FACTA UNIVERSITATIS
Series: **Automatic Control and Robotics** Vol. 14, N° 1, 2015, pp. 55 - 65

MODELING, SIMULATION AND ENERGY EFFICIENCY DETERMINATION OF A PNEUMATIC PRESSURE AMPLIFIER

UDC ((621.5+(621.31:065.11)):004.942

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***Abstract**. In order to increase energy efficiency of a pneumatic system the compressed air discharged from pneumatic actuator is being collected. In those conditions, the air contains a certain amount of energy and can be used at the points that require a lower level of pressure for their operations. If the collected air can not be directly returned and used in a pneumatic system, then the air pressure is increased by using pressure intensifier which is known in the commercial use as pneumatic booster. For that operation, the booster uses and consumes a part of the collected air. In this paper we analyze the dynamic behavior of a pressure booster and calculate its energy efficiency by using mathematical modeling and simulation in Simulink. The model of one pneumatic booster and its energy efficiency is verified by conducted experimental testing.*

Key words: *Pneumatic pressure amplifier, energy efficiency, modeling, simulation*

1. INTRODUCTION

Pneumatic systems, due to their good properties, are widely used in various fields, but they are known for their low energy efficiency. Increasing energy efficiency and energy savings can be achieved in several ways [1], and one of them is that a pneumatic system collects and reuses the air that is released into the atmosphere after the air finishes its work in the actuator. It turns out that when collecting the pressurized air it is necessary to limit the size of the air pressure in order to avoid its adverse effects on the dynamic characteristics of the actuator [2]. When the collected air, due to the lack of pressure, cannot return directly to the air system and use it, the pressure is increased by using a device called a pneumatic pressure amplifier or pneumatic booster [3].

Received December 15, 2014
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2. Principle of Operation of Pneumatic Pressure Amplifier

Pneumatic pressure amplifier, for its work, does not require additional power source, but uses the power of compressed air that comes from the primary compressor. The structure of the pressure amplifier is shown in Figure 1. The amplifier is composed of two chambers - 4 and 5, in which the pressure increases, the pistons 1 and 2, which are connected to the piston rod 3, and the two drive chambers, 6 and 7. The other essential components are: direction valve 8 to change the direction of motion of pistons, the control channels 9, to manage direction valve 8, the controller 10 and four check valves: 11.1, 11.2, 11.3 and 11.4. External connections are marked with 'I', 'O' and 'E', where is: I input, output O, and E is the port for venting to the atmosphere. The input is connected to the air pressure that have to be intensified, and the output O is connected to a reservoir in which obtains the increased air pressure. The port E discharges the used air in the atmosphere during the amplifier operation. When the input (I) has brought pressure, the air fills chambers 4 and 5 via check valves 11.1 and 11.2, and a flow through the output port (O) is created through the valves 11.3 and 11.4. All the valves are open. The port O should be blocked before the start of booster to avoid to the loss of air. Valve 8 is located in one of two possible states. By the controller 10 and the valve 8, the air pressure is applied, depending on the current state of valve 8, to the one of the operating chambers and the another operating chamber is connected with the atmosphere. If the initial state of flow direction valve 8 is as shown in Figure 1, with the atmosphere is connected chamber 6, and chamber 7 is powered, which leads to the movement of the pistons on the left.

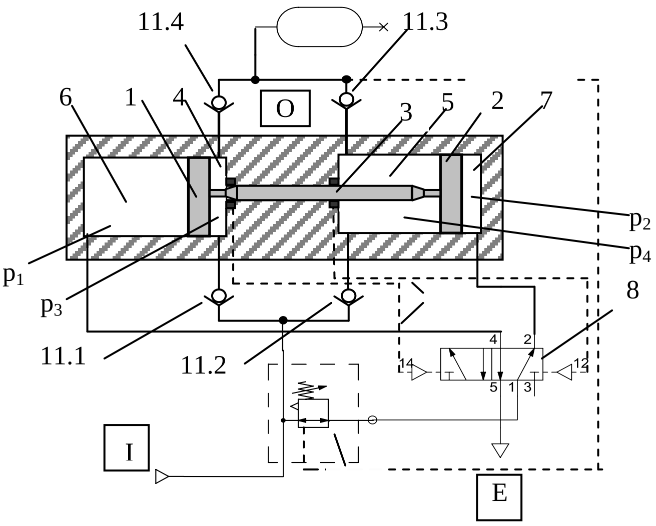

Fig. 1 Structure and principle of operation of pneumatic pressure amplifier

The air pressure in chamber 5 is increased because of the movement, thus it closes the valve 11.2, and the valve 11.3 is open until the discharge air, coming from the chamber 5, through the outlet port (O), to the attached reservoir. At the same time, chamber 4 is filled through the valve 11.1, and the valve 11.4 is closed. When the piston 2 reaches its final position, the cycle of movement to the left is over. Then the flow direction valve 8 receives the control signal through the channel 9 and changes its state, causing the drive chamber 7 to be connected with the atmosphere and the chamber 6 is filled. There is a movement of the piston in the opposite direction. This leads to an increase in pressure in the chamber 4, and when it rises above the already achieved pressure in the output tank, the valve 11.4 opens and the chamber 4 empties through the plug (O). During this time, the chamber 5 is full through the valve 11.2. When the piston 1 reaches its rightmost position, the valve 8 receives the control signal and changes the state. It establishes a continuous, cyclic operation of the amplifier, whereby the air from chambers 4 and 5, alternatively and with increased pressure is released through the outlet port (O). During this continuous cyclic operation the check valves 11.1, 11.2, 11.3 and 11.4, change their state (open-closed) in each cycle.

When the desired output pressure is reached, the regulator 10 turns off the air supply to the drive chamber and stops further work. The amount of air supplied to the drive chamber is discharged into the atmosphere during each movement of the piston rod and it is the consumption of the amplifier that matters for its work.

3. The Mathematical Model and Simulation of Pneumatic Pressure Intensifier

The mathematical model of the booster is done in Simulink. Based on the description of the work and views in Figures 1 and 2, the process simulation is carried out in following steps: a) Working pressure is fed into the chamber 7, 4, 5, and chamber 6 is open to atmospheric pressure; b) in the chamber 5 pressure increases due to reduced volume and, through the check valve, the air is discharged into the tank; c) when the piston reaches the end of the stroke, the working pressure is supplied to chambers 6, 5 and 4, chamber 7 is open to the atmospheric pressure, and the reservoir is filled from chamber 4. This procedure was further repeated cyclically.

The changing role of the chambers and changing the direction of motion of pistons is caused by the pneumatic valve 8, which is activated by the piston when it comes to one of the end positions. The directional valve function is modeled and simulated by switches that simulate the opening and closing of the air flow. To form the model, the appropriate equations are set.

Dynamic behavior of the piston is determined by the differential equation:

$$M\ddot{x} + B\dot{x} = p_1 A_1 + p_4 A_2 - p_2 A_1 - p_3 A_2 \tag{1}$$

wherein: the piston displacement x, M is the mass of moving parts, B is the coefficient of viscous friction, p_1 to p_4 the air pressure in chambers 1 through 4, $A_1 = A_2$ the area of the piston and $A_3 = A_4$ are area of the piston reduced by the cross-sectional surface of the piston rod.

By calculating the time derivative of the left and the right side of equation (1) and solving for $\dddot{x}$ gives:

$$\dddot{x} = \frac{A_1}{M}\dot{p}_1 + \frac{A_2}{M}\dot{p}_4 - \frac{A_2}{M}\dot{p}_2 - \frac{A_2}{M}\dot{p}_3 \frac{B}{M}\ddot{x} \tag{2}$$

To calculate the change in pressure in the cylinder chamber, it starts from the state equation for the ideal gas from which the following is obtained:

$$p = \frac{mRT}{V} \tag{3}$$

where R represents the universal gas constant, T is the absolute temperature, M is the mass of the gas, and V is the volume of the chamber in which the gas is located. Extracting the time derivative of the left and the right side of equation (3) gives:

$$\dot{p} \;=\; RT\,\frac{d}{dt}\left(\frac{m}{V}\right) \;=\; \frac{RT}{V}(\dot{m} - \rho\cdot\dot{V}) \tag{4}$$

The equation (4) shows that the derivative of pressure in the cylinder chamber depends on the mass flow rate, volume of the chamber and the rate of change of volume, and thus the piston displacement x. By integrating equation (4) is obtained the pressure change. To determine the mass flow rate, is used the equation for the mass flow of air through the hole surface A_v [4]:

$$\dot{m}(p_g, p_d) = \begin{cases} \sqrt{\dfrac{k}{RT}\left(\dfrac{2}{k+1}\right)^{\frac{k+1}{k-1}}}\, C_f\, p_g A_v, & \dfrac{p_d}{p_g} \le C_r \\ \sqrt{\dfrac{2k}{RT(k-1)}}\sqrt{1-\left(\dfrac{p_d}{p_g}\right)^{\frac{k-1}{k}}}\left(\dfrac{p_d}{p_g}\right)^{\frac{1}{k}} C_f\, p_g A_v, & \dfrac{p_d}{p_g} > C_r \end{cases} \tag{5}$$

Air flow through the aperture area A_v from areas of higher pressure to a lower pressure, can have the speed of sound, or subsonic speed depending on the relationship of pressure C_r [5].

By using the preceding equations for pressure, simulating a change five different pressures, in four chambers and in the outlet tank, are done to perform the simulation of the booster.

When the process starts from the state given in Figure 1, the pistons move from right to left and fill chambers 7 and 4, and empty chambers 6 and 5. The pressure changes are calculated as follows: the change in pressure in chamber 7, the calculation of mass flow rate, higher pressure is the operating pressure and the lower pressure is the pressure in chamber 7; the change in pressure in chamber 6, in calculating the mass flow rate, higher pressure is the pressure in chamber 6, and the lower the pressure is atmospheric pressure; the pressure change in chamber 5, when calculating the mass flow rate, higher pressure is the pressure in chamber 5, a lower pressure is the pressure in the tank connected to the output boosters; the pressure change in chamber 4, when calculating the mass flow pressure is above the working pressure and the lower pressure is the pressure in chamber 4. To change the pressure in the tank is connected to the output of the booster, when calculating the mass flow rate, higher pressure are alternately pressures in chambers 5 and 4 (depending on movement direction), while the lower pressure is the reservoir pressure booster in the given cycle.

To return the piston boosters in the previous position, means changing the meaning of the upper and lower pressure chamber, and re-calculated the change of pressure. The movement of the piston stops when pressure changes lead to balance of forces on the piston. For the calculation of the pressure in the chamber connected to the output of the booster, we used equation (4), while the right side is omitted as the part that takes into account the change in volume because the volume is constant and the equation takes the form:

$$\dot{p} = RT\frac{\dot{m}}{V_r} \tag{5}$$

where V_r is the output booster tank.

Simulation of mass flow for all sections, simulation of changes of pressure in all chambers and simulation of piston movement, are performed in SIMULINK.

4. Simulation Results

For modeling and simulation, the catalogue data for DP 63-10 booster, Festo production, are used as well as additional structural parameters obtained from the Technical Services from Festo for the purposes of this study (Table 1).

Table 1 Technical data for simulation

Name	Value	Unit
V_c	$0{,}2245 \cdot 10^{-3}$	m^3
V_0	$0{,}0374 \cdot 10^{-3}$	m^3
K_n	2	
L_{max}	$77 \cdot 10^{-3}$	m
D	$63 \cdot 10^{-3}$	m
d	$16 \cdot 10^{-3}$	m
V_{out}	$3 \cdot 10^{-3}$	m^3
V_{in}	$2 \cdot 10^{-3}$	m^3
p_d	$3 \cdot 10^{5}$	Pa
p_r	$3 \cdot 10^{5}$	Pa

In doing so, the following labels are used: V_C is the maximum volume of the working chamber of high pressure, V_0 is the minimum volume of high pressure, $L_{\max}$ for total piston stroke, the piston diameter is D, the diameter of the rod is d, V_{out} is the total output volume, V_{in} is the total input volume, p_r is the operating pressure, p_d is the pressure in the drive chamber, and $K_n = 2$ is the maximum gain of the amplifier.

4.1. Simulation of the pressure and flow of the booster

In Figure 2 are given: booster piston displacement, the pressure in the driving chambers 6 and 7 and the pressure in high pressure chambers 4 and 5.

The pressure in the high-pressure tank and the piston displacement are shown in Figure 3. The pressure is increased during operation boosters.

Diagram of the output mass flow is shown in Figure 4. The size of the output booster mass flow is reduced during the process of amplification of pressure.

Mass flow rate of the drive chamber, which booster use for its work, is shown in Figure 5. The size of mass flow rate does not change during operation, as well as pressure of the driving chambers. It represents the energy consumption for booster work.

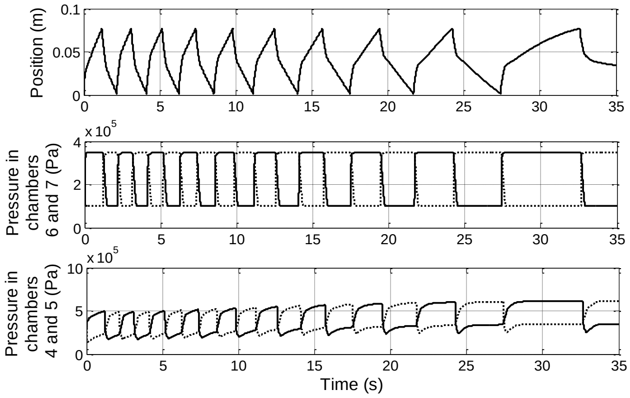

Fig. 2 Move of the piston and the pressure in the driving and high-pressure chambers

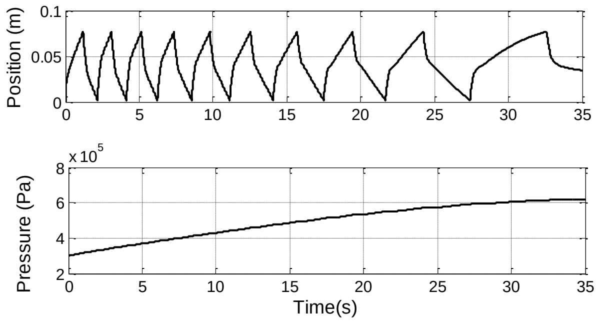

Fig. 3 The piston displacement and the pressure in the high-pressure reservoir

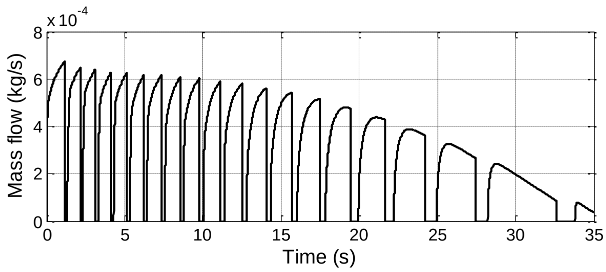

Fig. 4 The output booster mass flow

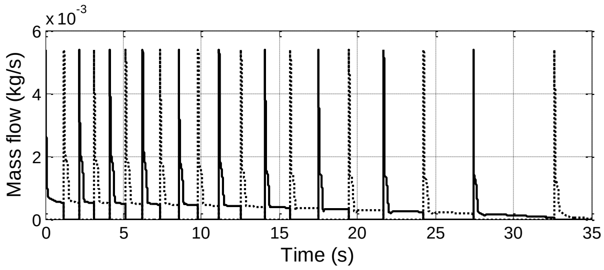

Fig. 5 Mass flow in driving chamber

During the amplification of pressure, discharge pressure increases until it reaches a certain threshold determined by the constant gain K. The output mass flow declines. The booster achieves the ultimate pressure after 19 cycles of operation for the data used in this simulation. Then the mass flow rate decreases to a value equal to zero.

4.2. Simulation of energy efficiency

The data above obtained by simulating for the change of pressure and mass flow during pressure amplification were used to simulate the energy efficiency of the amplification process when pressure booster is applied.

The general expression for the power of air pressure is [6]:

$$\dot{E} = \dot{m}RT_{atm} \ln\frac{p}{p_{atm}} + \dot{m}RT_{atm} \frac{k}{k-1}\left(\frac{T}{T_{atm}} - 1 - \ln\frac{T}{T_{atm}}\right) \quad (6)$$

where is used: $\dot{E}$ is the power of compressed air, $\dot{m}$ is the mass flow rate, T and p are the temperature and pressure of the compressed air, T_{atm} and p_{atm} the temperature and pressure of the atmospheric air, and k is the ratio of specific heat of air at constant pressure and constant volume. For conditions when the air temperature is equal to the ambient temperature $T = T_{atm}$, the equation (6) is reduced to the following equation:

$$\dot{E} = \dot{m}RT_{atm} \cdot \ln\frac{p}{p_{atm}} \quad (7)$$

The energy efficiency of the booster, in the course of amplification of the process pressure, is defined as the degree of utilization of air energy, and it is the ratio of the output energy and an energy of inlet air, as it is illustrated in Figure 6.

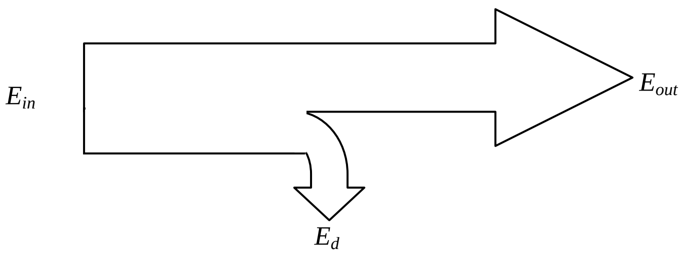

Fig. 6 Energy flow diagram of compressed air

The energy efficiency is determined as the degree of energy utilization η, given with equation (8)

$$\eta(\tau)=\frac{\int_0^\tau \dot{E}_{out}dt}{\int_0^\tau \dot{E}_{in}dt}=\frac{\int_0^\tau \dot{m}_{out}\cdot\ln\frac{p}{p_{atm}}dt}{\int_0^\tau \dot{m}_{out}\cdot\ln\frac{p}{p_{atm}}dt+\int_0^\tau \dot{m}_d\cdot\ln\frac{p_d}{p_{atm}}dt} \tag{8}$$

where is: p is the output pressure, $\dot{m}_{out}$ output mass flow and τ is the auxiliary variable which indicates the duration of the process of amplification of pressure, i.e. the booster running time to achieve output pressure. With $\dot{m}_d$ is marked mass flow of air used to drive the booster, and with p_d is marked pressure in the driving chamber.

To simulate the degree of energy utilization η, by the equation (8), the simulation results for the input and output mass flow, as well as for pressures, determined in previous section are used.

The resulting change in the energy efficiency is given in Figure 7.

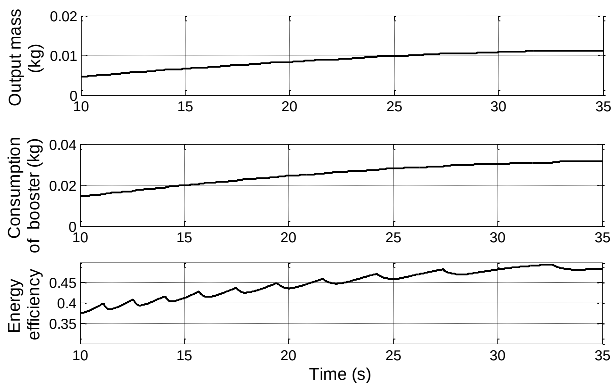

Fig. 7 Change in booster energy efficiency and air consumption

Energy efficiency is changing during the process of forming the output pressure. The figure also shows the mass quantity of high-pressure air, and the amount of air consumed during the amplification process. Final energy efficiency of the booster is 0.49 at the end of amplification process.

5. EXPERIMENTAL RESULTS

Verification of the model and the value of energy efficiency of the pneumatic pressure amplifier, previously obtained by simulation, is done trough the experimental procedure. We used the pneumatic booster Festo DP 63-10, as shown in Figure 8.

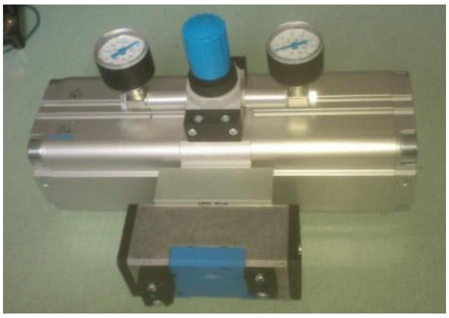

Fig. 8 Pneumatic booster Festo DP 63-10

The scheme of its connecting in a pneumatic circuit, which ensures to avoid the loss of air and allows to control the operation of the amplifier during the pressure amplification is shown in Figure 9.

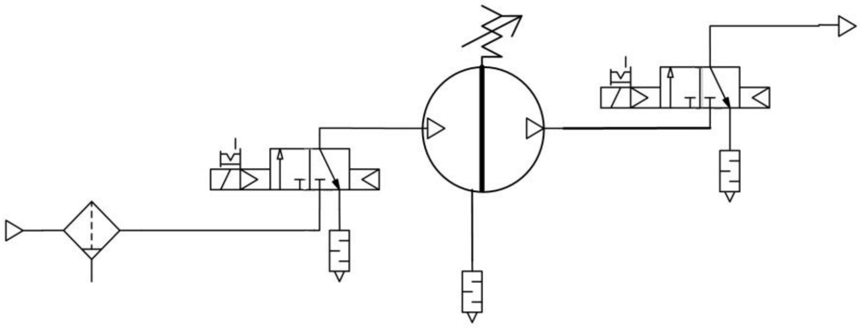

Fig. 9 Circuit diagram of a pneumatic booster

The experimental installation, which was used for booster model verification and determination of its energy efficiency is shown in Figure 10.

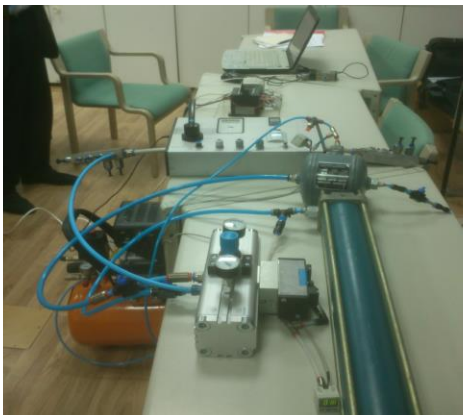

Fig. 10 Experimental installation for testing the booster

During the booster operation were measured: the input flow, output flow, the air flow that the booster releases to the atmosphere as well as input and output pressure, as a function of time during the process of increasing the air pressure.

The weight of compressed air which is obtained in the output reservoir, as well as the total weight of consumed air during the pressure intensifier were calculated by using the experimental data collected with testing instrument Festo AIR BOX GHD-FQ-M-FDMJ-A.

Diagrams that show the exhaust air mass and the total mass of air consumption, as a function of time, are given in Figure 11. The difference of these air masses value was used to operate booster. The loss of air is necessary in order to achieve the increasement of pressure in a booster circuit.

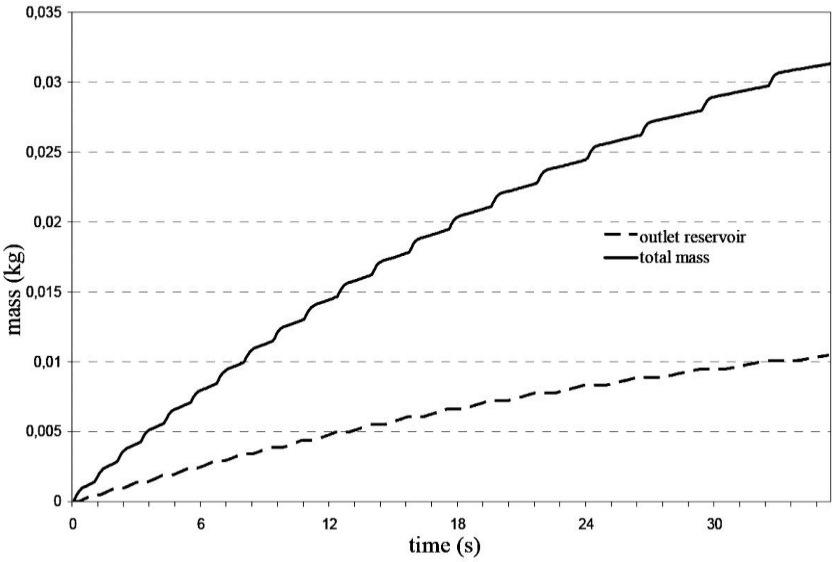

Fig. 11 Diagram of the outlet air total mass as a function of time

The ratio of the amount of air in the outlet tank and the total amount of used air from the inlet tank does not represent the ratio of their energy. For the purpose of calculating the energy efficiency, according to equation (8), the data files with the measurement results obtained in AIR BOX, as well as the data for the change in pressures are transferred to an Excel spreadsheet. The rate of energy efficiency is determined by numerical integration using the equation (8). The obtained value for energy efficiency, at the end of the amplification procedure, was 0.43 and that is in good agreement with the value obtained by simulation in section 4.2.

CONCLUSION

Due to its simplicity, small size and other good qualities, as well as that it does not use additional external power source for the work, pneumatic pressure amplifiers are of considerable use in pneumatic systems. For their work they use the energy of compressed air provided by the compressor. Because of their energy consumption their energy efficiency is an important issue.

The developed mathematical model and simulations allowed us to determine the pressure and flow rate. Energy efficiency is determined using developed mathematical model and results of simulation.

In order to verify the model, experimental testing is conducted. The experimental results show good agreement with the model simulation and they confirm the value of energy efficiency obtained by modeling.

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