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# Miller cycle application to the gaseous supercharged SI engine

*The paper contains results of tests on the spark ignited (SI) engine modified to work as the engine with the overexpanded thermodynamic Miller cycle. Investigation was particularly focused on thermodynamic properties of the applied Miller cycle as well as combustion progress in the supercharged engine fuelled with various gaseous fuels as follows: coke gas, natural gas and hydrogen. Crucial conclusions deal with experimental investigation. The conclusions showed the following: IMEP was maintained at the same level with aid of supercharging, thermal indicated efficiency increased.*

Key words: *gas engine, indicated parameters, Miller cycle*

## Zastosowanie obiegu Millera do doładowanego silnika gazowego o zapłonie iskrowym

*W artykule przedstawione zostały wyniki stanowiskowych silnika o zapłonie iskrowym przystosowanym do pracy na zasdzie obiegu Millera. Badania skupiały się na właściwościach termodynamicznych wykorzystanego obiegu Millera jak również przebiegu spalania w dołądowanym silniku zasilanym różnymi paliwami gazowym takimi jak: gaz koksowniczy, gaz ziemny, wodór. Główne wnioski uzyskane zostały w wyniku badań eksperymentalnych i wskazały wzrost odporności na spalanie stukowe przy wykorzystaniu obiegu Millera oraz podwyższenie sparawności indykowanej.*

Słowa kluczowe: *silnik gazowy, parametry indykowane, obieg Millera*

## 1. Introduction

Nowadays trends in engine design are concern both decrease in exhaust gas emission and increase in engine efficiency. One of the paths to achieve that is adaptation an engine to work on alternative fuels such as: hydrogen, methane, hythane, biogas or producer gas. All that mentioned fuels are characterized by lower C to H ratio which means that they will emit exhaust gas toxic compounds such as carbon monoxide (CO), unburned hydrocarbons (HC) at lower level. Also the emission of carbon dioxides ($CO_2$) will decrease as well. On the other hand, good way to lower emission of nitrogen oxides is to decrease the peak in-cylinder temperature during combustion process. To achieve it, two ways are proposed. One is based on exhaust gas recirculation (EGR) system which rely on returning exhaust gas to intake manifold and in this way reducing the amount of fresh charge content. The consequence of such operation is decrease in the peak in cylinder temperature. The second method is based on application of the overexpanded cycle to internal combustion (IC) engine. The over-expanded cycle is the engine cycle, in which the length of intake stroke is not equal to work stroke. In other words, compression ratio is lower than expansion ratio, what can by expressed with the equation:

$$\varepsilon_{cr} \neq \varepsilon_{ex}$$

where:
$\varepsilon_{cr}$ – compression ratio
$\varepsilon_{ex}$ – expansion ratio

Over-expansion cycle was developed by James Atkinson in XIX century and modified in the XX century by Ralph H. Miller. One of the advantages of the over-expanded cycle compared to the classic one as the Otto or the Diesel cycle, is that it reduces temperature in characteristic points of the cycle. The same effect in consequence also results from EGR system, which leads to lower emission of $NO_x$ [1, 2, 3]. Next advantage of the over-expanded cycle is increase in thermal efficiency of the engine and, as result, decrease in fuel consumption [4, 5].

Thanks to these features of the over-expanded cycle, it seems to be good for the IC engine working on alternative fuels especially those with high content of hydrogen eg. producer gas, hythane, coke gas and pure hydrogen. Such properties of hydrogen as wide flammability limits, low energy of ignition, high self-ignition temperature, high diffusivity, high laminar flame speed, cause hydrogen to be considered as a promising energy carrier which can be used as fuel to the IC engine.

Apart from increase in engine thermal efficiency by applying the over-expanded cycle to IC engine, it is also increase in thermal efficiency caused by fueling the engine with a fuel of high content of hydrogen, what approaches the engine cycle to the ideal constant volume cycle (Otto cycle).

The main objective of this study was to investigate influence of the over-expanded cycle application to the IC supercharged gas engine on engine indicated parameters, especially thermal efficiency. The test rig was done for the engine in configuration as classic one and modified to work as the over-expanded one and the results were compared.

All tests were conducted in similar condition for load, over boost pressure, ignition timing and mixture composition.

## 2. Test rig description

Test rig is equipped with the single cylinder, water cooled spark ignited engine. The engine is coupled with a synchronous generator which generates a load for the engine and maintain constant speed during the tests. The engine is adopted to work as the over-expanded engine by modification of a camshaft cam. The modified cam provides the same valve opening angle as in the engine with classic cycle and closing intake valve at 20 ° CA before bottom dead center (BDC). Parameters for the classic camshaft and the modified one is presented in table 1.

*Tab. 1 Engine camshaft parameters*

| | | |
|---|---|---|
| Intake valve opening angle | *deg* | 11ATDC |
| | | 11 ATDC (Miller) |
| Intake valve closure angle | *deg* | 30 ABDC |
| | | 20 BBDC (Miller) |
| Exhaust valve opening angle | *deg* | 30 BBDC |
| Exhaust valve closure angle | *deg* | 0 TDC |

Due to early intake valve closure angle, the valve rocker was changed from flat-shape to rolling one. The rolling rocker provides proper cooperation with the cam. If the flat rocker is used, the top curve of the intake cam will be cut and the cam will be damaged. The research engine is also equipped with a supercharger and an intercooler for cooling down the fresh charge flowing through the supercharger. The intercooler is drawn in a water tank to keep temperature of intake charge at constant level independently from boost pressure level. The view of test rig is presented in figure 1.

*Fig. 1. Test rig overview*

More details about the test rig is presented in [6].

## 3. Research procedures

The research was divided into two parts. In first part the engine characteristics of ignition timing were made for the engine without modifications and the MBT timing was determined for the naturally aspirated (NA) engine as well for the supercharged (SC) engine with two overpressure of 0,3 and 0,6 bar. The same procedures were done for the modified engine to work as the over-expanded one. When the optimal ignition timing was set the tests were repeated for both engine configurations where the over pressure was changed in range from 0 to 0,6 bar with step of 0,1 bar. During tests the engine was fuelled as follows: by CNG with 99% methane content, by coke gas which consisted of CNG and hydrogen at volumetric share of 40% and 60% for CNG and hydrogen, respectively. Test setup is shown in table 2.

*Tab. 2. Test setup*

| Fuel | Ignition Timing (deg BTDC) | λ (-) | $p_{boost}$ (bar) |
|---|---|---|---|
| CNG | 28 | 1,05±0,05 | 0,0÷0,6 |
| Coke Gas | 14 | 1,05±0,05 | |
| Hydrogen | 4 | 1,55±0,05 | |

To avoid problems with overheating the engine, temperature of it was kept in limits between 60 and 70°C. The temperature of the water in intercooler tank was kept at level of 20°C during the research. All tests where done for wide open throttle conditions (WOT).

## 4. Results and discussion

Figure 2 presents comparison of non-firing cycles for the engine not-modified (classic cycle) and for the modified engine (Miller cycle). As seen, the modified engine has the lower compression pressure which is caused by lower volumetric efficiency.

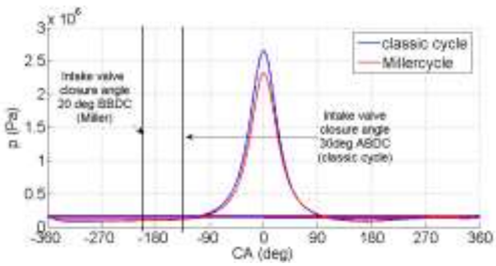


*Fig. 2. Comparison of motored pressure trace for the engine with classic cycle and Miller cycle*

In figure 3 several pressure traces for the engine with classic cycle and Miller cycle are shown. During these tests the engine was working on CNG.

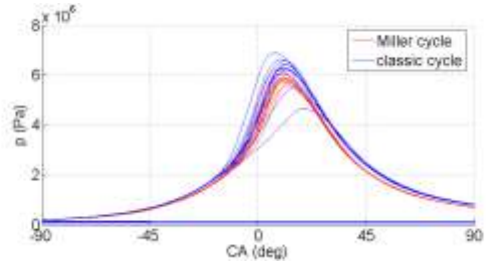


*Fig 3. Combustion pressure comparison for classic cycle engine and Miller cycle engine fuelled with CNG (NA engine)*

Figure 4 shows comparison of pressure data vs. crank angle for engine with classic cycle and Miller cycle fuelled with coke gas.

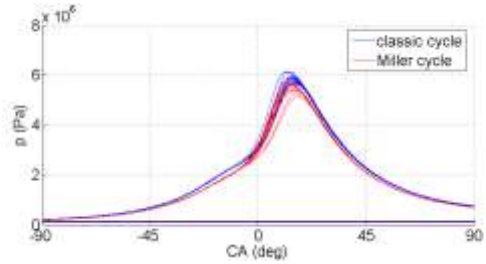


*Fig. 4. Combustion pressure comparison for classic cycle engine and Miller cycle engine fuelled with coke gas (NA engine)*

In figure 5 pressure data for engine working with classic cycle and Miller cycle fuelled with hydrogen is depicted.

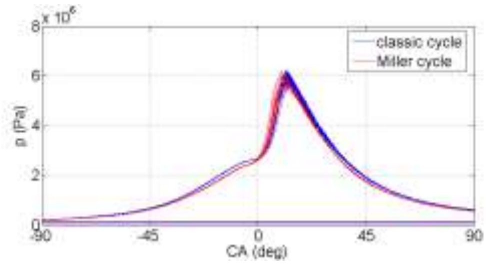


*Fig. 5. Combustion pressure comparison for classic cycle engine and Miller cycle engine fuelled with hydrogen (NA engine)*

As seen in figures 3-5, with increase in hydrogen share in fuel delivered to the engine, the maximum pressure for the classic and the Miller cycle is closing to each other. Another characteristic feature is that the pressure rise with increase of hydrogen dose is steeper which is connected with high laminar flame speed of hydrogen. With application of over-expanded cycle to the engine the maximum in-cylinder temperature decreases.

Figure from 6 to 8 show comparison of in-cylinder temperature for the engine with classic cycle and Miller cycle fuelled with three different gaseous fuels: CNG, coke gas and hydrogen. For more clear comparison, the in-cylinder temperature was computed for the NA classic cycle engine and the SC Miller cycle engine with boost pressure of 0,6 bar.

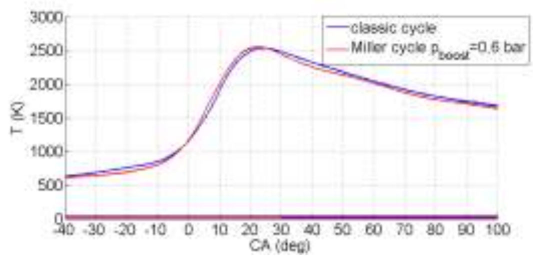


*Fig. 6. Comparison of maximum in-cylinder temperature for the NA classic engine end the SC Miller cycle engine ($p_{boost}$=0,6 bar), fuelled with CNG*

As seen in figure 6, temperature at the end of compression stroke, which in this case corresponds to crank angle at MBT timing is lower for the engine working as the over-expanded one than for the engine working as the classic one. The maximum temperature is almost at the same level for both engine configurations.

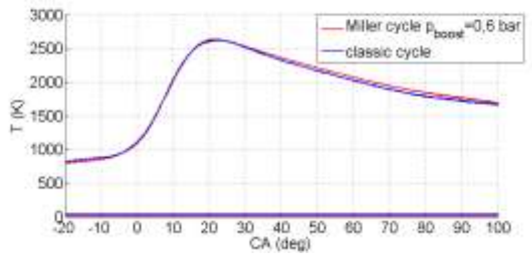


*Fig. 7. Comparison of maximum in-cylinder temperature for NA classic engine end SC Miller cycle engine ($p_{boost}$=0,6 bar), fuelled with coke gas*

As plotted in figure 7, temperature at the end of compression stroke is lower for the engine with Miller cycle configuration if compared to the engine with the classic cycle configuration. The maximum in-cylinder temperature is also for both cases on the same level, although it is higher than for the engine working on CNG fuel.

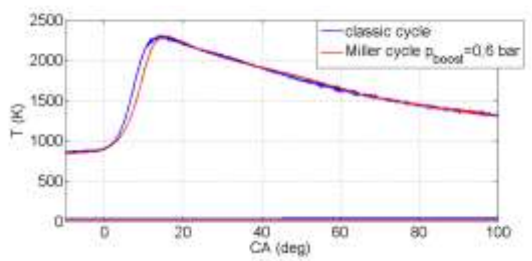


*Fig. 8. Comparison of maximum in-cylinder temperature for NA classic engine end SC Miller cycle engine ($p_{boost}$=0,6 bar), fuelled with hydrogen*

As seen in figure 8 in this case the temperature at the end of compression stroke is also lower for the modified engine to work as the over-expanded one compared to the not modified engine. The maximum in-cylinder temperature for both engine configurations are at the same level. The maximum in-cylinder temperature for the engine fuelled with hydrogen is lower compared to value for CNG and coke gas, this is caused by combustion of lean hydrogen-air mixture with excess air ratio of 1,5.

Due to applying the over expanded cycle to the IC engine and working at WOT, the indicated mean effective pressure (IMEP) decreases, to recompense this loss, supercharging is used. Comparison of IMEP as a function of $p_{boost}$ for all investigated gaseous fuels is shown in figures from 9 to 11.

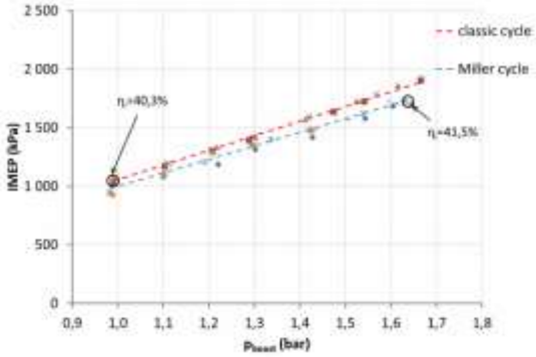


*Fig. 9. IMEP as function of $p_{boost}$ (fuel CNG)*

As presented in figure 9 IMEP for the engine working with the over-expanded cycle in all $p_{boost}$ is lower when compared to the engine working with the classic cycle. However, the decrease in IMEP was observed, but the indicated efficiency increases with applying the over-expanded cycle. To reduce negative influence of the over-expanded cycle on the IMEP, the engine was supercharged.

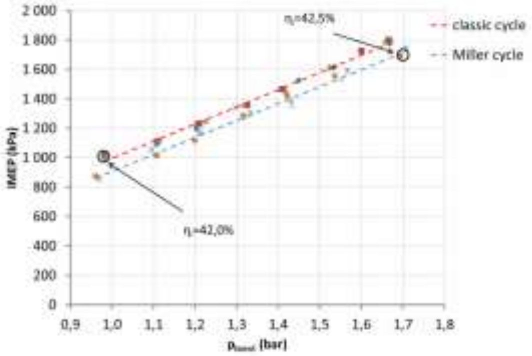


*Fig. 10. IMEP as function of $p_{boost}$ (fuel coke gas)*

Figure 10 depicts the same trend which is shown in figure 9. The IMEP for the over-expanded engine configuration is lower than for the classic configuration. The maximum IMEP for coke gas fuel is slightly lower if compared to the engine fuelled with pure CNG, this is caused by lower calorific value of the intake charge because of higher hydrogen content in fuel mixture.

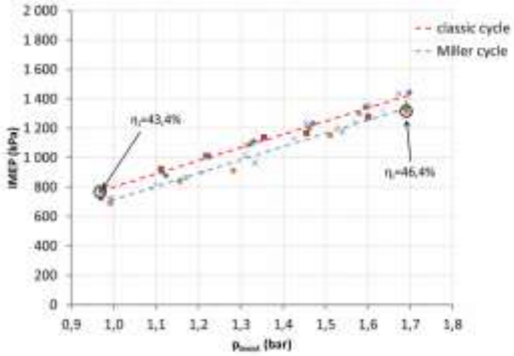


*Fig. 11. IMEP as function of $p_{boost}$ (fuel hydrogen)*

Figure 11 presents IMEP for both the classic cycle and the Miller cycle configurations, as seen in this case, also the IMEP for the over-expanded cycle is lower than for the classic cycle. Characteristic is that the IMEP for the engine fuelled with hydrogen is lower than for both CNG and coke gas. The reason is the engine fuelled with hydrogen was working with leaner mixtures expressed by the excess air ratio $\lambda$=1,55±0,05. The second reason of such low IMEP is that hydrogen has a low density what leads to a lower calorific value of fuel-air mixture. Comparison of IMEP for both engine configurations fuelled with CNG, coke gas and hydrogen are presented in table 3.

*Tab. 3. Comparison of indicated efficiency ($\eta_i$) for engine with classic and Miller cycle*

| Gaseous fuel | $\eta_i$ (%) | |
|---|---|---|
| | Classic cycle NA engine | Miller cycle SC engine |
| CNG | 40,3 | 41,5 |
| Coke gas | 42,0 | 42,5 |
| Hydrogen | 43,4 | 46,4 |

## 5. Conclusions

The research was focused to examine influence of applying the over-expanded cycle to IC engine on engine parameters and indicated efficiency for three different gaseous fuels. On the basis of this research the following conclusions were drawn:

1. Application of an over-expanded cycle causes decrease in volumetric efficiency of the engine. This action leads to decrease in IMEP. To eliminate this drawback, supercharging the engine was introduced.
2. Over-expanded cycle contributes to decrease in temperature at the end of the combustion stroke. The same maximum in-cylinder temperature, as for the NA engine with classic cycle, was observed in the over-expanded SC engine with boost overpressure $p_{boost}$=0,6 bar.
3. The maximum in-cylinder temperature decreases with hydrogen content in gaseous fuel mixture, what is caused by lower calorific value of the fuel-air mixture.

4. Increase in indicated efficiency for the over-expanded cycle SC engine in comparison to the NA classic cycle engine is presented below:
   a. CNG $\eta_i$=40,3% to $\eta_i$=41,5%
   b. Coke gas $\eta_i$=42,0% to $\eta_i$=42,5%
   c. CNG $\eta_i$=43,4% to $\eta_i$=46,4%
5. The maximal increase in indicated efficiency was denoted for hydrogen fuel and is probably caused by hydrogen high laminar flame speed.

## Nomenclature/*Skróty i oznaczenia*

BDC Bottom Dead Center/*dolny martwy punkt*
CNG Compressed Natural Gas/*sprężony gaz ziemny*
LPG Liquified Petrolum Gas/*gaz skroplony*
CA Crankshaft Angle/*kąt obrotu wału korbowego*
EGR Exhaust Gas Recirculation/*recyrkulacja spalin*
IC Internal Combustion/*wewnętrzne spalanie*
$\varepsilon_{cr}$ Compression ratio/*stopień kompresji (sprężania)*
$\varepsilon_{ex}$ Expansion ratio/*stopień eksapnsji*
NA Naturally aspirated/*wolnossący*
SC Supercharged/*doładowany mechanicznie*
$p_{boost}$ Boost overpressure/*nadciśnienie doładowania*
IMEP Indicated Mean Effective Pressure/*średnie ciśnienie indykowane*
$\eta_i$ indicated efficiency/*sprawność indykowana*

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