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PROPOSAL OF A PISTON ENGINE WITH CLOSE THERMAL CYCLE OF WORKING MEDIUM

Władysław Mitianiec

Cracow University of Technology
Jana Pawla II Av. 37, 31-864 Krakow, Poland
tel: +48 12 6283692; Fax: +48 12 6283690
e-mail: wmitanie@usk.pk.edu.pl

Abstract

Ecological aspects and utilization of biomass as a fuel leads to applying of a closed work cycle in the piston engine. It forces usually to delivering of heat to working medium through a heat exchanger. The heat may get from any type of fuel in an external combustion chamber, which allows on precisely control of combustion process. The paper describes a new conception of the engine operating in two-stroke cycle with working medium being in the close system, the best with the perfect gas as argon or helium. The delivering process of working medium with high temperature from the heat exchanger takes place through the inlet valve during a few dozen degrees of CA rotation in piston position at TDC. Expansion stroke takes place until outlet valve opens shortly BBDC. The outlet period from the cylinder follows almost at constant pressure and at low temperature to an adiabatic chamber, from where the working medium is compressed by an adiabatic compressor to pressure near pressure being in the heat exchanger. The engine works in two-stroke cycle and enables to get low temperature and pressure as early as BDC through a long time of opening of the outlet valve. The paper presents the ideological scheme of the engine system and theoretical thermal cycle. On this basis one presents the theoretical description of the individual thermodynamic processes with determination of thermal parameters of the characteristic points of the cycle. This article determines also the thermal efficiency of such closed cycle. The presented engine may have a practical applying as a stationary engine in energetic systems, where as fuel may be biomass, which globally influences on decreasing of CO_2 and NOx by temperature control of the combustion process.

***Keywords**: transport, combustion engine, thermal cycles, closed system*

1. Engines for energetic power plants

The transport sector and the energetic sector still are looking for a best method of combustion of biomass fuel, because of decreasing of fossil fuel and environmental requirements with respect to harmful components of exhaust gases. Nowadays direct combustion of biomass in internal combustion engines is not possible. The gasification of the biomass is widely used for obtaining of gaseous fuel or applying the fluidization of the biomass by using Fischer-Tropsch method [2]. However this technology requires big financial sources and very complicated chemical reactors, which is considered in whole world in respect to fluidization and gasification of coal. In small energetic sectors it is only possible way to used directly the biomass in thermal machines for production of the heat and electric power. Usage of biomass and alternative fuels is widely described in literature [7, 9]. There are many possibilities of driving systems in electric and heat generation, such as gas turbines, water turbines, steam turbine, internal and external combustion engines or numerous non-conventional driving systems. In transport sector more popular are hybrid driving systems [3, 13]. The gas, steam and water turbines required high technology [11] and are very expensive and for local electric power generation are not possible to apply them. Direct combustion of biomass is possible in the boilers, which can be external source of heat for feeding both turbines and reciprocating engines. Particularly the applying of piston engines is very promising, because of their common application in the transport sector and industry sector.

Utilization of the biomass is highly recommended in respect to exhaust gas emission.

Formation of CO_2 during combustion process in the boiler is consumed by the plants in the process of photosynthesis and we have the close cycle of CO_2 production. Taking into account all this requirements and environmental protection the author presents a new idea of the piston two-stroke engines with external combustion chamber working at low temperature.

2. Piston engine working in closed cycle

For many years there are known several thermal machines working in closed cycle with external combustion chamber designed for industry applications such as the Stirling engine or Ericsson engine [6]. The first uses the cooler- regenerator-heater system for transfer the heat from "hot" cylinder to "cold" cylinder in order to change the heat on mechanical work. This engine has two cylinders with special crank mechanism uses the heat deriving from combustion or ambient heat. There are known many types of Stirling engines described by Zmudzki [14] and applied for example in submarine boats or in electric power generators in big farms. The second case with the Ericsson engine concerns also to heat exchange between two cylinders, where delivering of the heat follows during expansion process at constant temperature. Outflow of gas to the second cylinder takes place also at constant temperature during compression process. Both systems work in the closed cycle without gas exchange with the atmosphere or ambient medium and may use the noble gases such as helium, argon, krypton, xenon or radon and also the air. Each theoretical thermal cycle of the engine should be near the Carnot cycle with high thermal efficiency. In order to maintain the fixed thermodynamic parameters the best solution is to apply a noble gas with high and constant specific heat ratio. The ideal gas used in the engine with closed cycle enables working in adiabatic conditions.

From mechanical point of view the engine working in two-stroke mode in comparison to four-stroke engine is better solution enabling to obtain higher indicated mean pressure (*imep*) and smooth working of the engine. The temperature of the gas delivering from the boiler to the engine should not be so high in respect to resistance of materials used in the boiler and engine. Thus the engine should work at low temperature below 1300 K. In respect to thermodynamic efficiency the temperature difference should be biggest as possible between high and low heat sources. In such case the flowing out gas from the cylinder to the boiler containing the heat exchanger has to be cooled in order to obtain lower temperature during gas outflow. It can be done by water injection directly in the cylinder or by cooling the flowing gas in a special chamber by cold water flown in the coil pipe. The gas in the heat exchanger of the boiler is at high pressure and takes the heat from combustion process of the biomass. The whole engine system emits the same harmful components as in the conventional engines fuelled by fossil fuels, but with CO_2 being consumed by nature and lower NOx content.

3. Design of two-stroke engine with external combustion chamber

In order to obtain high thermal efficiency the thermal engine cycle in p-V system should be near rectangular form. The proposed design of the two-stroke engine includes both inlet and outlet valves locating in the cylinder head. Working of conventional two-stroke engine is detailed described in literature [1, 5],The inlet valve opens the flow of the hot gases from the boiler to the cylinder and the outlet valve opens the gas flow from the cylinder do the external chamber with constant pressure. The biomass is burnt in the boiler and the released heat Q_1 is delivered by convection and conductivity to the gas in the coin pipes. The boiler works at constant (ambient) pressure and temperature. Temperature of combustion should be controlled and it should not exceed the creep temperature of the used materials. The mass of inflow and outflow gases in the closed cycle is the same. The inlet valves are opened shortly BTDC (several CA degree) in order to equal the pressure inside the cylinder after compression process. The hot gases are delivered to the cylinder through the inlet valves. The filling process with the gas lasts tens CA degrees and can be assumed that takes place partly at constant volume and constant pressure. The greater part of filling process occurs when pressure inside the cylinder and in the boiler is the same.

The diagram of two-stroke engine with external combustion chamber working in closed cycle is shown in Fig. 1. The black thick line shows the gas flow in the system. The final temperature of the charge in the cylinder after closing of inlet valves is lower than temperature in the heat exchanger. The real expansion process lasts until the outlet valves begin to open. Opening of the outlet valve is over a dozen CA degrees BBDC.

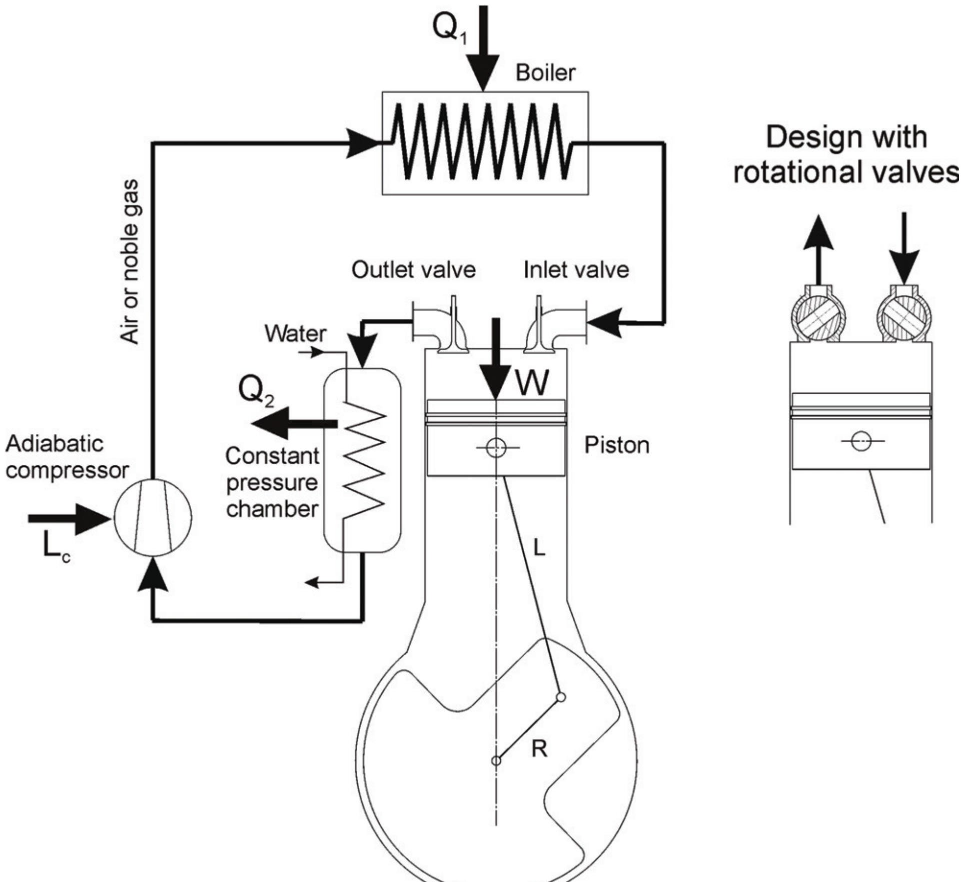

Fig. 1. Scheme of two-stroke external combustion engine

Next the gas flows through the outlet valves to the chamber with constant pressure during motion of the piston in direction of TDC. Outflow of the gas is caused mainly by pressure difference between the cylinder and the chamber and by piston movement. Because of constant pressure inside the chamber one can say that greater part of the gas outflow takes place at constant pressure with small change of gas temperature in the cylinder. For practical point of view one can apply the poppet valves or rotational valve, which can be driven from the crankshaft. A proposal of engine design with rotational valves is also shown in Fig. 1. The valves have longitudinal holes, which are opened and closed by the housing walls. Filling and emptying of the cylinder from the charge is depended on valve timing. Determination of the initial values of valve's opening and closing angles may be obtained from the computer simulation of thermodynamic engine cycle with taking into account the charge exchange [4, 10].

The gas in the chamber is cooled by water in order to decrease the temperature. In such case amount of heat Q_2 is consumed by the water and may be used for heating any device (for example house). Before delivering of the cold gas to the heat exchanger of the boiler it is compressed adiabatically in the piston compressor, which may be driven from the crankshaft. There is needed external power for driving of the compressor defined as L_c. From the compressor the gas under assumed pressure flows into the heat exchanger in the boiler. The thermal efficiency of the boiler is high, because of constant parameters of the combustion process [10] and takes place at adiabatic conditions. For today's gas boilers thermal efficiency reaches value almost 92%. Because of lower temperature of the gas delivered to the cylinder there is low heat transfer to the walls and such engine may be treated as adiabatic engine. Such solution enables obtaining a high thermal work in comparison to known thermal cycles of piston internal combustion engines. This new conception of two-stroke external combustion engine is proposed for local energetic sector in order to use the biomass instead of fossil fuels with high thermal efficiency. Valve timing of this engine is shown in Fig. 3. Compression process and heat delivering take place in very short period. In order to prevent escaping of the gas into the inlet pipe at the beginning of valve opening, the cylinder pressure at the end of compression should be lower than in the inlet pipe.

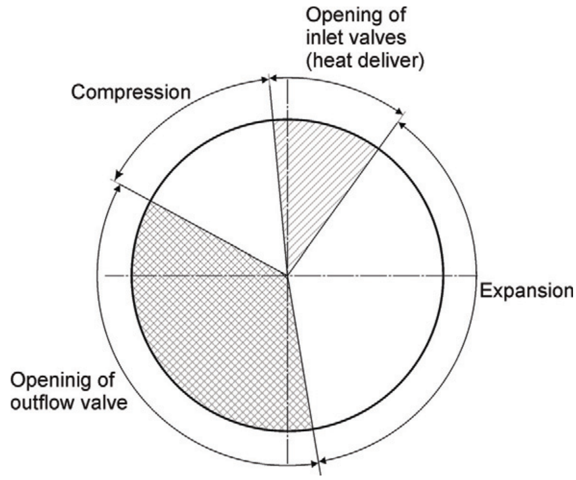

Fig.2. Phases of engine work

4. Engine thermal cycle

Thermal closed cycle of the two-stroke external combustion engine is presented in Fig. 4. Heat delivering takes place in two thermodynamic processes: isochoric with quantity Q_{d1} and isobaric with quantity Q_{d2}. The main part of the delivering heat occurs in isobaric process. During inflow process temperature of the gas inside the cylinder increases from value T_3 to mean value T_5. Expansion process in the engine occurs from point 5 to point 6 and for the ideal gas the polytrophic expansion coefficient is equal constant adiabatic coefficient $m=k$, where k is specific heat coefficient ratio [8, 12]. Temperature T_6 and pressure p_6 depends on volume V_5, temperature T_5 and pressure p_5.

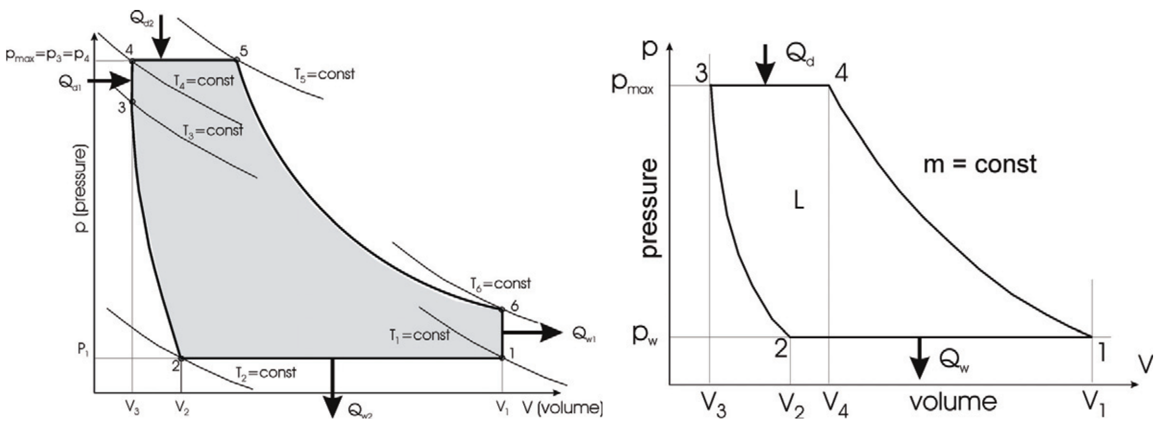

Fig. 3. Extended and simple theoretical cycle of two-stroke external combustion engine

Outflow of the gases at low temperature begins at point 6 and the first period takes place at constant volume during over a dozen of CA degrees to point 1. The proper gas outflow begins from BDC, while the pressure inside the cylinder changes with small value and this period may be defined as isobaric process. Pressure at point 2 is equal to pressure in the chamber behind the outlet pipe. Because of long time of outflow temperature of the gas is low despite there is any scavenging with fresh gas as in classic engines. Next the residual gas with mass m_2 is compressed by the piston motion in the TDC direction. The compression period is treated as isentropic process at constant specific heats ratio k.

Each thermal cycle of working machine may be presented in temperature-entropy *T-s* system. Such cycle of the new external combustion two-stroke engine is shown in Fig. 4. The cycle has six processes: the divided inflow process (deliver of heat), the divided outflow process, expansion and compression processes, which may be presented as isentropic processes. The simplified cycle with delivering of the heat and loss of the heat at constant pressure is shown on the right in Fig. 4.

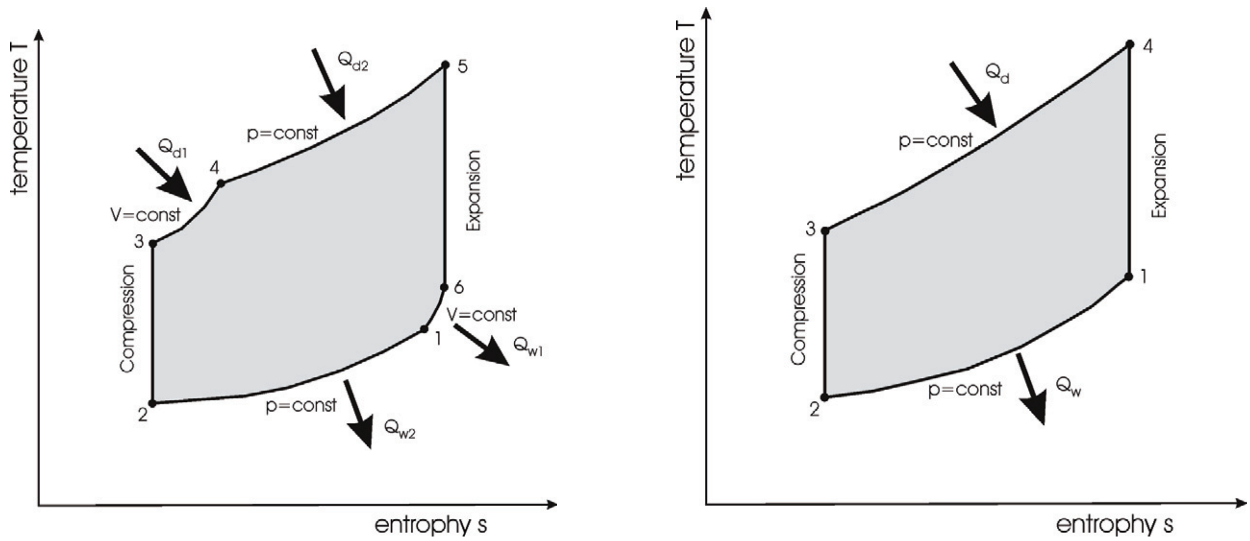

Fig. 4. Extended and simple engine cycle in T-s system of two-stroke external combustion engine

The thermal cycle of the engine is closed to Carnot cycle. In the considered engine the heat is delivered shortly at constant volume and mostly at constant pressure close to pressure in the boiler's heat exchanger. Main mass of the gas first is cooled in the external chamber and next is compressed by adiabatic compressor and is pumped to the boiler. Theoretically the heat delivered to the gas Q_d by convection and conductivity in the boiler is equal the heat delivered to the cylinder during inlet process.

5. Theoretical model of engine with close cycle

The accurate model requires determination of inflow and outflow phenomena with variation of gas flow through the valves. Theoretical consideration enables a rough determination of temperature and pressure in the defined points of the cycle. Mathematical model of the engine will be considered to simple theoretical cycle shown both on the right sight of Figures 3 and 4. The constant mass of the charge in close system should be taken into account. Despite of decreasing of the mass in the cylinder during outflow process and increasing of the charge during inlet process the mass does not change in the whole system. The basic part of the mass is compressed by the adiabatic compressor and only rest of charge after outflow process is compressed by the piston in the cylinder. For that reason it may be considered that compression process take place in the cylinder with constant mass of the charge. For ideal gases the specific heat ratio k is defined by formula:

$$k = \frac{c_p}{c_v} = \frac{c_v + R}{c_v}, \tag{1}$$

where:

c_p – specific heat at constant pressure,

c_v – specific heat at constant volume,

R – individual gas constant.

Theoretical efficiency of the engine is determined on specific delivered heat Q_d and outflow specific heat Q_w:

$$\eta_t = 1 - \frac{Q_w}{Q_d}. \tag{2}$$

The delivered specific heat from the boiler is determined as follows:

$$Q_d = c_p (T_4 - T_3). \tag{3}$$

The outflow specific heat at constant pressure p_1:

$$Q_w = c_p \left(T_1 - T_2\right). \tag{4}$$

After substitution (3) and (4) to equation (2):

$$\eta_t = 1 - \frac{T_1 - T_2}{T_4 - T_3}. \tag{5}$$

Thermodynamic parameters of the engine cycle depend on pressure p_4 and temperature T_4 in the boiler limited by permissible stress of used materials. At such assumption temperature in point 3 at constant pressure $p_3 = p_4$ may be calculated as follows:

$$T_3 = T_4 \frac{V_3}{V_4}. \tag{6}$$

After expansion to assumed volume V_1 temperature and pressure at point 1 amount:

$$T_1 = T_4 \left(\frac{V_4}{V_1}\right)^{k-1}, p_1 = p_4 \left(\frac{V_4}{V_1}\right)^{k}. \tag{7}$$

The outflow process takes place at constant pressure $p_1 = p_2$. Final temperature at point 2 is calculated from the formula:

$$T_2 = T_1 \frac{V_2}{V_1} = T_4 \left(\frac{V_4}{V_1}\right)^{k-1} \frac{V_2}{V_1}. \tag{8}$$

Temperature in point 3 after compression by the piston should be the same as in (6):

$$T_3 = T_2 \left(\frac{V_2}{V_3}\right)^{k-1} = T_4 \left(\frac{V_4}{V_1}\right)^{k-1} \frac{V_2}{V_1} \left(\frac{V_2}{V_3}\right)^{k-1} = T_4 \left(\frac{V_4}{V_1}\frac{V_2}{V_3}\right)^{k-1} \frac{V_2}{V_1}. \tag{9}$$

After comparison of (6) and (9) the following relationship is obtained:

$$\frac{V_2}{V_1}\left(\frac{V_4}{V_1}\frac{V_2}{V_3}\right)^{k-1} = \frac{V_3}{V_4}. \tag{10}$$

This equation defines point 2 determining closing of the outflow valve:

$$V_2 = V_3\left(\frac{V_1}{V_4}\right)^{\frac{1}{k}}\left(\frac{V_1}{V_4}\right)^{\frac{k-1}{k}} = V_3\frac{V_1}{V_4}. \tag{11}$$

After substitution (7), (8) and (9) into (5) the theoretical efficiency is a function of volumes and ratio of specific heats *k*:

$$\eta_t = 1 - \frac{1-\frac{V_2}{V_1}}{1-\frac{V_3}{V_4}}\left(\frac{V_4}{V_1}\right)^{k-1}. \tag{12}$$

Theoretical work is evaluated from the formula:

$$L_t = \eta_t Q_d, \tag{13}$$

where Q_d amounts:

$$Q_d = mc_p(T_4 - T_3). \tag{14}$$

The mass of charge is calculated at point 1:

$$m = \frac{p_1 V_1}{RT_4}\left(\frac{V_1}{V_4}\right)^{k-1}. \tag{15}$$

Theoretical mean pressure:

$$p_t = \eta_t\frac{p_1V_1}{RV_s}c_p\left(1-\frac{V_3}{V_4}\right)\left(\frac{V_1}{V_4}\right)^{k-1} = \eta_t\frac{p_1}{R}c_p\left(1+\frac{1}{\varepsilon}\right)\left(1-\frac{V_3}{V_4}\right)\left(\frac{V_1}{V_4}\right)^{k-1}. \tag{16}$$

The analysis of thermal efficiency of the cycle shown on the left in Figures 3 and 4 requires additional information about gas mass flow rate through the valves.

6. Example of calculation of engine parameters

The described engine is designated for energetic sector working at low rotational speed and higher bore and stroke values. For example it was assumed the following parameters:

- bore D = 120 mm,
- stroke S = 200 mm
- compression ratio $\varepsilon = 12$,
- rotational speed *n* = 750 rpm
- maximum pressure in the boiler $p_3 = p_4 = 3$ MPa,
- pressure during outflow process $p_1 = p_2 = 0.2$ MPa,
- temperature in the boiler $T_4 = 1300$ K,
- working medium: argon with R = 207.85 J/(kg K) and air with R = 287 J/(kg K).

Simple calculations give the following results:

- stroke volume $V_s = 2262$ cm^3,
- minimum cylinder volume $V_3 = 205.6$ cm^3,
- maximum cylinder volume $V_1 = 2467.6$ cm^3,
- coefficient *k* = 1.67 for argon and *k* = 1.4 for air,
- volumes $V_4 = 487.6$ cm^3 and $V_2 = 1040.7$ cm^3 for argon,
- volumes $V_4 = 356.6$ cm^3 and $V_2 = 1422.7$ cm^3 for air,

- theoretical efficiency $\eta_t = 0.595$ for argon,
- theoretical efficiency $\eta_t = 0.538$ for air,
- theoretical mean pressure $p_t = 0.552$ MPa for argon,
- theoretical mean pressure $p_t = 0.374$ MPa for air.

The example indicates lower theoretical efficiency and lower theoretical mean pressure for air than for noble gas such as argon.

7. Summary

This work concerns to new driving source and using of new fuel and presents a new idea of the energetic engine fuelled by the biomass with external combustion process taking place in constant conditions. The engine is designated for production of mechanical work mainly for driving electric generator and also as a source of the heat for industry or local utilization. The engine design is based on two-stroke cycle with higher useful work than in four stroke engine. The work presents a preliminary consideration of the engine cycle and gives the simple theoretical fundamentals of its processes. On basis of the presented considerations the following observations are given:

1. the engine is working on the heat delivered from the external boiler with burning of biomass fuel in different various forms,
2. the engine works in two-stroke cycle with six processes, where outflow process occurs at constant pressure and compression process occurs in short period with residual gas only,
3. the engine work in such configuration enables to obtain higher thermal efficiency despite the inserted work in the adiabatic compressor. Using of noble gases as a gas medium gives higher theoretical efficiency than using the air,
4. total emission may be neglected, because CO_2 is consumed by nature during photosynthesis and circulates in a closed cycle,
5. thermal loads of the engine are lower because of lower combustion temperature in the boiler,
6. resistance temperature of used materials determines upper limits of temperature in the boiler and in the cylinder,
7. controlling of the combustion process in the boiler is simpler than in the internal combustion engine, because the process takes place at constant conditions and at lower temperature.

References

[1] Blair, P. G., *Design and simulation of two-stroke engines*, SAE, 1996.

[2] Dry, M.E., *Catalytic aspects of industrial Fischer-Tropsch synthesis*, Journal of Molecular Catalysis, 17, 133-144, 1982.

[3] Fraidl, G., Herzog P., *Multiple benefit technology development for gasoline-diesel-hybrid powertrains*, Combustion Engines 1/2007(128), PTNSS-2007-SS1-202, Bielsko-Biała 2007.

[4] Guzella, L., Onder, C. H., *Introduction to modeling and control of internal combustion engine systems*, Springer-Verlag, Berlin 2010.

[5] Heywood, J. B., *Internal Combustion Engine. Fundamentals*, McGraw-Hill, New York 1988.

[6] Kowalewicz, A., *Wybrane zagadnienia samochodowych silników spalinowych*, Wyższa Szkoła Inżynierska w Radomiu, Radom 1996.

[7] Kropiwnicki, J., *Comparison of energy efficiency of vehicles powered by different fuels*, Combustion Engines 3/2012(150), PTNSS-2012-SS3-304, Bielsko-Biała 2012.

[8] Look, D. C., Sauer, H. J., *Engineering Thermodynamics* PWS Engineering, Boston 1986.

[9] Niewczas, A., Gil, L., Ignaciuk, P., *Chosen aspects of biofuel usage on the example of Amelina oil metyl ester*, Combustion Engines 1/2012(148), PTNSS-2012-SS1-112, Bielsko-Biała 2012.

[10] Ragland, K., Bryden, K., *Combustion Engineering*, CRC Press Taylor & Francis Group, Boca Raton, FL, USA 2011.
[11] Rajewski, A., *Plains End Power Station-gas reciprocating engines in a grid-stability power plant*, Combustion Engines 2/2010 (141), PTNSS-2010-SS2-202, Bielsko-Biała 2010.
[12] Szargut, J., *Termodynamika*, PWN, Warszawa 1975.
[13] Szumanowski, A., *Hybrid electric vehicle drives fitted with combustion engines*, Combustion Engines 1/2009(136), PTNSS-2009-SS1-102, Bielsko-Biała 2009.
[14] Żmudzki, S., *Silniki Sterlinga*, WNT Warszawa 1993.