use of oil that is supplied together with the feed air, it is necessary to maintain considerable bearing clearance, which prevents them from a seizing. An increase in the bearing clearance will, however, lead to greater system leakage. In addition, it was observed that the increase of the bearing clearance has a negative impact leading to the interference with the rotational components of the motor, and can result in the motor seizing. The potential for the improvement of the motor characteristics can be sought by replacing slide bearing by the use of rolling bearings with a sealant. Such a solution can secure the adequate tightness of the system while minimizing the axial play in the bearings. In addition, rolling bearings do not require as intensive lubrication as slide bearings, hence, the amount of oil that is transported in the feed air will be sufficient.

Summary

Empirical studies have confirmed the preliminary hypothesis, that the output power would be low if the engine is measured within the chosen range of pressure. It should be emphasized, that the tests are however indicative. Tests also confirm, that the prototype's kinematics are functional and – considering the low funding of that project – can be considered a success. The tests also confirmed a certain relation between efficiency and the pressure. That relation will be subject to further analysis. Perhaps the greatest power losses occur in the area of piston sealing and between the piston and housing. Further research will focus on these areas. It is also expected, that the changing of proportions between the length of piston and its diameter or a development of a dynamic sealing system could improve the overall performance. That, however, requires many tests to be conducted, including some new material and different shapes of sealant tests. Another scope of the research is the use of hydraulic oil as the working medium.

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