Chapter 7

# Modern Pneumatic and Combustion Hybrid Engines

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Additional information is available at the end of the chapter

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**Abstract**

This chapter presents the possibility of use of the pneumatic piston engine with two-stroke cycle or four stroke-cycle of the work as an alternative driving source or additional power for the battery regeneration in the electric vehicles. Additionally, such engine can work together with combustion engine as a drive unit in a road vehicle. During city driving, such engine is driven by compressed air. The energy for the engine work is taken from the energy of the air stored at high pressure (about 30 MPa) in bottles or tanks. The chapter presents the thermodynamic theory included in the mathematical model of the engine based on thermodynamic processes (mass and energy balance). On such considerations, the chapter shows the results obtained from specially written computer program 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 rotational speed) on the engine working parameters. Certain chapters concern to a hybrid combustion system with an air injection only for a compression ignition engine in order to achieve higher indicated mean pressure and lower fuel consumption.

**Keywords:** pneumatic piston engines, alternative power source, air injection, efficiency, emission, gas flow

## 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 homogeneous charge compression ignition (HCCI), controlled auto-ignition (CAI) [1], ATAC [2] 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 takes place in big cities with transportation vehicles, where only the fossil fuels are used. Recently, the hybrid systems and fuel cell system are considered for future transportation means. Until now the electricity is produced mostly in many countries by burning 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. Up to now, the highest distance for such vehicles reaches maximum 150 km at medium speed and load, but real distance is up to 100 km. For that reason, an additional source power for generating an electric energy or driving source is still required. Many works are concerned on range-extender vehicles with a piston engine driving the electrical generator that charges the batteries. The current from batteries is delivered to the electric engine connected with a driving gearbox that transmits power to the wheels. The combustion engine works only outside the city.

The alternative proposition of power source is to apply the air energy stored in the tank at high pressure. The idea of air-powered engines is known from many years. Already in the nineteenth century, were given concepts of such an engine. In 1847, Mr Parsey invented the air-compressed locomotive and after many years in 1896, the conception of Porter's pneumatic locomotive appeared [3]. The idea of pneumatic engines for transportation was revived again at the end of twentieth century. Many scientific and research works on pneumatic piston engines were carried out across the world in the past few years [4–6].

A car using energy stored in compressed air produced by a compressor has been suggested as an environmentally friendly vehicle in the future by Creutzig et al. [7, 8]. They analysed the thermodynamic efficiency of a compressed air car powered by a pneumatic engine and consider the merits of compressed air versus chemical storage of potential energy. Many proposals of applying the air piston engines were presented by researchers from Asia [9, 10]: for application in transportation. The researchers presented theoretical studies on engines of a typical small-scale passenger car, which are used for the analyses, and the comparison is based on the shaft work, cooling, efficiency and energy density. They found that optimization of the internal-combustion and recycling of the exhaust energy can increase the vehicle's efficiency from an original 15 to 33%, an overall increase of 18%. A hybrid pneumatic system with recirculation of exhaust gases was proposed by Huang et al. [11]. Huang et al [12] carried out a modification of four-stroke engine for operation in two-stroke engine, which was fed with compressed air. Their study presents an experimental investigation on a piston engine driven by compressed air. The compressed air engine was a modified 100 $cm^3$ internal combustion engine obtained from a motorcycle manufacturer. The experimental and theoretical analysis of a compressed air four-stroke engine was conducted by Chinese researchers, Yu and Cai [13]. The results show that the prototype of such an engine has a good economic performance under low speed and when the supply pressure is 2 MPa. Many works concern to application of the air engine in motorcycles [14], particularly in regions where motorcycle is a main transportation source. A prototype was built with a fuzzy logic speed controller and tested on the real road. Another prototype of motorcycle air engine with a capacity of 100 $cm^3$ was built by Wang et al. [15]. The motorcycle installed with the compressed air engine can operate at a

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maximum speed of around 38.2 km/h and a distance up to 5 km equipped with two 9 l bottles filled by air under pressure of 25 MPa.

Currently across the world, there are realized several projects of road vehicles with pneumatic drive, including project developed by Motor Development International (MDI) [16], and sold under the name of the Indian company TATA under the name Tata Air Car Mini Cat [17]. This engine operates in a four-stroke cycle and outside air is drawn into the compression chamber and compressed to 20 bar. At top dead centre (TDC), this air reaches 400°C, and at that point, air from the storage tank is injected into the combustion chamber. The compressed air is stored in carbon fibre tanks at 30 MPa. Recently, the company Peugeot has developed a drive internal combustion engine with a hydraulic system driven by compressed air under the name Peugeot 2008 Hybrid Air [18]. This solution continues to include the concept of the engine powered only with air or the two drive units. The proposed solution is also unique in the world because it includes a combustion engine and air in one drive unit, providing a compact whole drive without having to install a complicated powertrain unit as the current hybrid structures.

## 2. Principles of work of pneumatic engine

### 2.1. Why air compressed two-stroke engine?

The energy of the air pressure is delivered to the engine in strictly defined period in order to force the piston in the cylinder of almost standard engine. 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 for every rotation of the crankshaft. The two-stroke engine with port timing is cheaper and simply designed compared to the four-stroke engine of the same capacity. Theoretically, the two-stroke engine gives two times higher power than the four-stroke engine, and a direct fuel injection can fulfil environmental requirements [19]. The energy of the compressed air is converted 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 transferred to the cylinder and thus the 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 tank is high enough to fill the cylinder. The value of torque depends on the air mass delivered from the tank trough valve to the cylinder. One of the most important factors influencing the work of the pneumatic engine is valve timing and a value of the air pressure. The pneumatic engine enables the driving of the vehicle with real-zero emission without any combustion process. The vehicle mobility can be increased by adding 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 has been carried in whole across the world and some vehicles appeared for testing on the road.

### 2.2. Operation of pneumatic engine

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 **Figure 1** from pressure $p_1$ to pressure $p_2$ with temperatures $T_1$ and $T_2$, respectively [20]. The thermodynamic process between point 1 and point 2 is non-isentropic process, and the work $l_s$ has lower value than the isentropic process [21]. In order to obtain the higher power during one work cycle, the higher pressure of the higher heat source (tank) is required. If temperature of the air in the tank has value near the ambient temperature $T_1$ then temperature of the expanded air $T_2$ has lower temperature than ambient temperature. But, in a real pneumatic engine, the air injection takes place at the maximum value of compressed air delivered to the cylinder during the intake process. Therefore, the temperature $T_1$ has higher value than ambient temperature.

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 that causes only small compression of the air. 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 and timing of valve and port opening are shown in **Figure 2**. 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 a 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 after top dead centre (ATDC), and on the other hand, the opening of the pneumatic valve lasts very short (about 40–60° CA) and due to this reason, the natural frequency of the moving elements

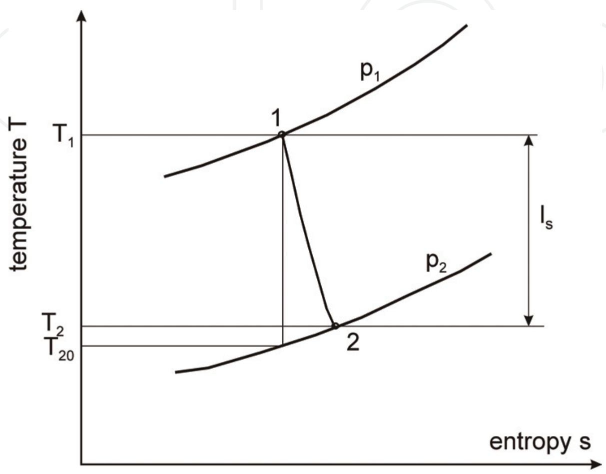


**Figure 1.** Non-isentropic work during air expansion.

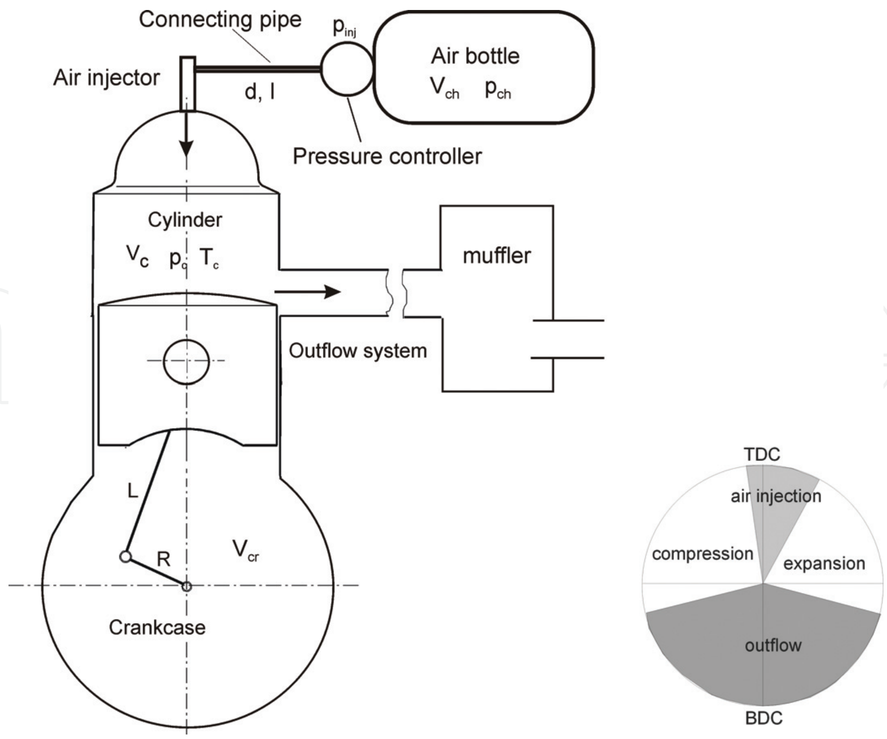


**Figure 2.** Diagram of two-stroke pneumatic engine and engine timing.

in the valve should be high. The engine is equipped with a muffler for damping the air outflow from the cylinder after opening the exhaust port. Depending 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.

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. Modelling of physical processes in piston pneumatic engine

The mathematical model of the pneumatic engine was carried out 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 [22].

### 3.1. Mass balance

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 was solved by using the Lax-Harten-Leer scheme [23] based on Godunov's method. The engine parameters were determined on the basis mass and energy balance of the charge in the cylinder. Based on the mass balance law, the increment of the air mass in the cylinder can be expressed by the following equation:

$$dm_c = F_1 \cdot u_1 \cdot \rho_1 \cdot dt + F_{\text{inj}} \cdot u_{\text{inj}} \cdot \rho_{\text{inj}} \cdot dt - F_2 \cdot u_2 \cdot \rho_2 \cdot dt \tag{1}$$

where $F_1$ = cross section area of the inflow pipe (delivered air from the regulator), $F_2$ = cross section area of the outflow port, $F_{\text{inj}}$ = cross section area of injector nozzle, $u$ = charge velocity in the pipes, $\rho$ = charge density in the pipes, $t$ = time, $inj$ = air injector.

### 3.2. Conservation of energy

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

$$dU = i_1 \cdot dm_1 + i_{\text{inj}} \cdot dm_{\text{inj}} - i_2 \cdot dm_2 + dQ_h - p_c dV \tag{2}$$

where $Q_h$ = heat exchange with walls, $i$ = enthalpy of the air at defined temperature, $V$ = cylinder volume, $dm$ = mass flow rate in the pipes and through the injector, $p_c$ = cylinder pressure.

### 3.3. Determination of cylinder pressure

After some simplifications and assuming $k$ as specific heats ratio ($k = c_p \ / \ c_v$), the energy equation gives the formula of the pressure increment in the cylinder:

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

Equation (3) does not contain the component of fuel combustion as in the real combustion engine. All these components depend on time, an increment of the inflow air mass takes place during opening of transfer ports and increment of outflow air mass takes place only during opening of the exhaust port, whereas the air injection lasts very short and begins when piston is near TDC.

### 3.4. Mass flow rate through injector nozzle

The mass flow rate of the injected air depends on pressure difference between the injector and the cylinder. During calculation, one should check whether the flow is critical or subcritical. For the second case, the mass flow rate is determined from the following equation:

$$\frac{dm_{inj}}{dt} = \frac{\Phi \cdot F_{inj} \cdot p_{inj} \cdot \sqrt{k}}{a_{inj}} \sqrt{\frac{2k}{k-1}\left[\left(\frac{p_c}{p_{inj}}\right)^{\frac{2}{k}} - \left(\frac{p_c}{p_{inj}}\right)^{\frac{k+1}{k}}\right]} \tag{4}$$

where $\Phi$ = flow resistance through the injector nozzle, $F_{\text{inj}}$ = injector flow area, $p_{\text{inj}}$ = pressure of injected air, $a_{\text{inj}}$ = sound velocity of injected air ($a_{\text{inj}} = \sqrt{kRT_{\text{inj}}}$), $p_c$ = pressure of air in cylinder and $R$ is an individual constant of air.

In most cases, the air injection takes place at a critical flow, because pressure in the injector is several times higher than in the cylinder. The critical flow occurs when the following condition is fulfilled:

$$\frac{p_c}{p_{inj}} \leq \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{5}$$

In such a case, the mass flow rate is calculated as follows:

$$\frac{dm_{inj}}{dt} = \frac{\Phi \cdot F_{inj} \cdot p_{inj} \cdot k}{a_{inj}} \sqrt{\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{6}$$

Gaseous constant $R$ of the air in the cylinder does not depend on temperature and $k$ is the specific heat ratio and should be calculated for every considered time step $\Delta t$ on the basis of the change of temperature in the cylinder and pipes [23] which means that $k = f(T)$.

### 3.5. Unsteady gas flow in feeding ducts

The mathematical model of gas flow in the pipes and engine ducts takes into account pressure wave motion, which means that flow is unsteady. 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:

**a.** For sonic flow:

$$\frac{A^2 B^{2c}}{\Psi^2 b^c} - b\left(B^2 + \frac{A^2}{c}\right)^{c+1} = 0 \tag{7}$$

**b.** For subsonic flow

$$A^2 = c\frac{B^2 - 1}{B^{2c} - \Psi^2}\Psi^2 \tag{8}$$

where $B = \frac{p}{\hat{p}}$, $c = \frac{2}{k-1}$, $b = \frac{2}{k+1}$, $\hat{a}$ = substitute of gas sound speed, $\hat{p}$ = substitute of pressure, $\Psi$ = general flow coefficient.

Gas velocity $u$ is calculated from the given nonlinear equations by solving variable $A$. The same equations enable the calculation of the air outflow velocity in the pipe near the exhaust port.

### 3.6. Heat transfer and kinematic dependencies

The 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 $T_w$ [24]:

$$dQ_h = -h_c \cdot F_h \cdot (T_c - T_w) \cdot dt \tag{9}$$

After finding cylinder pressure $p_c$ and knowing the charge mass $m_c$, we can find temperature from the equation of general gas state:

$$T = \frac{p \cdot V}{m \cdot R} \tag{10}$$

Cylinder volume $V$ is determined from the dependency:

$$V = \frac{\varepsilon}{\varepsilon - 1} V_s \tag{11}$$

where ε = compression ratio, $V_s$ = engine piston displacement.

Cylinder piston displacement is determined from kinematics dependencies of the crank-piston system in dependence on crank angle position $\alpha$:

$$V_s = \frac{\pi \cdot D^2}{8} \cdot s \cdot \left(1 + \frac{\delta}{4} - \cos\alpha - \frac{\delta}{4}\cos 2\alpha\right) \tag{12}$$

where $D$ = piston diameter, $s$ = piston stroke, $\delta$ = crank ratio ($\delta = s/(2L)$) and $L$ = connecting rod length. The processes taking place in the cylinder, inlet valve and exhaust pipe are fully described in the literature [21, 22, 25]. The whole model takes into account a wave pressure motion in the pipes and changes of the thermodynamic parameters in each time step (semi-perfect gas). The model enables the calculation of the pressure, temperature, density, air velocity in the inlet and outlet pipes and also the air consumption.

## 4. Calculation results of two-stroke pneumatic engine

The presented mathematical model was the basis for the development of a computer program in order to simulate the processes taking place in the virtual pneumatic engine. Several works concerning to a piston pneumatic engine were published by Mitianiec and Wiatrak in engine's literature [26, 27]. For this elaboration, the calculations were carried out for different rotational speeds, different filling pressure of the air and valve control parameters.

### 4.1. Geometrical parameters of engine and boundary conditions

The simulation process considers to the two-stroke engine Robin EC12 with bore $D$ = 75 mm, stroke $S$ = 55 mm and compression ratio 6.5 and opening of exhaust port at 106° CA ATDC, which was fully tested in the standard version. Initial pressure in the tank was assumed as 300 bar. The pipe connecting the reducer and the valve with length 80 mm amounted had 8 mm of diameter. The valve lift during opening was assumed as sinusoidal. The air temperature in the tank was near ambient temperature and amounted 300 K. The higher filling pressure also causes higher cylinder pressure, as is shown in **Figure 3**, at a rotational speed of 2400 rpm.

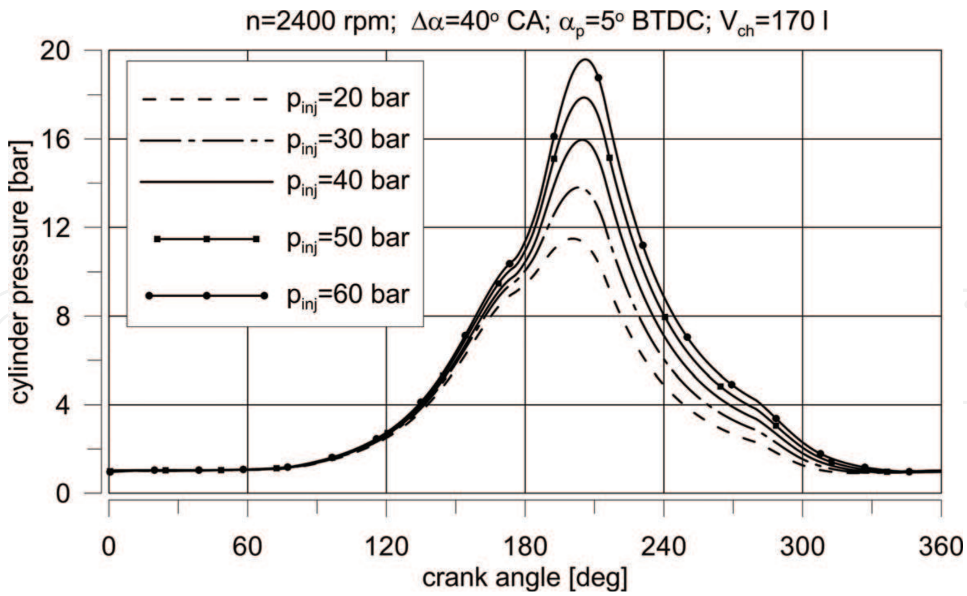


**Figure 3.** Cylinder pressure in a function of crank angle at different air injection pressure.

The filling pressure of 60 bar causes the pressure increase in the cylinder to maximum value 20 bar. The calculations were carried out at a valve opening 5° CA before top dead centre (BTDC) and duration 40° CA.

### 4.2. Thermodynamic parameters of pneumatic two-stroke engine

The higher indicated mean effective pressure (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 **Figure 4**. The calculations were performed at the same control parameters as for pressure calculations. One can 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.

At higher injection pressure, temperature in the cylinder decreases and at value of 60 bar, the maximum temperature at TDC is below 400 K. This situation causes the transfer of heat from the walls to the charge in the cylinder. The characteristic of engine effective power has quite different variation than characteristic of the classic two-stroke engine (**Figure 5**). The engine has bigger power at low rotational speed at the same valve timing. The characteristic was obtained for air injection pressure of 25 bar. In the pneumatic two-stroke engine, the highest value of brake mean effective pressure (bmep) takes place at lowest rotational speeds. This phenomenon is like as in electrical engines. Higher bmep 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 of increasing of bmep is increasing the duration of valve opening at the same filling pressure. The increase of the air injection pressure causes almost linear increase of bmep (**Figure 6**), but this causes increase of specific air consumption (SAC) value. The

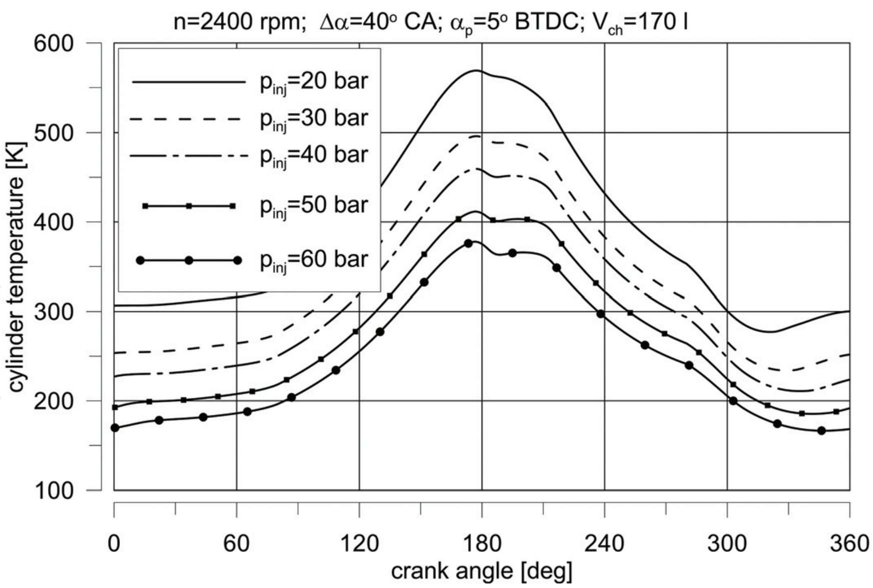


**Figure 4.** Cylinder temperature in a function of crank angle at different air injection pressure.

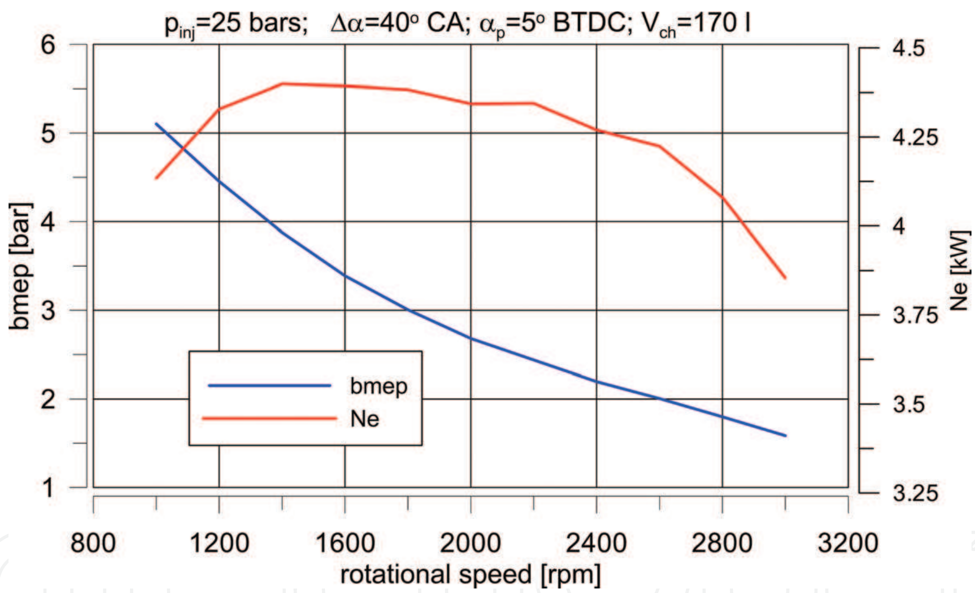


**Figure 5.** Effective power and torque in a function of rotational speed.

calculations were carried out for valve opening 5° CA BTDC, $n$ = 2400 rpm, wide opening throttle (WOT) and the opening duration 40° CA.

The change of the engine torque requires an automatic control of the filling pressure in the reducer. The same graph shows variation of SAC, which depends linearly on the injection pressure. Lower specific SAC values occur at lower pressure of air injection. Thus very important is reduction of air pressure from high value in the bottle to lower value in the injector.

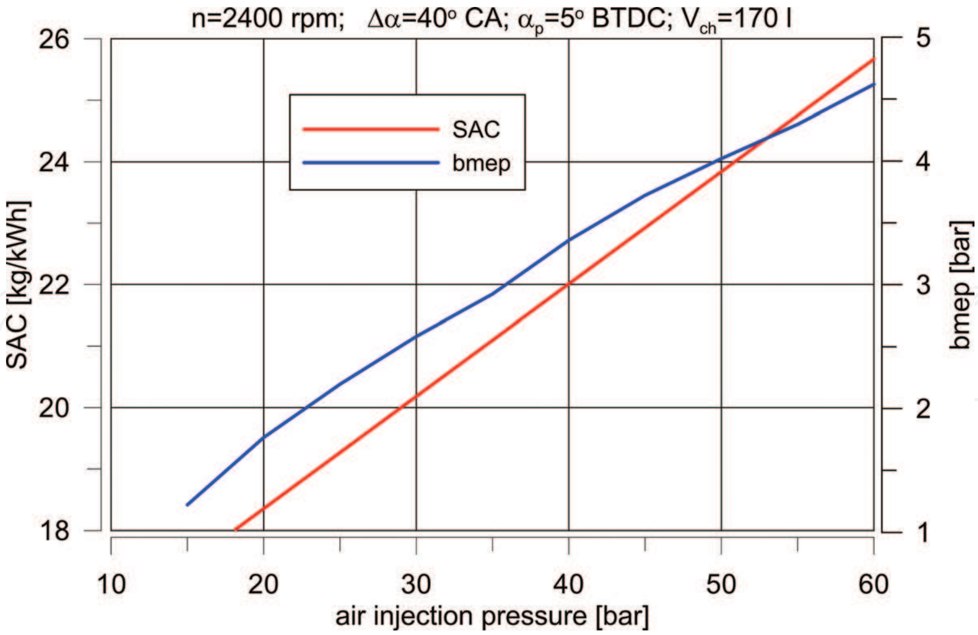


**Figure 6.** Torque and specific air consumption in a function of injection pressure.

### 4.3. Air consumption in pneumatic two-stroke engine

As internal combustion engines, the efficiency of the pneumatic engine can be determined by an amount of air mass needed for producing power unit. During valve opening, the air mass delivered to the cylinder was calculated as a sum of partial masses at every time step. Variations of SAC and air mass per cycle (AMPC) as a function of engine rotational speeds are presented in **Figure 7** at an injection pressure of 25 bar. With increasing of rotational speed at the same angle of opening of the injector (shorter time), one can observe a decrease of air mass consumption per cycle, but the amount of cycles increases in the same period.

For higher specific air consumption, 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. Variation of time emptying in a function of the filling pressure is shown in **Figure 8** at a rotational speed of 2400 rpm. Emptying time of the tank at air injection pressure of 20 bars for 55 minutes for the tank with volume 170 l and emptying time of tank with another volume will be almost proportional to that volume.

The simulation shows a small change of the emptying time at medium rotational speeds and constant air injection pressure. It is caused by influence of non-steady gas flow on the ducts of the two-stroke engine. This time is almost proportional to the tank volume. **Figure 9** shows the variation of emptying time as a function of the engine rotational speed at air injection pressure of 25 bar of a tank with volume 100 l at full engine load (WOT). Emptying time does not change rapidly for considered volume of the bottle.

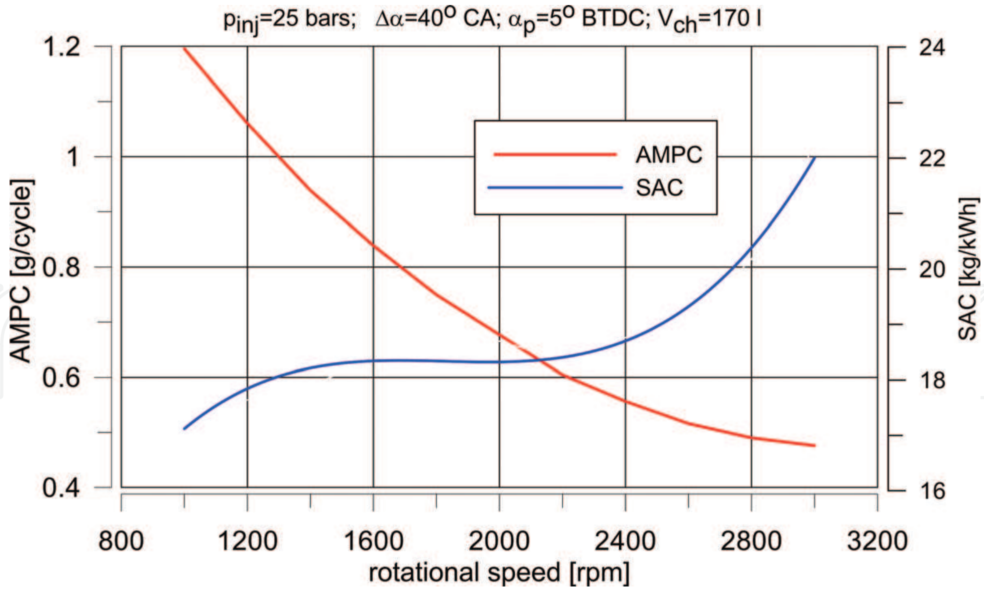


**Figure 7.** Consumption of air mass per cycle and specific air consumption in a function of rotational speed at air injection pressure 25 bar.

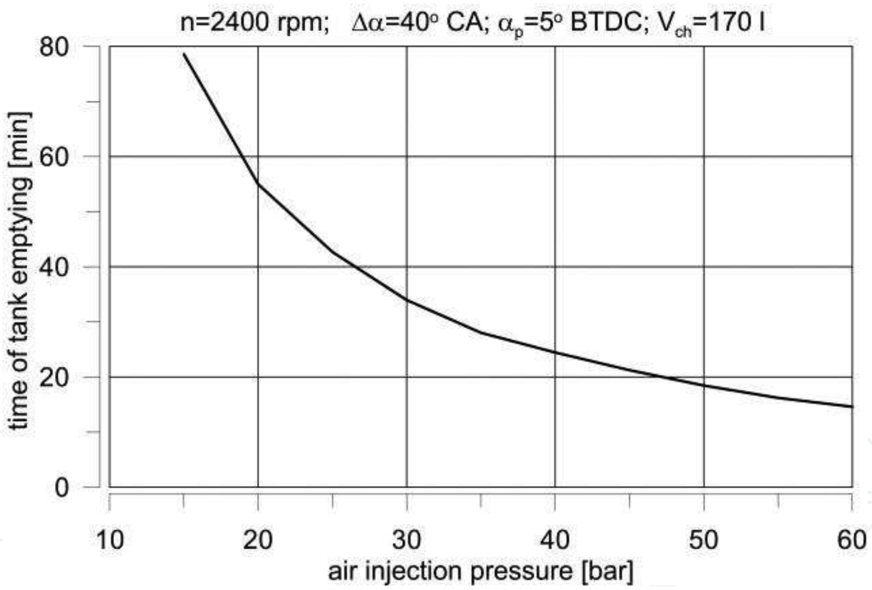


**Figure 8.** Emptying time of air for a tank with volume 170 l at $n$ = 2400 rpm and different injection pressure and full load.

The pneumatic valve controlled by the 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.

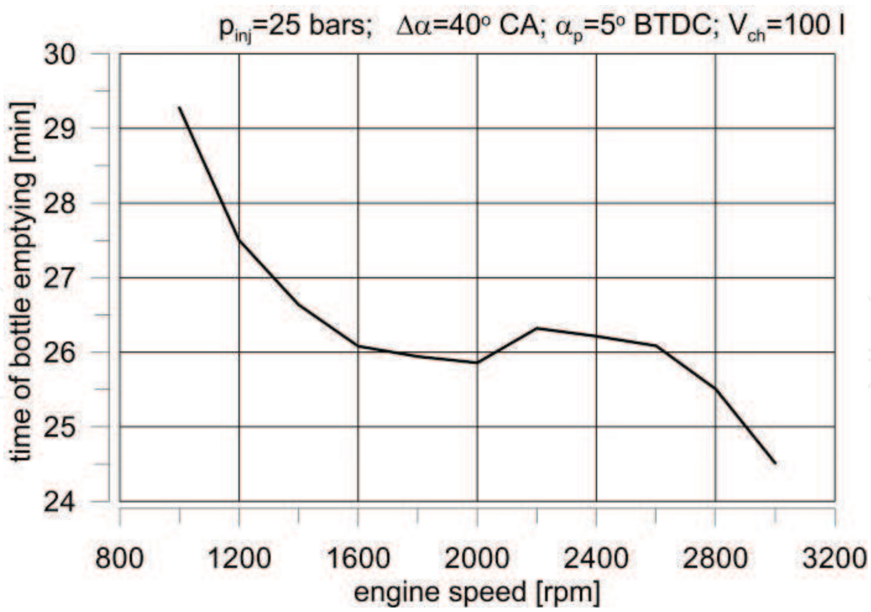


**Figure 9.** Emptying time of a tank with volume 100 l in a function of engine speed at air pressure 25 bar and full load (WOT).

## 5. Assessment of two-stroke pneumatic engine

The numerical analysis of the work of the pneumatic two-stroke engine based on the mathematical model and results from the simulation was carried out by theoretical considerations and results obtained from computer program. Most of previously done research works presented in introduction and this work was concentrated on air two-stroke engines. On the basis of the simulation results, the following remarks can be drawn:

1. The two-stroke engine with air injection indicates smoother work than the four-stroke engine for the same air injection pressure and enables better utilization of the compressed air than the rotor engine. Every rotation of crankshaft produces power and such engine only wasted the air to the exhaust port during the scavenge process, not during air injection. For the same rotational speed and pressure of air injection below 150 bar, the four-stroke engine indicates lower bmep and also lower SAC than the two-stroke engine. This air comes from the process of normal filling of the cylinder.

2. Every pneumatic engine indicates higher value of bmep at lower rotational speeds and enables better starting of vehicle. Good characteristic of the two-stroke engine depends on very short crank angle injection with value near 40° CA and start of air injection about 5° CA.

3. The time of engine work depends on the air filling pressure and tank volume. It should be emphasized short time operation of the pneumatic engine under heavy loads. It would add the tanks of greater volume or more resistant (tanks made from composites) to greater pressure to about 700 bar.

4. The increase of the engine torque can be assured by the increase of the air injection pressure but it causes higher specific air consumption.

5. Low temperature at the end of expansion process should not cause a lubrication problem, because the mean temperature of the charge is near the ambient temperature. The wall temperature in every two-stroke engine is stable for steady load. In such case, the engine does not require any cooling system. Lubrication in such engine should be carried out by dosing of lubrication oil to the inlet pipe by a special needle valve with possible regulation of mass flow rate.

The design of the pneumatic engine is based on the classic two-stroke engine and it needs small changes in order to mount the air feeding system with electronic control unit (ECU) system.

## 6. Practical solutions of pneumatic piston engines

The pneumatic two-stroke piston engine is a simple solution of a real non-conventional driving system, which does not produce toxic gaseous components and does not burn any fuel. However, for filling the bottle with the air under high pressure, a mechanical energy is required for driving of a compressor. It is mostly a piston compressor allowing for obtaining high pressure driven by an electric motor, and energy is obtained from power station (combustion of coal, biomass, nuclear energy, gasification of coal).

### 6.1. Control valves of air inflow

The important element of every pneumatic engine is the pneumatic valve, which delivers the air in defined time to the cylinder. The air is injected by the valve to the cylinder, where the air charge is compressed due to the movement of the piston towards TDC. The greater outlet area of the injector is required for a large mass flow rate of air. For such case, the poppet valve in the injector sometimes is used. The proposal of the injector with poppet valve is shown in **Figure 10**, where the movement of the valve is controlled by a cam mechanism. Because of high pressure from the inlet side, the moving part of the valve has two parts: poppet and cylindrical parts with the same diameter. This arrangement allows for maintenance of the valve in the closed condition without additional force and closing of the poppet valve required a small force of the return spring. The piston of the valve has a labyrinth sealing and also sealing between the valve stem and the body. The whole controlled mechanism is like as in the timing mechanism in the four-stroke engine. The cam system gives a constant angle of opening of the valve (in CA deg) in relation to crankshaft rotation. Better solution of controlled motion of poppet valve in the air injector is applying of an electronic unit by using an induction coil where electromagnetic forces enable the movement of valve stem. The simpler but practical solution of the air injector controlled by solenoid unit is shown in **Figure 11a**. The valve stem should have a limiter of movement. Electromagnetic force for opening of valve lasts very short and is independent of the movement and position of the crankshaft. The poppet valve can be opened and closed at any time. Another proposed solution is utilization of the standard

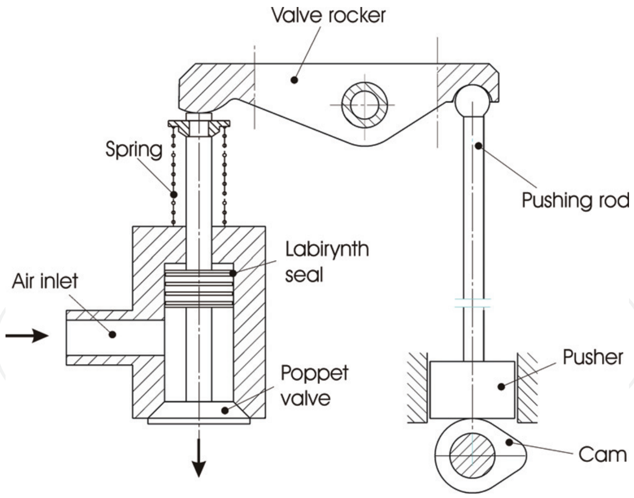


**Figure 10.** Proposal of air dosing valve driven by a cam mechanism.

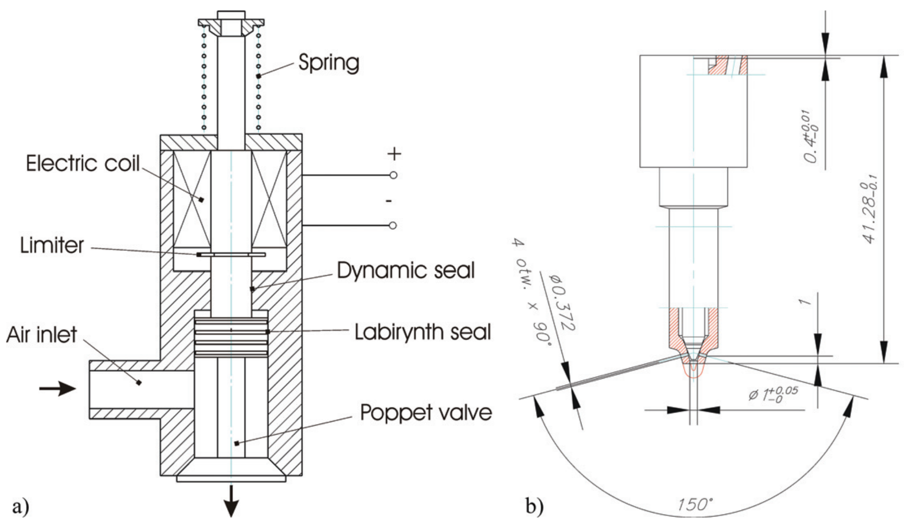


**Figure 11.** Electromagnetic valves: (a) air poppet valve controlled by ECU and electric coil and (b) utilizing of standard sprayer of CI engine.

sprayer of diesel oil with higher nozzle diameter and by cutting of the dispenser cap, but with contact of the needle spray with the body (**Figure 11b**).

Such design of an injector tip revamped is presented in **Figure 11b** and it was applied by Wiatrak [30] in his pneumatic engine in moped. This configuration of the air injector does not require any modification of ECU and allows control of air injection in any way. Limitation of applying such injector tip is only the required air mass flow rate.

### 6.2. Two-stroke Indian pneumatic engine

Some solutions of pneumatic engines can be found in the literature and widely in Internet. One of the promising solutions was given by Kumar et al. [28]. They tested a two-stroke engine equipped with storage cylinder, pressure regulator, air filter and lubricator, modified flywheel

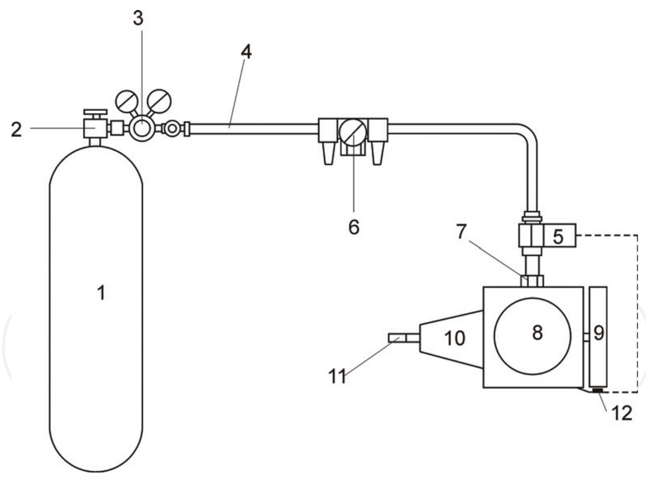


**Figure 12.** Scheme of compressed air engine: 1, storage cylinder; 2, stop valve; 3, pressure regulator; 4, hose; 5, solenoid valve; 6, air filter and lubricator; 7, adapter nipple; 8, two-stroke SI engine; 9, flywheel; 10, gearbox; 11, transmission shaft; 12, magnetic sensor [28].

and solenoid valve working with 24 V DC with a maximum pressure of 10 bar. A schematic diagram of compressed air engine worked out by Indian scientists is shown in **Figure 12**.

### 6.3. Small power air engine

Another solution was presented by Chinese scientists, represented by Xu et al. [29], in their work concerning an adaptation of four-stroke engine working on compressed air. They have developed a mathematical model of filling the cylinder and control model of the engine. The virtual model of the pneumatic engine is shown in **Figure 13**. Their work concerns mainly to theoretical analysis of working performance also in dynamic loads by using SIMULINK. The

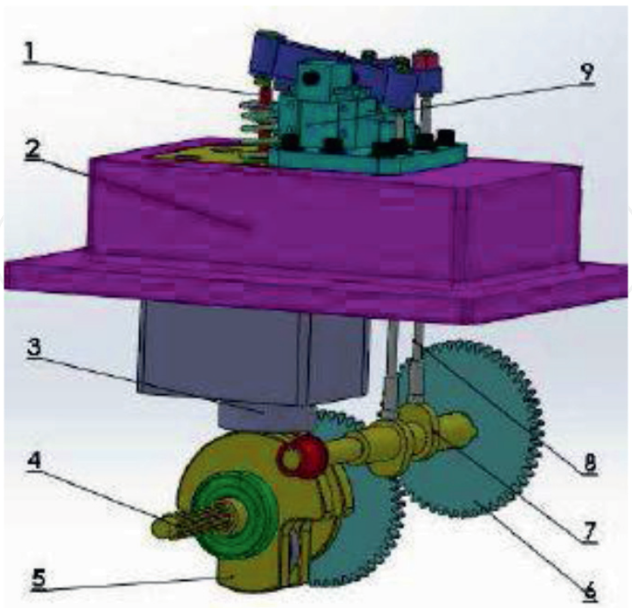


**Figure 13.** Physical model of APE: 1, balanced valves; 2, cylinder cover; 3, cylinder; 4, crankshaft; 5, crank piston mechanism; 6, timing gears; 7, camshaft; 8, cam follower; 9, tunable rocker mechanism [29].

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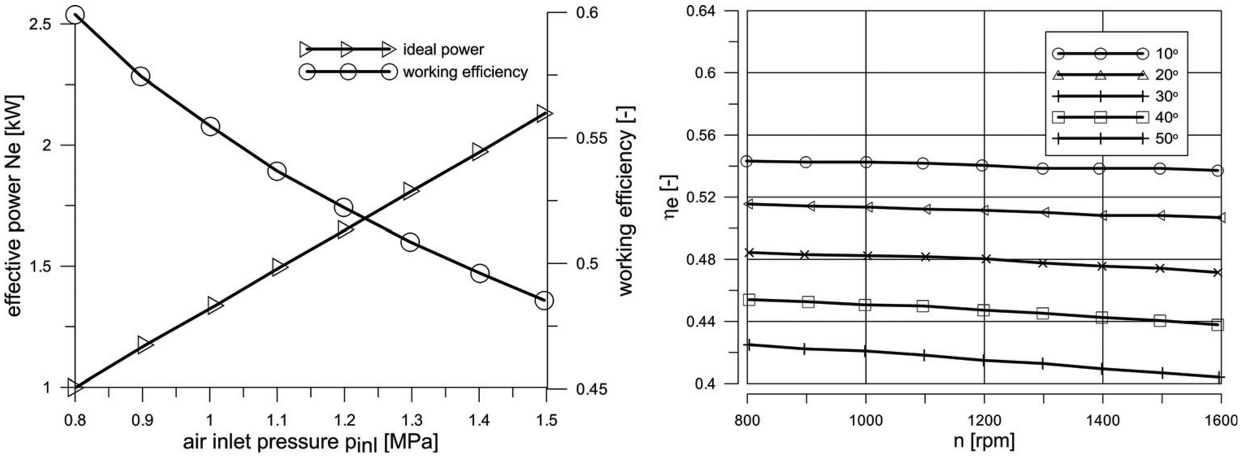


**Figure 14.** Engine performance: (a) ideal power and working efficiency at different air inlet pressure and (b) working efficiency of APE at different rotational speeds [29].

Chinese researchers conducted numerous analyses of a small engine to find an optimal work efficiency, high torque and an optimal control parameters of injection of the air. **Figure 14a** presents an ideal power and engine efficiency as a function of pressure of the injected air. The engine power decreases with increasing of the air pressure, but engine efficiency linearly increases. It should pay attention to high efficiency above 56% at a pressure inlet of 1.5 MPa.

Engine efficiency depends mainly on timing of the injection valve. **Figure 14b** presents the total efficiency of air powered engines (APE) for different duration of the air injection from 10° to 50° CA at a starting point of injection 5° CA BTDC. Engine efficiency slightly decreases with increasing of rotational speed and for longer opening of the air injector, the engine efficiency decreases from 54 to 42% at an engine rotational speed of 800 rpm.

The Chinese researcher found that 'the virtual prototype of the APE can make the simulation more precise and reduce the cost of the design. This research can provide theoretical supports to the new APE prototype's design and optimization' [16].

## 7. Pneumatic and combustion hybrid engine

### 7.1. Conception of vehicle with pneumatic and combustion engine

The proposal concerns to a certain hybrid combustion system in internal combustion engines both compression and spark ignition (SI) in order to achieve higher indicated mean pressure and lower fuel consumption. The solution is combination of two fuelling systems: the first direct fuel injection and the second high pressure air injection. The dosing of both fluids is shifted in CA one relative to second. The additional air helps in the charge mixing, increasing of charge turbulence and causes a quicker combustion process by additional oxygen in the regions, where local excess air coefficient is small (below ignition boundary). Besides the fuel dose, the additional air increases the mass of charge in the cylinder causing a significant increment of pressure. This elaboration concerns only to applying of an air injection in compression ignition (CI) engines. The influence of an additional air dose on compression ignition engines can help to break the fuel jet with possibility to burn the droplets in the kernel of fuel jet. In this way, CI engine can reduce the amount of emitted soot and nanoparticles. The presented solution of combustion and pneumatic engine is based on the patent applications made by the Wiatrak and Mitianiec [30, 31]. The simple diagram of the solution is presented in **Figure 15** for CI engine, but the same solution can be applied for SI engine and in this case instead of the diesel oil injector a spark plug will be located.

A high-pressure bottle contains the air under pressure below 500 bar, and the air is supplied to the pneumatic injector through the safe valve, pressure controller, which reduces high pressure according to the engine load. The electrical signal from ECU controls both the air pressure and time of opening and closing of the pneumatic valve.

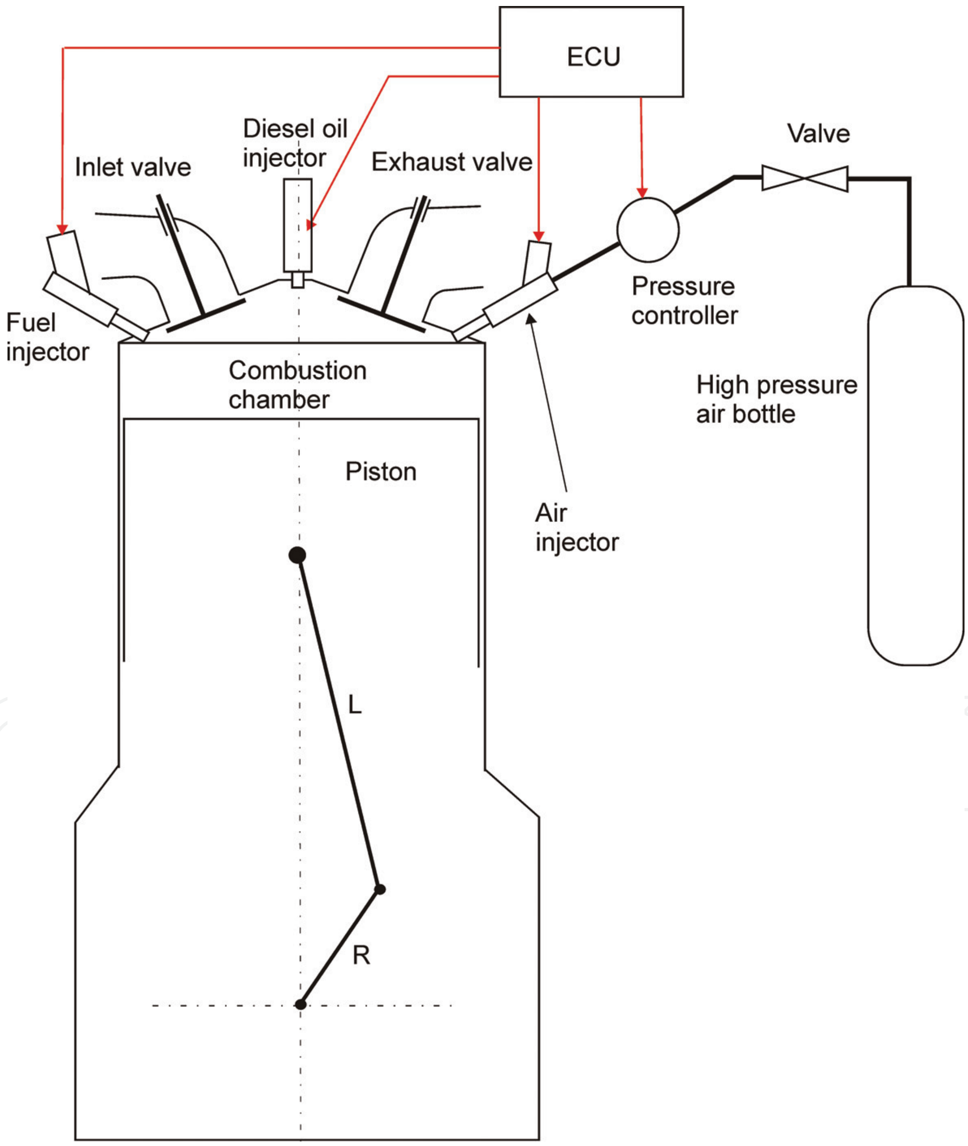


**Figure 15.** Diagram of combustion and pneumatic CI engine [31].

The electrical signal from ECU controls both the air pressure and time of opening and closing of the pneumatic valve. The electronic control of fuel injector and air injector enables to obtain optimal engine parameters by a small amount of fuel and air. The car with combustion and pneumatic engine can be driven by the piston engine working in four modes as follows:

1. Pneumatic mode (air injection at high pressure to the cylinder) without combustion.
2. Combustion (CI or SI) engine (standard mode).
3. Combustion and full pneumatic mode for temporary high power during acceleration, climbing and high velocity.
4. Combustion with micro-dose of injected air for small increase of car load.

The combustion and pneumatic engine depending on working modes enables the following factors:

- Increasing of engine torque (power).
- Decreasing of specific fuel consumption.
- Driving of the vehicle with real-zero emission as a result of lower temperature (decreasing of NOx emission) and full fuel combustion by adding more air, which enables CO absence.
- Decreasing of soot emission in diesel engines as a result of higher concentration of oxygen in the core of fuel jets (by optimal direction of injected air).
- Decreasing of cooling heat from engine to the cooling system.

The driving resistance power depends on rolling forces and air resistance forces. The resistance force was measured by the Netherlands automotive research institution (TNO) [32] for car with mass 1700 kg and the following formula was given:

$$F = 114.22 + 0.3861 \cdot v + 0.0281 \cdot v^2 \text{ [N]} \tag{13}$$

where $v$ is velocity of car on flat road in km/h. The car with mass 1250 kg driving with velocity 50 km/h on the flat road requires only 2.83 kW of power. Maximum power of engine which was tested according to New European Driving Cycle (NEDC) ($t$ = 400 s) amounts 19 kW and engine work during the NEDC test reaches value 0.314 kWh. Another formula for calculation of driving forces of passenger cars in NEDC was given by the Austrian automotive research company founded by Helmut List (AVL), on the basis of their measurements:

$$F = 102 + 6376.5 \cdot \sin\alpha + 0.02592 \cdot v^2 \text{ [N]} \tag{14}$$

where $\alpha$ is an angle of inclination of the road and $v$ is velocity of the car in km/h.

### 7.2. Pneumatic CI engine

For simulation of combustion and air injection process in internal combustion engine (ICE), a diesel engine being in production was chosen and some results of simulations are presented below. Simulation was carried out only on one-cylinder compression ignition (CI) four-stroke engine with a capacity of 450 cc. The results of calculations were obtained from the computer program by using 0-D thermodynamic model of engine work cycle with unsteady gas flow in engine pipes.

*Technical data of engine*:

Bore/stroke = 82/85 mm

Length of connected rod = 130 mm

Compression ratio = 16

Number of valves = 4

Inlet valve timing = 20° BTDC/35° ABDC

Exhaust valve timing = 56° BBDC/20° ATDC

*Parameters of air injection:*

Pressure = 350 bar

Timing of injector = TDC/35° ATDC

Flow area of valve exit = 5 $mm^2$.

The diagram shown in **Figure 16** presents variation of mean effective pressure and specific air consumption, which was fuelled only by the air at high injection pressure. Variation of these parameters is the same as for the two-stroke pneumatic engine. When the engine is supplied only with air, bmep rapidly decreases with growing rotational speed (lower value of torque).

The air mass consumption per one cycle decreases with rotational speed at the same air injection parameters, however, the specific air consumption increases with rotational speed.

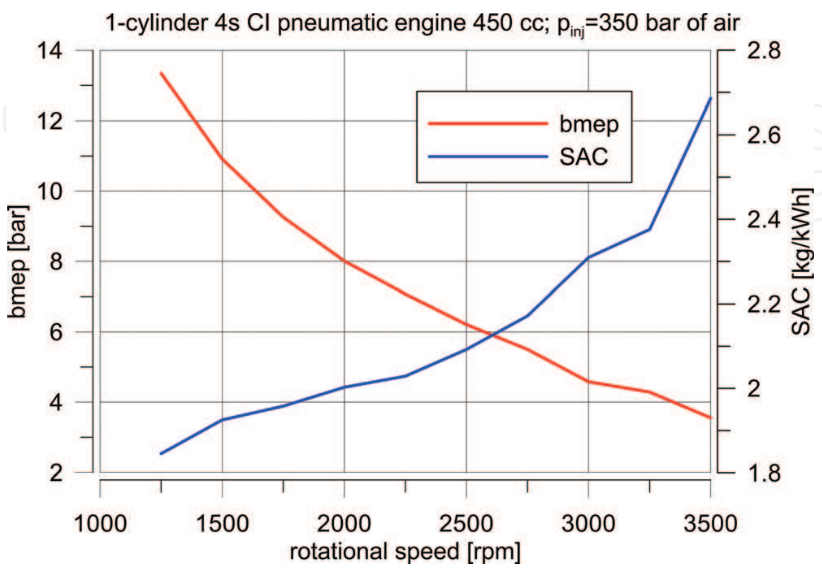


**Figure 16.** Mean effective pressure and specific air consumption of one-cylinder CI four-stroke engine fuelled only by air injection at injection pressure 350 bar.

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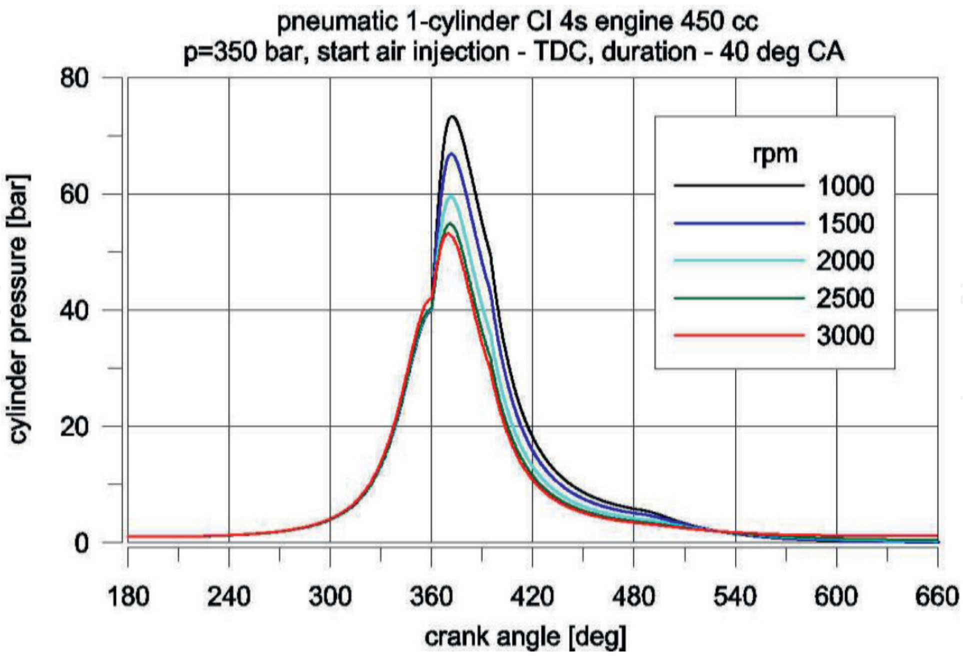


**Figure 17.** Cylinder pressure traces in one-cylinder CI four-stroke engine fuelled only by air injection at pressure 350 bar for different rotational speeds.

At higher rotational speeds, the pneumatic engine has lower efficiency at the same air injection parameters. With increasing of engine rotational speed, the cylinder pressure decreases, because the time of air injection is shorter for the same duration of crank angle of the air valve opening.

**Figure 17** shows traces of pressure in one cylinder for considered CI pneumatic engine at different rotational speeds. The higher maximum pressure in the diesel engine supplied only with air takes place at lower rotational speeds. With the increase of engine speed, the maximum of air pressure in the cylinder still decreases. Calculations were carried out for CI engine at start of air injection at TDC, duration of injection 40° CA and air injection pressure 350 bar. The diesel pneumatic engine indicates higher specific air consumption at higher rotational speed, where the engine power has lower value. These parameters show that the pneumatic diesel engine indicates better working parameters at lower rotational speeds.

### 7.3. Combustion engine with additional dose of injected air

Simulation of CI engine with the same geometrical parameters as in the first option with additional air injection (350 bar) was carried out for different rotational speed. Variation of cylinder pressure is shown in **Figure 18** for the CI engine fuelled only by diesel oil and for CI engine (the same air excess ratio $\lambda = 1.5$) with additional air injection. It is seen higher pressure in the cylinder during expansion stroke for the combustion and pneumatic mode than for CI engines only. Start of air injection was constant for all presented rotational speeds: opening 25° CA ATDC and duration 40° CA.

**Figure 19** presents the variation of engine torque for both cases as a function of rotational speed. The big difference of engine torque and also engine power is observed particularly at

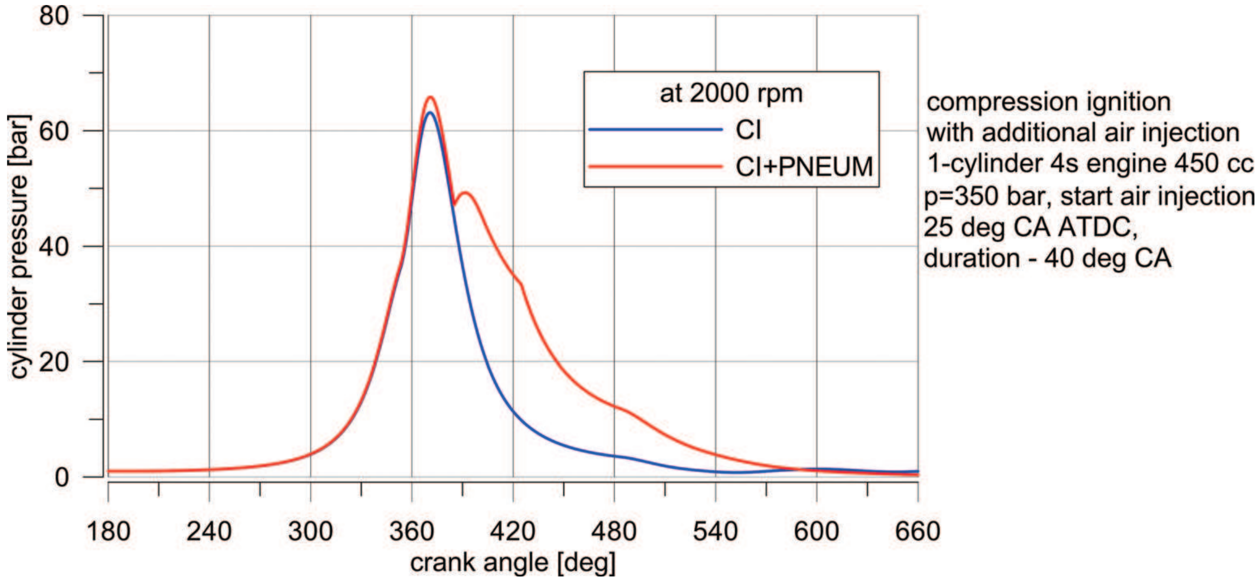


**Figure 18.** Comparison of cylinder pressure in the four-stroke CI engine and CI engine with additional air injection at 2000 rpm.

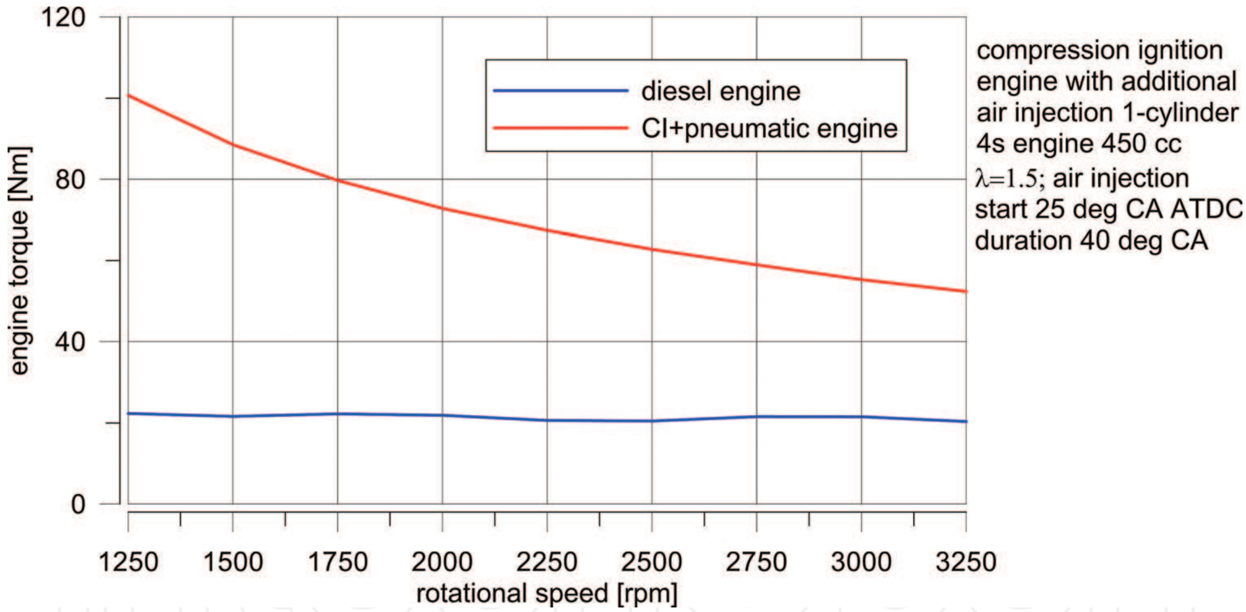


**Figure 19.** Comparison of engine torque in the four-stroke CI engine and CI engine with additional air injection at different rotational speeds.

lower rotational speed, because in the pneumatic engine at the same duration of opening, the air injector more air is delivered to the cylinder in lower rotational speed because of longer time of opening of the air injector.

By adding the pressured air into small volume of the combustion chamber (almost at TDC), the engine power rapidly grows and for that reason the specific fuel consumption (diesel oil) decreases considerably, as shown in **Figure 20** for engine with additional dose of the air. This

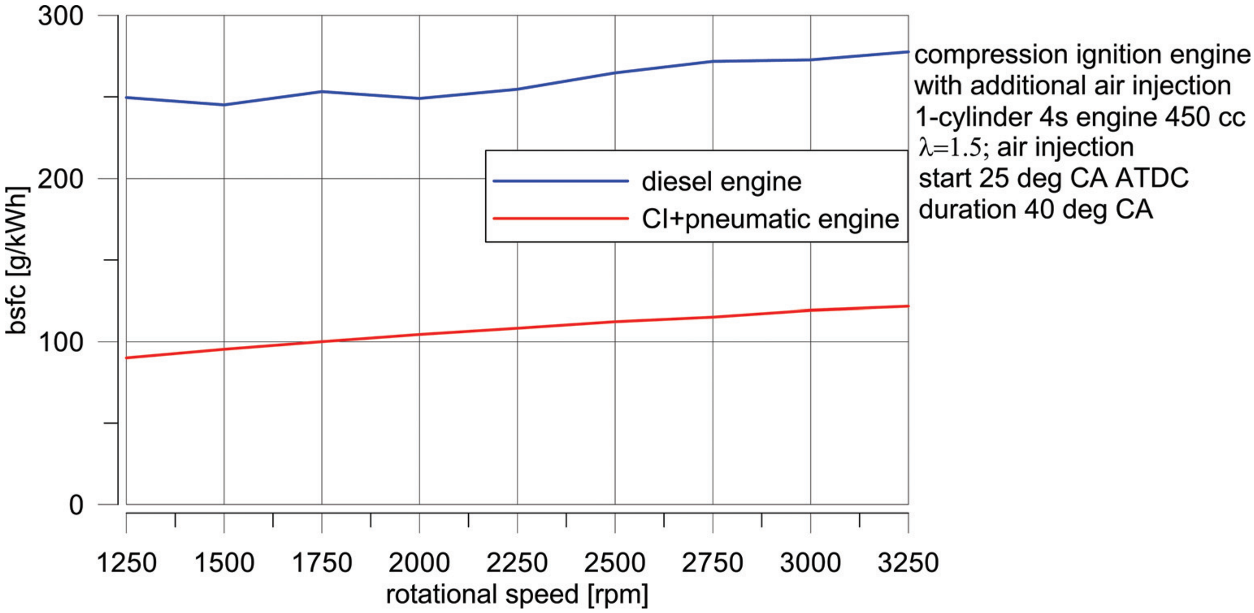


**Figure 20.** Comparison of specific fuel consumption in the four-stroke CI engine and CI engine with additional air injection at different rotational speeds.

mode of engine work is needed for higher acceleration and load of the car and enables the retrieving of very high power density with dose of the air for only short time of operation. At higher rotational speeds, only small dose of the air is required.

This mode of engine work is needed for higher acceleration and load of the car and enables the retrieving of very high power density with dose of the air for only short time of operation. At higher rotational speeds, only small dose of the air is required.

### 7.4. ICE with micro-dose of air

One of the possibilities of the combustion and pneumatic engine is working with a micro-dose of the pressurized air during normal compression ignition engine operation (combustion mode). The micro-dose of air is required, for example, by reducing CO emission or reducing combustion temperature, which influences on decreasing of NOx emission. However, this small dose of air increases significantly the engine power. This mode can be fulfilled by changing of duration of air injection. **Figure 21** shows the variation of engine effective power with micro-dose of the air in comparison to the standard engine as a function of duration of the air valve opening. The specific fuel consumption for such working mode is considerably reduced (**Figure 22**). The presented results were calculated for 2500 rpm and at an air pressure of 350 bar. The value of brake specific fuel consumption (bsfc) decreases rapidly as a result of a longer opening of air valve and delivering more air to the cylinder.

### 7.5. Strategy of control of air injection

Change of pressure trace in the cylinder in the combustion and pneumatic engine depends on timing of the air valve. Variation of cylinder pressure is shown in **Figure 23** for the same pressure of injected air (150 bar) but at different valve opening and at the same duration of

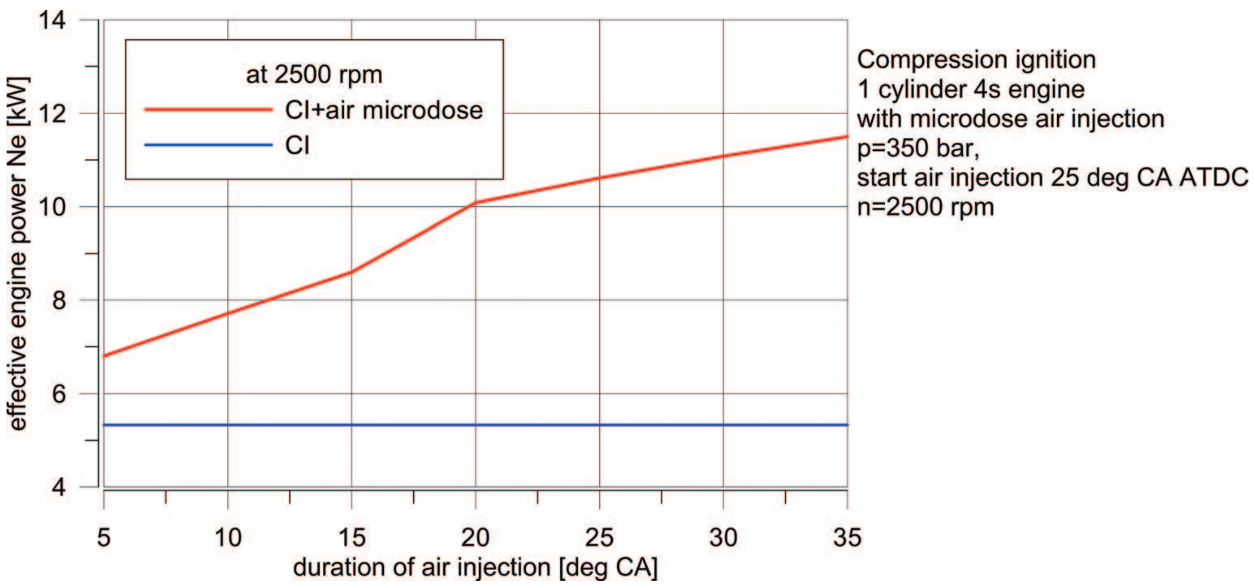


**Figure 21.** Influence of duration of air injection on engine effective power at 2500 rpm.

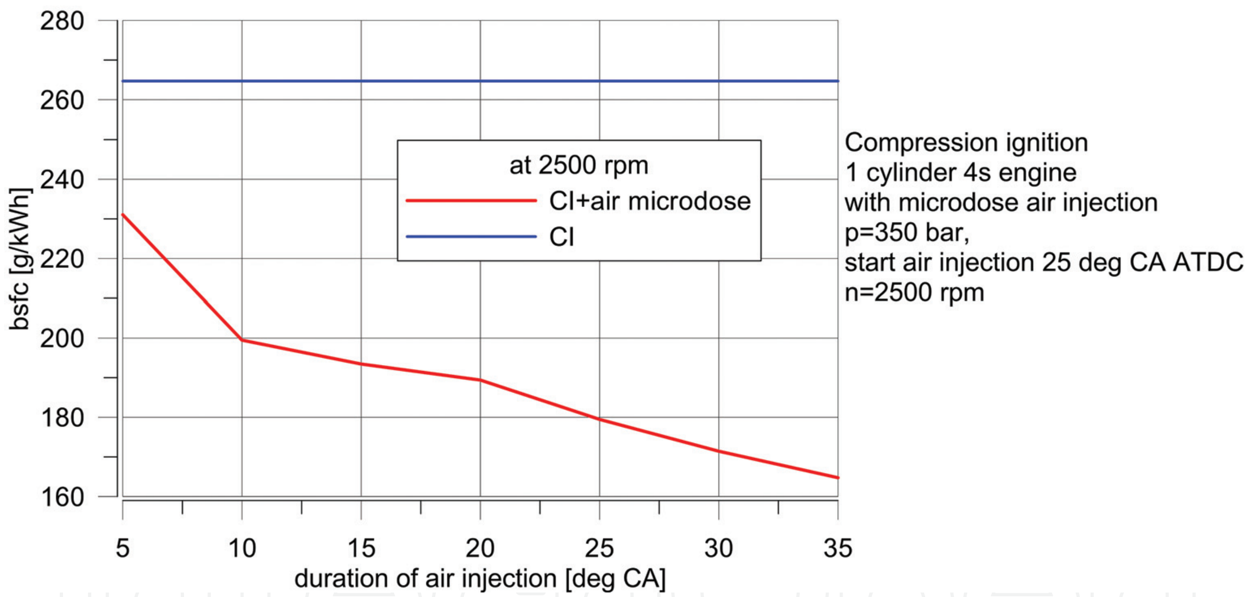


**Figure 22.** Influence of duration of air injection on specific fuel consumption at 2500 rpm.

valve opening. By earlier opening of the air valve, one obtains a higher mean indicated pressure. The control of engine work can be realized by changing of timing of air injector opening for constant pressure. At high inlet air pressure, the flow is critical (sonic) and air velocity is constant and equalled to the local sound speed. The mass dose of the air can be controlled also by changing of the pressure, however, such regulation is not suitable for this application. The air is stored in the pressurized tank or bottles, which can be located in different places in the car. Simulation carried out in GT-Power program indicates lower emission of carbon monoxide in SI engine with air-added injection than in standard SI engine, because of higher concentration of oxygen in the combustion chamber (**Figure 24**).

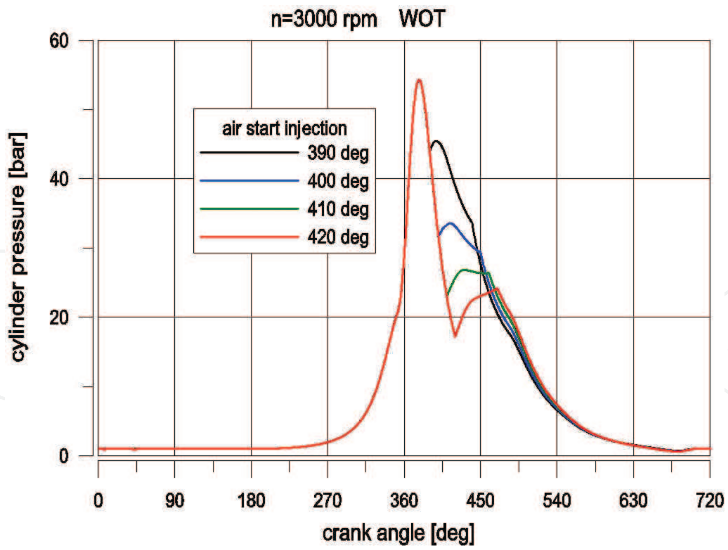


**Figure 23.** Pressure variation in a cylinder for different angles of air injection start at 3000 rpm in the four-stroke CI engine (combustion + air injection).

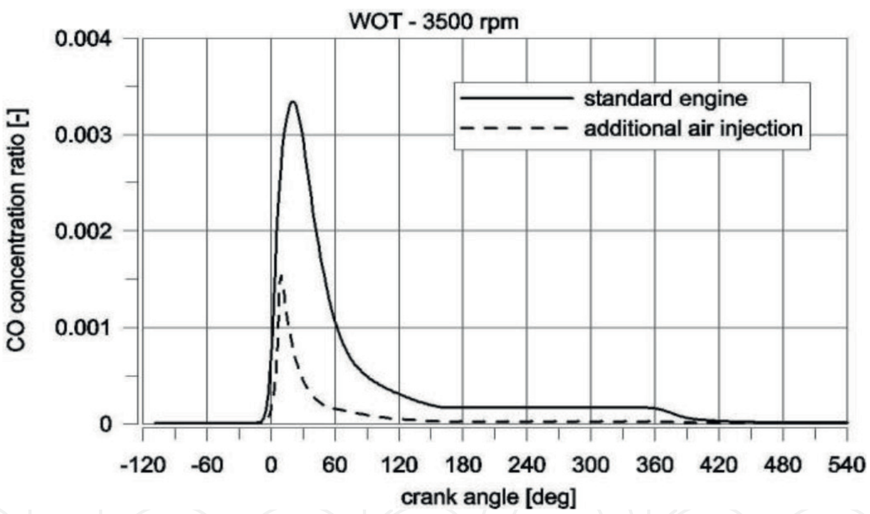


**Figure 24.** Comparison of cylinder CO mass concentration at 3500 rpm for standard four-stroke CI and hybrid engine at full load.

The pneumatic system also enables the reducing of soot emission in diesel engines by earlier air injection in the region of the fuel jet core, where the amount of oxygen is not enough for complete burning and thus the soot is formed. Simulation of work performance was also carried out for SI engine with a compression ratio $\varepsilon = 10$ for the same geometrical data as for the compression ignition combustion and pneumatic engine. The obtained results have the same tendency of increasing power and decreasing of specific fuel consumption. The main task of the proposed system is applying of vehicles without exhaust pollution in the cities ('zero emission') and enabling a higher engine performance at different load of the car.

## 8. Car pneumatic system

### 8.1. Proposal of combustion and pneumatic hybrid vehicle

The proposal of the hybrid car driven by combustion and pneumatic engine is shown in **Figure 25**. During normal driving on the highway or high speed road (outside of the city), the diesel or gasoline engine drives the piston air compressor, which loads the air to the tank. The work done for the air compression is recovered during driving in the city or car acceleration. The system has possibility of filling the air tank during stop in the garage or on special filling stations. The air pressure is controlled by a regulator. Each cylinder or only chosen cylinders are equipped with the air injectors, which are controlled by ECU (electronic control unit). The air injection is applied only in the cities in special regions for the 'zero emission' mode on the distance maximum 10 km or higher and for sudden change of engine load. Some energy for driving of the compressor can be obtained from braking energy (recovering energy) during deceleration of the car. It requires some changing in the electric control system by applying of an electric motor for the piston compressor drive.

### 8.2. Required amount of air during urban drive

For driving in the city with mean velocity $v$ = 50 km/h, the car with mass $m$ = 1250 kg requires power $P$ about 4 kW. Such value of power can be obtained in the CI pneumatic engine at rotational speed above $n$ = 3500 rpm with air consumption in one cylinder $m_{cycle}$ = 0.12 g/cycle.

The amount of air injection pulses during road distance l = 10 km:

$$i = \frac{60 \cdot l \cdot n}{2 \cdot v} = \frac{60 \cdot 10 \cdot 3500}{2 \cdot 50} = 21,000 \text{ cycles} \tag{15}$$

The required mass of air for pneumatic driving:

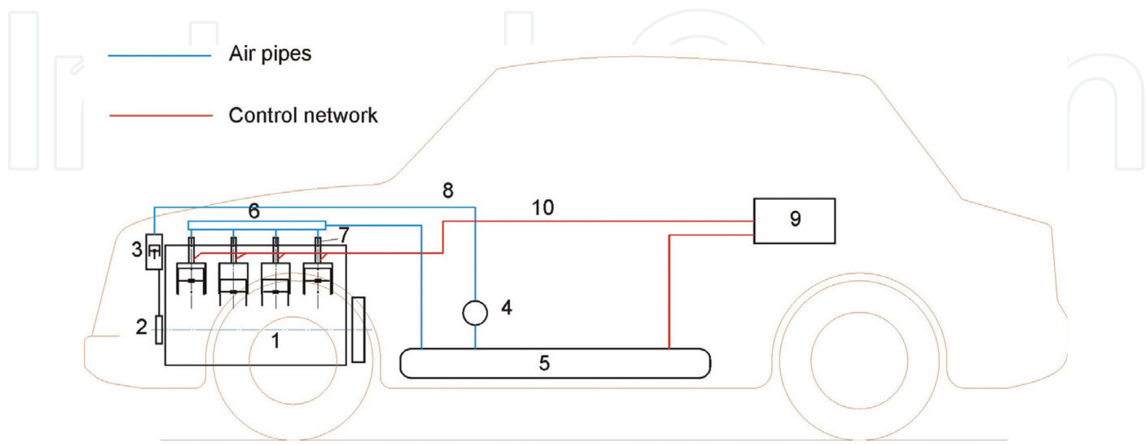


**Figure 25.** Scheme of pneumatic system of combustion engine in the car. 1, engine; 2, clutch of compressor drive; 3, piston compressor of high pressure; 4, pressure regulator; 5, high pressure air tank; 6, air common rail; 7, air electromagnetic injector or valve; 8, air high pressure line; 9, ECU; 10, electronic control network.

$$m_{air} = i \cdot m_{cycle} \ = \ 21,000 \times 0.12 \ = \ 2520 \text{ g} \ = \ 2.520 \text{ kg} \tag{16}$$

This mass value corresponds to volume of the tank filled with air at pressure 350 bar and temperature 300 K:

$$V = \frac{m_{air}}{\rho_{air}} = \frac{m_{air}RT}{p} = \frac{2.520 \cdot 287 \cdot 300}{350 \cdot 10^5} \ = \ 0.0062 \text{ m}^3 = \ 6.2 \text{ l} \tag{17}$$

The higher volume is required because during consumption of air by the engine, the air pressure in the tank decreases. The calculations carried out by the authors indicated that a required volume of the tank not greater than 30 l. The required bottle volume of air with pressure 350 bar for the following road distance at a constant velocity of 50 km/h:

1. 5 km—3.1 l
2. 10 km—6.2 l
3. 15 km—9.3 l
4. 20 km—12.4 l

For driving of the car according to drive test NEDC, where mean velocity amounts only 17.8 km/h, the required bottle volumes can be less as shown above. The same bottle volumes are needed for full combustion and pneumatic engine operation, because at 3500 rpm, the engine consumes 0.12 g/cycle. Obtaining of high performance for four-cylinder engine fed by the pressurized air is possible with the total air consumption 0.48 g/cycle. At this rotational speed for only 5 min of the drive, only 4.2 kg of air is needed, which requires the bottle volume about 10 l.

## 9. Summary

Across the world, some universities and companies successfully manufactured different types of air powered engines (APEs). But generally limited by low working efficiency of the compressed air, low-temperature ice block and critical parts' performance, the APE is still in the development stage. Therefore, precise modelling and simulation cannot only lay a foundation for the design of the APE but also save development costs.

1. Two-stroke pneumatic engine enables higher values of bmep at lower air pressure (below 150 bar), but at higher air pressure, the four-stroke engine gives the same bmep but indicates lower value of SAC. A higher compression ratio in the four-stroke engine than in the two-stroke engine forces of applying of higher pressure of the injected air.
2. The two-stroke pneumatic engine indicates smoother work because of existence of expansion process every rotation of the crankshaft and show high power at smaller air pressure, but show also a higher value of SAC. Working parameters of such engine depend mainly on pressure of the injected air, start point and time of duration of air injection, design of the air valve, way of opening of the air valve and other control parameters.

3. Higher injection pressure of the air increases bmep as well as increases the value of SAC. The engine at full load shows a decrease of bmep and an increase of SAC with growing of rotational speed at the same injection pressure.

4. The mean temperature of working medium should be at above 300 K for proper lubrication of the two-stroke pneumatic engine. Because of such requirement, the injection pressure of air should be above 50 bar (see **Figure 4**).

5. The presented hybrid vehicle with the combustion and pneumatic engine enables to achieve higher mean effective power and torque in comparison to the standard engine. The described hybrid engine can work in four modes (Section 6.1) depending on required power and reduction of exhaust gas emission.

6. In the pneumatic working mode, the CI engine does not emit any toxic chemical species (zero emission) mostly in urban drive, which causes also a lower heat exchange with a cooling system (higher thermal efficiency).

7. During the pneumatic working mode, the CI engine demands the air volume equal above 6 l under pressure 350 bar for the driving with constant velocity of 50 km/h in the city with a distance 10 km. For higher driving distance, the foreseen tank volume amounts not more than 30 l. Applying an additional high pressure air injection above 350 bar, one increases the theoretically total efficiency of the engine from 4 to 19% at micro-dose of air depending on the duration of air injection. The engine operating in the air microdose mode of the air can indicate the total efficiency higher than 50%. The engine working at full dose of air (combustion and pneumatic mode) indicates much higher total efficiency reaching value 60%.

8. Additional air in CI engines decreases CO, HC and NOx emission, which is caused by additional oxygen and lowering of temperature in the cylinder. In the compression ignition engine, a lower soot emission is expected, which is caused by penetration of fuel jet core by the injected air. The hybrid vehicle with combustion and pneumatic engine enables to reach zero emission of exhaust gases with high engine performance, despite it requires an additional power for compressor drive, which is recovered during vehicle deceleration.

In this chapter, we presented only chosen aspects of clean pneumatic and hybrid combustion and pneumatic piston engines for application in transportation based on the own works. The presented experimental and theoretical works of other researchers indicate the needs of alternative and more ecological driving sources.

## 10. Future work

Future works should be concentrated on optimization of the air injection parameters in order to obtain a maximal efficiency. This can be performed also by simulations, but the control parameters should be verified on the experimental stand with real engine. Without the national subsides or financial support from industry, the research work in scientific institutions will not be possible. Now the passenger cars are equipped only with four-stroke engine. For that reason, the research work should be carried out on pneumatic four-stroke engine and hybrid pneumatic and combustion engines of the same type. A wider use of considered engines requires also an engagement of the industry. Research work under development of pneumatic and hybrid engines will be focused on further simulation and adaptation of production engines for the pneumatic feeding and testing them on laboratory stands also in dynamic modes. Correlation of simulation and experimental results will give a more precise model of the pneumatic engine.

## Abbreviations

| | |
|---|---|
| HCCI | Homogeneous charge compression ignition |
| CAI | Controlled auto-ignition |
| ATAC | Active thermo-atmosphere combustion |
| CI | Compression ignition |
| SI | Spark ignition |
| CA | Crank angle |
| TDC | Top dead centre |
| BDC | Bottom dead centre |
| ATDC | After top dead centre |
| BTDC | Before top dead centre |
| WOT | Wide opening throttle |
| ECU | Electronic control unit |
| bmep | Brake mean effective pressure |
| imep | Indicated mean effective pressure |
| bsfc | Brake specific fuel consumption |
| SAC | Specific air consumption |
| AMPC | Air mass per cycle |
| Λ | Air excess ratio |

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