PNEUMATIC TWO-STROKE ENGINE AS AN ALTERNATIVE POWER SOURCE

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Abstract

The paper presents the possibility of use of the pneumatic piston engine with two-stroke cycle of the work as an alternative drive source or additional power for the battery regeneration in the electric vehicles. The energy for the engine work is taken from the energy of the air stored at high pressure (about 30 MPa) in the bottle. The pressure in the bottle is reduced to smaller value and the air is injected to the cylinder at short time when piston is in TDC position by the pneumatic injector. The engine has not the transfer ports and its torque depends on the air pressure, injection timing and engine speed. The two-stroke cycle work enables better efficiency and specific air consumption than that with a four-stroke cycle of the work. The pneumatic engine of small dimensions, however with high power fulfil the regulations of the environmental protection with zero emission. The paper presents the mathematical model of the engine based on thermodynamic processes (mass and energy balance). On such considerations the computer program was written by the author for the determination of the most important factors. The results of the calculations are included in the graphs showing the influence of the control parameters (air pressure, injection timing and flow area of the injector on the engine working parameters.

Keywords: *transport, simulation, combustion engines, environmental protection*

1. Introduction

Nowadays the environmental regulations of the exhaust emission from internal combustion engines are more rigorous every year. Despite the high progress of the new types of combustion processes such HCCI, CAI [6] ATAC [9] and other or applying of different complicated fuel injection systems the emission of the combustion products of the hydrocarbon fuel is still high, particularly in lower engine loads. Only small energy of fuel (about 25 - 45%) depending on the engine type is transformed into mechanical power. The application of alternative energy sources and alternative driving system is need instead of those based on fossil fuels. However the main environmental problem is in big cities with transportation where only the fossil fuels are used. Recently there are considered the hybrid systems and fuel cells system for future transportation means. Till now the electric power is produced mostly in many countries on the fossil fuels. It is connected with production of CO_2 and emission of the toxic components of exhaust gases. The electric vehicles have small possibility to drive a long distance. Till now the highest distance for such vehicles reaches maximum 150 km at medium speed and load. For that reason an additional source power for generating an electric energy or driving source is required.

The proposition of alternative power source is to apply the air energy stored in the tank at high pressure. The energy of the air pressure is delivered to the engine in strictly defined period to force the piston. The work cycle follows only when piston moves down. For that case the best solution is applying of the two-stroke engine, which performs the real work every rotation of the crankshaft. The two-stroke engine with port timing is simply designed and cheaper made than the four-stroke engine of the same capacity. Theoretically the two-stroke engine gives two times higher power than four-stroke engine and a direct fuel injection can fulfil environmental requirements [4]. The energy of the compressed air is changed during the expansion process on the mechanical work. The temperature of air stored in the tank is the same as the ambient temperature, thus the energy depends only on the pressure. The temperature can be increased by heating of the air flown to the cylinder and energy delivered to the cylinder is higher. However the thermal losses during opening the exhaust port are also higher. The heat exchange with cylinder walls is smaller than in the classic IC two-stroke engine, because the charge temperature inside the cylinder is low even in TDC.

The pneumatic engine works until the pressure in the filling tank is high enough to fill the cylinder. Value of torque depends on the air mass delivered from the tank trough valve to the cylinder. One of the most important factors influencing on work of the pneumatic engine is valve timing and value of the air pressure. The pneumatic engine enables the driving of the vehicle with real zero emission without combustion process. The vehicle mobility can be increased by adding of an additional heat source in order to deliver higher energy to the cylinder. The pneumatic two-stroke engine together with electric engine will fulfil the future environmental requirements. The experimental set-up of the pneumatic engine is now carried out in CUT and the test results will be published in future.

2. Pneumatic engine operation

The work performed by the pneumatic engine depends on the pressure difference between higher and lower heat source. The air expansion process is shown in Fig. 1 from pressure p_1 to pressure p_2 with temperatures T_1 and T_2, respectively. The thermodynamic process between point 1 and point 2 is non-isentropic and the work l_s has lower value than in isentropic process [7]. In order to obtain the higher power during one work cycle the bigger pressure of the higher heat source (tank) is required.

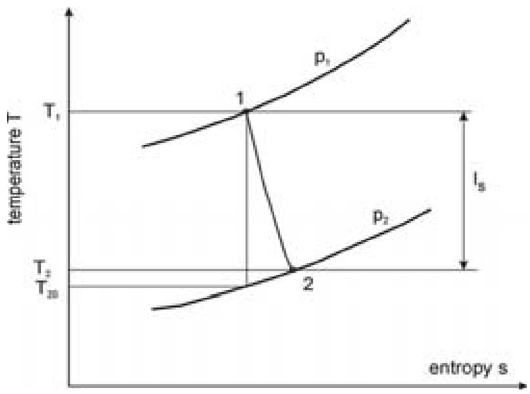

Fig. 1. Non-isentropic work during air expansion

The engine is filled only by the air at high pressure when the piston is at TDC. The pneumatic engine can be simply done by modification of the design of the classic two-stroke engine. The engine does not require the inlet port delivering the air to the crankcase. The crankcase has a vent which causes only small compression of the air. However, the crankshaft is made traditionally with rolling bearing. The lubrication takes place at lower temperatures of the charge and elements. The oiling of the bearings and the cylinder surface is ensured by a small oil pump or by oil drop valve in a close cycle. The schematic idea of the pneumatic two-stroke engine is shown in Fig. 2. The engine has any transfer ports, because delivering of the air is not from the crankcase. Only one exhaust port is used for the gas exchange in the cylinder. The engine has an injector or pneumatic valve controlled by the electronic unit. The bottle of certain volume contains the air at high pressure. The pressure of stored air in the bottle or tank (about 300 bar) is reduced by pressure regulator to smaller injection pressure about 20-30 bar. The pressure is controlled by the sensor and the air is delivered by the pipe of small diameter (about 5-8 mm) to the valve. The air volumetric flow rate through the valve is rather high in comparison to the liquid fuel injection. The use of the electromagnetic stem valve requires high voltage and high electric power. For that case the electromagnetic pneumatic valve used in industry is better solution. The air flow control should enable the high pressure in the cylinder ATDC and on the other hand the opening of the pneumatic valve lasts very short (about 40-60 deg CA) and for this reason the natural frequency of the moving elements in the valve should be high.

The engine is equipped with muffler for damping the air outflow from the cylinder after opening the exhaust port. The timing of the pneumatic two-stroke engine is shown in Fig. 3. In dependence on the rotational speed and load the air injection period begins several degree of CA before TDC. The expansion follows after the air injection and it lasts until the exhaust port opens.

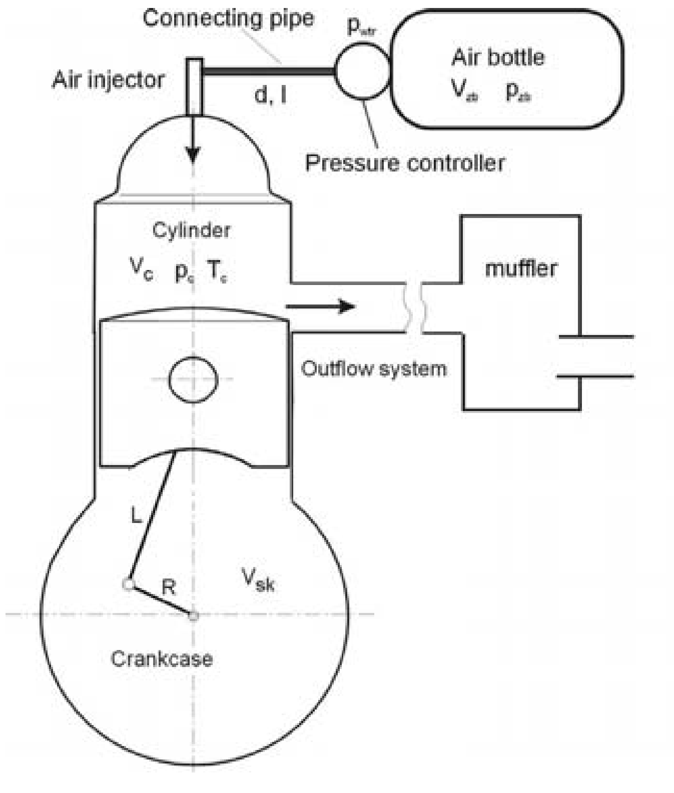

Fig. 2. Diagram of two-stroke pneumatic engine

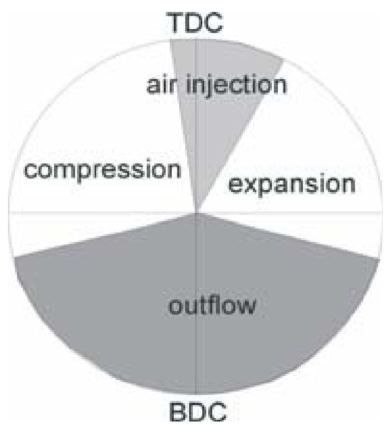

Fig. 3. Engine timing

The engine power is controlled only by change of the valve timing. The friction losses, compression stroke, pumping losses in the crankcase and outflow energy decrease the total engine efficiency.

3. Governing equations

Mathematical model of the pneumatic engine was carried out in order to determine the engine performance at different control parameters. Calculation of the air mass delivered to the cylinder by determination of velocity and density of the air in inlet duct in front of the pneumatic valve enables assessment of engine work time at given tank volume and initial pressure. The air was treated as semi perfect gas, where the specific heat ratio was calculated every time step [8]. The air thermodynamic parameters in the pipes and ducts were determined at assumption of unsteady gas flow from the three hyperbolic nonlinear partial differential equations: mass, momentum and energy balance. The system of the equations were solved by use Lax-Harten-Leer scheme [3] based on Godunov method. The engine parameters were determined on the basis mass and energy balance of the charge in the cylinder. On the mass balance law the increment of the air mass in the cylinder can be expressed by the following equation:

$$dm_c = F_1 \cdot u_1 \cdot \rho_1 \cdot dt - F_2 \cdot u_2 \cdot \rho_2 \cdot dt, \tag{1}$$

where:
F_1 - cross section area of the inflow pipe (delivered air from the regulator),
F_2 - section area of the outflow port,
u - charge velocity in the pipes,
ρ - charge density in the pipes,
t - time.

Change of the internal energy E in the time increment dt is determined by the formula:

$$dE = i_1 \cdot dm_1 - i_2 \cdot dm_2 + dQ_h - p_c dV, \tag{2}$$

where:
Q_h - heat exchange with walls,
I - enthalpy of the air,
V - cylinder volume,
p_c - pressure.

After some simplifications and assuming k as specific heats ratio, the energy equation gives the formula of the pressure increment in the cylinder:

$$dp_c = \frac{k-1}{V}\left(dQ_h - kp_c dV + kR(T_1 dm_1 - T_2 dm_2\right). \tag{3}$$

Gaseous constant R of the air in the cylinder is constant and k is the specific heats ratio and should be calculated for every considered time step Δt on the basis of the change of temperature in the cylinder and pipes [10]. Non-dimensional velocity $A = u/\hat{a}$ of the air flown into the cylinder is calculated on the thermodynamic equations for isentropic unsteady gas flow through contraction:
[1] for sonic flow:

$$\frac{A^2 B^{2c}}{\psi^2 b^c} - b\left(B^2 + \frac{A^2}{c}\right)^{c+1} = 0, \tag{4}$$

[2] b) for subsonic flow:

$$A^2 = c\frac{B^2-1}{B^{2c}-\psi^2}\psi^2, \tag{5}$$

where:

$B = \frac{p}{\hat{p}}, \quad c = \frac{2}{k-1}, \quad b = \frac{2}{k+1},$

$\hat{a}$ - substitute of gas sound speed,

$\hat{p}$ - substitute of pressure,

ψ - general flow coefficient.

Gas velocity u is calculated from the given nonlinear equations by solving variable A. The same equations enable calculation of the air outflow velocity in the pipe near the exhaust port. Amount of the heat transfer to the walls is calculated on the basis of the conductive heat coefficient h_c, area of heat exchange F_h and the temperature difference between gas T_c and walls T_w:

$$dQ_h = -h_c \cdot F_h \cdot (T_c - T_w) \cdot dt. \tag{6}$$

The processes taking place in the cylinder, inlet valve and exhaust pipe are fully described in the literature [2, 5, 8]. The whole model takes into account unsteady gas motion in the pipes, changes of the thermodynamic parameters in each time step (semi-perfect gas) and enables the calculation of the pressure, temperature, density, air velocity in the inlet and outlet pipes and also the air consumption.

4. Calculation results

The described mathematical model was a basis for writing by author the computer program in order to simulate the processes taking place in the pneumatic engine. The calculations were carried out for different rotational speeds, filling pressure of the air and valve control parameters. The simulation process considers to the engine which geometrical parameters are specified in Tab. 1.

Tab. 1. Engine specification

Number of cylinders	1
Bore D	75 mm
Stroke S	55 mm
Connecting rod length L	115 mm
Compression ratio ε	6.5
Crankcase compression ratio	1.34
Opening of exhaust port	106°CA ATDC
Exhaust port width	42 mm

Initial pressure in the tank was assumed as 300 bar. Diameter of the pipe connecting the reducer and valve was 8 mm and the valve lift during opening was assumed as sinusoidal. The air temperature in the tank was near ambient temperature and amounted 300 K. The pressure inside the cylinder depends on the reduced pressure behind the tank and valve timing. The higher filling pressure causes also higher cylinder pressure as is shown in Fig. 5 at rotational speed 2400 rpm. The filling pressure equal 60 bars causes the pressure increase in the cylinder to maximum value 20 bar. The calculations were carried out at valve opening 5 deg CA BTDC and duration 40 deg CA.

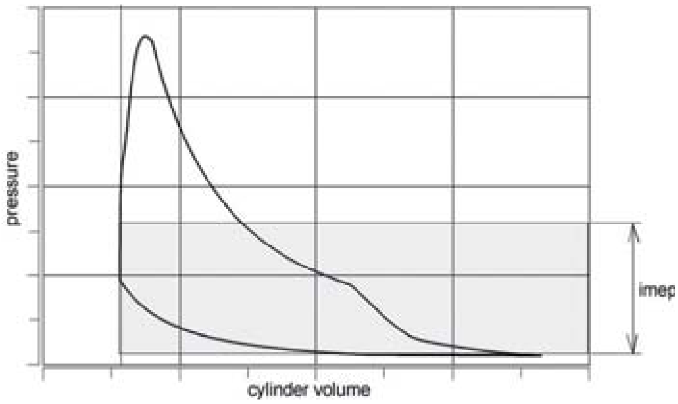

Fig. 4. Closed work cycle of pneumatic engine

The change of pressure in the cylinder is presented in Fig. 4 in closed work cycle. The higher imep value is obtained at lower compression pressure which takes place at lower compression ratio. The air temperature inside the cylinder depends also on the filling pressure. Higher filling pressure causes higher temperature of the air in the cylinder. Variation of the cylinder temperature is presented in Fig. 6.

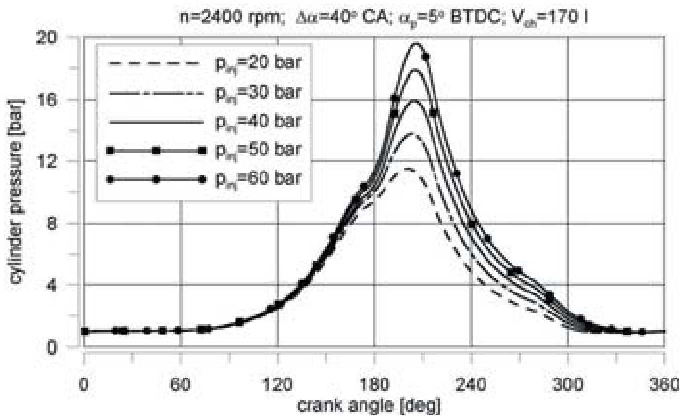

Fig. 5. Variation of cylinder pressure in a function of crank angle at different air injection pressure

The calculations were done at the same control parameters as for pressure calculations. It is needed to observe very low temperature at the end of the expansion process. At low filling pressure for example 20 bar the cylinder temperature decreases below 200 K. This situation causes the transfer of heat from the walls to the charge in the cylinder.

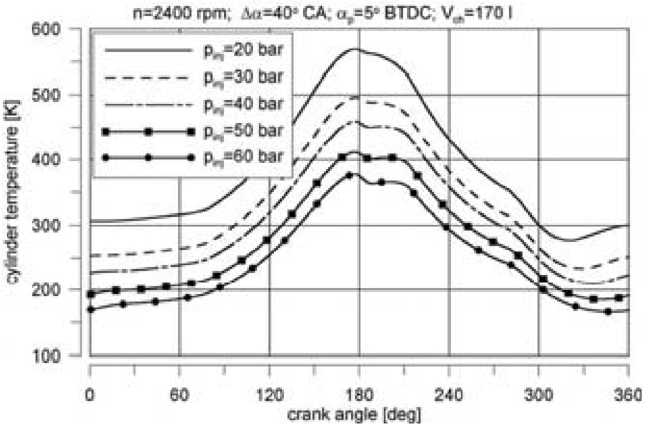

Fig. 6. Variation of cylinder temperature in a function angle at different air injection pressure

The characteristic of engine power has quite different variation than characteristic of classic two-stroke engine. The power variation of the pneumatic two-stroke engine in a function of rotational speed is presented in Fig. 7. The engine has bigger power at low rotational speed at the same valve timing. The characteristic was obtained for air injection pressure equal 25 bar.

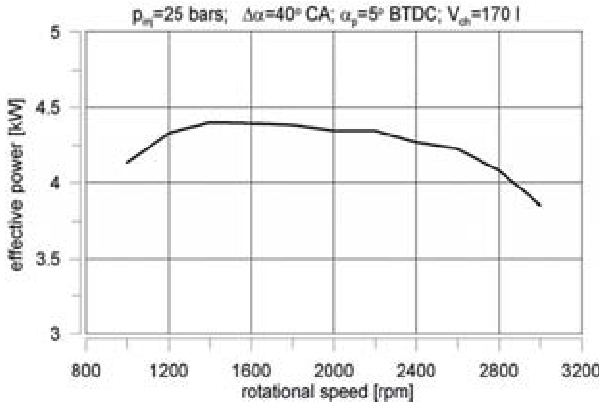

Fig. 7. Power performance in a function of crank of rotational speed

The engine power is a function of torque and for the pneumatic two-stroke engine the highest value of torque takes place at lowest rotational speeds. This phenomenon is like as in electrical engines. The high torque enables better driving of vehicles equipped with such engine. Variation of the engine torque is shown in Fig. 8.

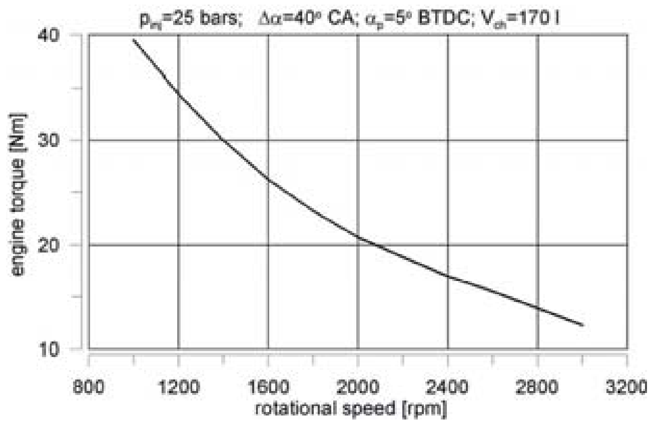

Fig. 8. Engine torque in a function of rotational speed

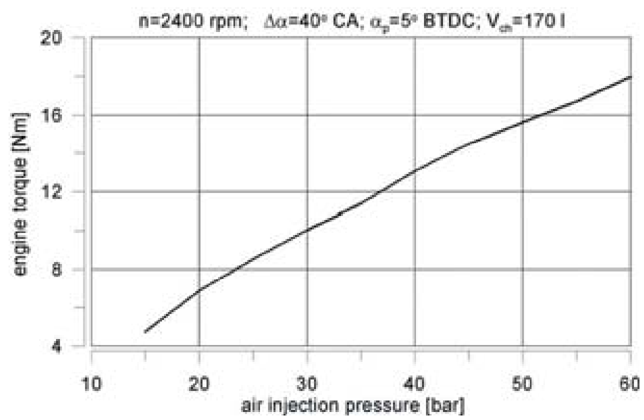

Fig. 9. Engine torque in a function of air injection pressure at 2400 rpm

Higher torque value at higher rotational speeds can be assured by higher filling pressure, which causes a bigger air dose injected by the valve to the cylinder. Another way is to lengthen the duration of valve opening at the same filling pressure. The first case of the torque increase is shown in Fig. 9 at constant rotational speed 2400 rpm. The increase of the air injection pressure causes almost linear increase of the engine torque. The calculations were carried out for valve opening 5 deg CA BTDC and the opening duration 40 deg CA. The change of the engine torque requires the controlling of the filling pressure in the reducer.

Like in internal combustion engines the efficiency of the pneumatic engine can be determined by the amount of air mass needed for producing power unit. The specific air consumption was calculated by the computer program. During valve opening the air mass delivered to the cylinder was calculated as a sum of partial masses at every time step. Variation of the specific air consumption as function of engine rotational speeds is presented in Fig. 10 for injection pressure equal 25 bar.

The pneumatic engine has higher specific air consumption at higher rotational speeds. For this reason the total efficiency is lower at higher rotational speed. This indicates to use the pneumatic engine at lower rotational speeds. The simulation showed the dependence of emptying of the tank on the air injection pressure. Two tanks were considered: one of volume 100 l and the other of volume 170 l.

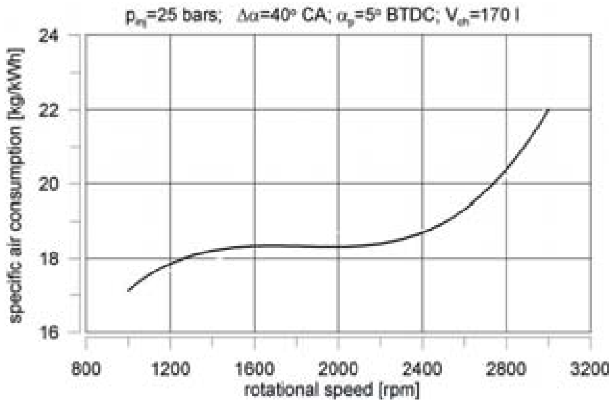

Fig. 10. Specific air consumption in a function of rotational speed

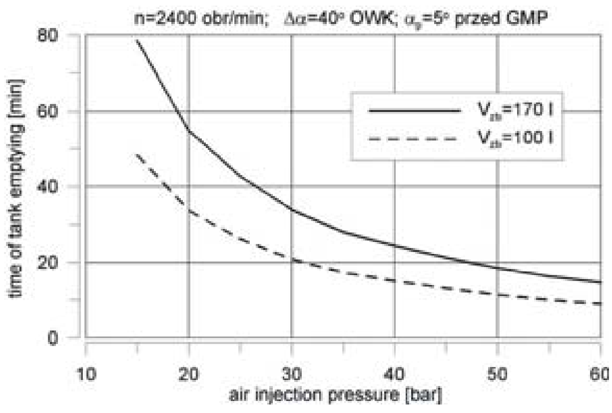

Fig. 11. Time of tank emptying in a function of air injection pressure for two tank volumes

Variation of time emptying in a function of the filling pressure is shown in Fig. 11 at rotational speed 2400 rpm. Emptying time of the tank at air injection pressure 20 bars amounts 55 minutes for the tank with volume 170 l and 35 minutes for the tank with volume 100 l. The simulation shows the independence of the emptying time at medium rotational speeds and constant air injection pressure. This time is almost proportional to the tank volume. The Fig. 12 shows variation of emptying time as a function of the engine rotational speed at air injection pressure 25 bars.

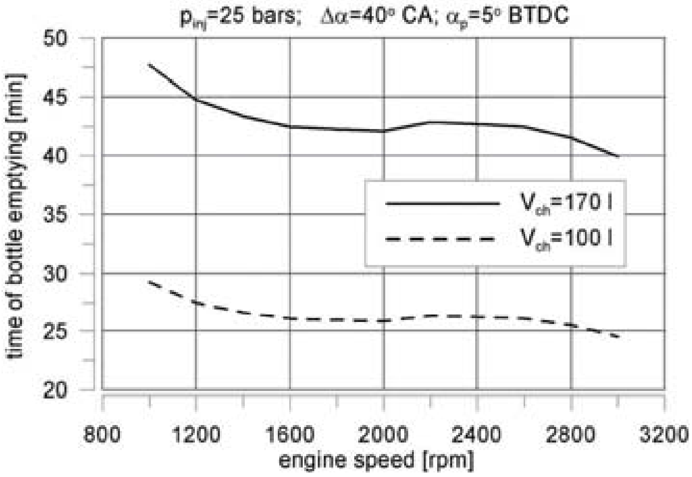

Fig. 12. Emptying time of tank in a function of engine speed at air pressure 25 bars for two tank volumes

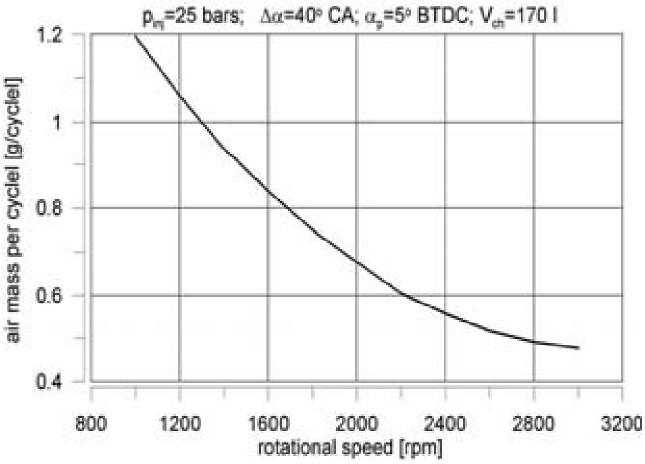

Fig. 13. Air mass consumption per one work cycle at different rotational speeds and air injection pressure 25 bars

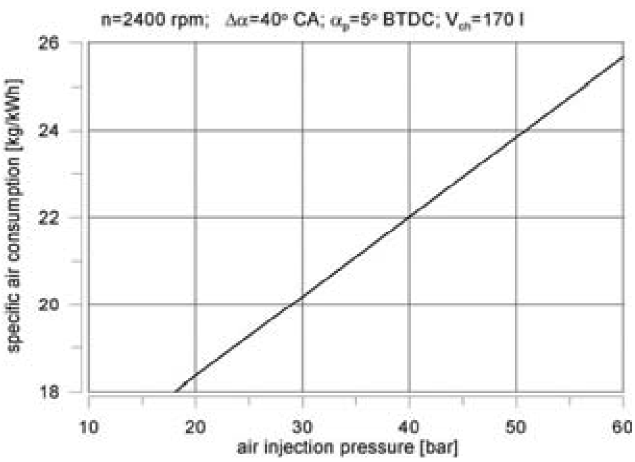

Fig. 14. Specific air consumption at different air injection pressure and n = 2400 rpm

The pneumatic valve controlled by electronic unit must enable an adequate air mass flow rate in a short time. The dose of air per cycle is one of the most important parameters needed for the design of the pneumatic valve. The required air dose per cycle in a dependence of rotational speed is shown in Fig.13 at the air injection pressure 25 bars. The specific air consumption depends linearly on the injection pressure at the same rotational speed which is shown in Fig.14 for n=2400 rpm.

5. Conclusions

The paper presents the numerical analysis of the work of the pneumatic two-stroke engine based on the mathematical model and results from the simulation done by computer program. On the basis of the preliminary results the following conclusions can be drawn:

1) The two-stroke engine with air injection has higher power than the four-stroke engine and enables better utilization of the compressed air than rotor engine.
2) The pneumatic engine has very good torque characteristic - higher value at lower rotational speeds.
3) The time of engine work depends on the air filling pressure and tank volume.
4) Increase of the torque can be assured by the increase of the air injection pressure.
5) Low temperature at the end of expansion process will cause a lubrication problem, however the mean temperature of the charge is near the ambient temperature.
6) The design of the pneumatic is based on the classic two-stroke engine and requires small changes in adaptation of the air filling system.

6. Acknowledgment

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