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Effects of Water Injection on Performance of 5-Stroke SI Engine

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Abstract

The objective of this work is to investigate the effects of water injection on performance of 5-stroke SI engine converted from the conventional 4-stroke SI engine. The cylinder head of the 2nd and 3rd cylinder was modified and connected to each other to be the ultra-expansion stroke or second expansion stroke (5th stroke). The engine was performed on a dynamometer at different engine speeds and loads of 1,500 to 3,000 rpm and 25% to 75% of full load, respectively. The water was injected during the second expansion stroke (5th stroke). Fuel and air consumptions, engine torque, rotational speed, air/fuel ratio and temperatures of intake air, engine oil, cooling water and exhaust gas were recorded to use for calculating brake specific fuel consumption (BSFC) and engine efficiency. The results showed that at low engine speed of 1,500 rpm for all loads, the water injection improves BSFC and the engine efficiency by 26% and 3.3%, respectively. However, a large amount of injected water shows insignificant improvement on BSFC and the engine efficiency due to short residence time, especially at high engine speed. The deterioration of engine oil can be observed after test. These findings are relevant to engine design or modification, especially at low engine speed.

Keywords: 5-stroke SI Engine; Water Injection; Performance

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1. Introduction

Although hybrid and electrical systems are developed in automotive area,the reciprocating internal combustion engines are still necessary and commonly used to generate the electricity.

Miller cycle (Sometimes called Atkinson cycle [1]) using strategy of ultra-expansion stroke, i.e. shortening compression stroke relative to expansion stroke, is one of the promising choice for hybrid vehicles because these cycles are more efficient than Otto cycle [1], [2]. Heat loss, friction and specific heat ratio of Miller cycle show significantly effect on fuel efficiency [3]-[6]. However, it has some limitation about downsizing and intake boosting [1].

Another development using the ultra-expansion cycle to improve the power requirement and thermal efficiency is the 5-stroke cycle [7]-[10]. The concept is to increase the expansion stroke without shortening the compression stroke. The 5-stroke cycle consists of 3 cylinders including two identical high pressure (HP) cylinders working in conventional 4-stroke cycle and one low pressure (LP) cylinder working in expansion and exhaust stroke using the discharged exhaust gas from the HP cylinders. In comparison with 4-stroke engine, Schmitz [7] concluded that fuel consumption decreased at full load by 16% and at low load up to 30%. The total displacement could be reduced by 37% with remaining the identical torque with 4-stroke SI engine. A more compact combustion chamber can be design for HP cylinders and different and new materials are available in 5-stroke engine building at the HP and LP area. High pressure drop at the beginning of intake increases the turbulence and air-fuel mixing in HP cylinder. However, some problems may raise with 5-stroke engine, e.g. sophisticated power regulation, cooling system for increased heat loss of HP cylinder and engine balance for the different masses of piston.

Afterward, there are many attempts to develop in the 5-stroke cycle [11]-[17]. Kéromnès et al. [11] developed the five-stroke engine with turbo charger to use as a range extender for hybrid vehicles. Zero and one dimensional simulation and engine bench tests were performed at engine speed of 3,500 rpm to 4,500 rpm. The results showed that at engine speed of 4,000 rpm and a brake power of 32.5 kW, the fuel conversion efficiency is improved up to 36.1% corresponding to BSFC of 226 g/kWh.

The theoretically and experimentally comparative studies between traditional 4-stroke and modified 5-stroke engines were performed by Noga et al. [12], [13]. The comparison was investigated at some points with less torque than the half of the conventional engine. The results showed that the total efficiency up to 17% can be achieved at the engine speed of 2,400 rpm because of the reduction of displacement by half. Nuntapap et al. [14]

also showed that the optimum operating point of 5-stroke engine is at engine speed of 2,500 rpm, where the promising performance of 5-stroke engine is obtained for all engine loads. Another study of the 5-stroke engine with turbocharging was done by Lu and Pei [15]. They found that fuel consumption was improved by 8% to 18% with the increase of maximum torque at low and medium engine speed. However, there are some points that have to deal with knock in the simulation and the geometries of modified engines. Most recently, Li et al. [1] compared between Miller and five-stroke cycles for enabling deeply downsized, highly boosted, spark-ignition engines with ultra expansion. The results showed that for the most frequently operated points on the torque-speed map, at low loads the Miller cycle shows superior fuel conversion efficiency, while at higher loads the 5-stroke cycle shows higher efficiency. For the WOT operation at the engine speed below 1,700 rpm, the deeply downsized engine using the Miller cycle fails to deliver the torque comparable to the traditional engine even using the two-stage booster, while the five stroke cycle engine can achieve the targeted WOT torque at all the engine speeds except 800 rpm.

Another way to improve fuel conversion efficiency can be done by heat recovery from exhaust loss, using water injection. Mingrui et al. [18] studied the influence of water injection on the performance and emission characteristics of a SI direct injection (GDI) engine under light load conditions. The results were revealed that a 15% water by mass injecting together with fuel gave the best engine performance resulting in the improvement of indicated mean effective pressure and efficiency. In addition, NO_x and soot reduction can be obtained by water injection. Shafee and Srinivas [19] also showed the improvement of fuel efficiency in a small petrol engine by using water injection. They found that increasing injected water amount decreases fuel consumption and the exhaust gas temperature. Bozza et al. [20] showed the potentials of water injection and cooled EGR for knock resistance and fuel consumption improvements of SI engines. The results show that both water injection and cooled EGR show significant BSFC improvements, especially at medium engine speeds. The heat absorbed by the water evaporation reduces the knock tendency, resulting in the possibility to advance the combustion phasing and improvement of fuel consumption. Arabaci and Içingür [2] investigated the effects of the amount of water injection and timing on engine performance in a sixstroke engine. They realized that water injection timing and amount are the keys for higher engine performance.

In summary, both 5-stroke engine and heat recovery by water injection showed the improvement of engine performance, but gaps exist in previous works. Engine performance in term of brake specific fuel consumption and engine efficiency have not been extensively studied in 5-stroke engine with water injection. It is possible that engine performance will be improved because the discharged gas temperature from the HP cylinder is over 1,000 ^{o}C [21].

Therefore, the objective of this study is to investigate the effects of water injection on performance of 5-stroke SI engine. The recorded data is used to calculate brake specific fuel consumption and engine efficiency. Fundamentally, use of 5-stroke engine and water injection to improve engine performance are rudimentary, yet the findings are relevant to novel engine design and provide extended data on 5-stroke engine with water injection. These will probably make them suitable for realistic.

2. Research Methodology

The experimental setup and test condition used for this study are described in this part.

2.1 Experimental setup

The experiments were carried out on a 5-stroke SI engine connected to a dynamometer, which provided the different engine loads. Torque was calculated from force measured by a load cell connecting with dynamometer. **Fig. 1** shows the schematic diagram of this study. The 5-stroke SI engine was converted from the typical 4-stroke SI engine with the same concept of Noga and Sendyka [12] shown in **Fig. 2.** The cylinder head of the 2^{nd} and 3^{rd} cylinders were modified and connected to each other to be the 5^{th} stroke where it is the additional expansion stroke and heat loss is recovered.

The operating principle of 5-stroke engine with water injection is that combustion and 1^{st} expansion are occurred in the 1^{st} or 4^{th} cylinder, then the discharged exhaust gas from the 1^{st} or 4^{th} cylinder (high pressure cylinder; HP) is secondly expanded in the 5^{th} stroke (at 2^{nd} and 3^{rd} cylinder or low pressure cylinder; LP). At the beginning of 5^{th} stroke, water was injected by injector mounted at the connecting exhaust port.

Also, the intake camshaft showing in **Fig. 3** has been modified for adjusting intake valve timing to obtain 5-stroke engine. The conventional camshaft was divided into 3 parts, which connected to each other by new design connectors.

The technical specifications of the modified engine and valve timing are described in **Table 1**.

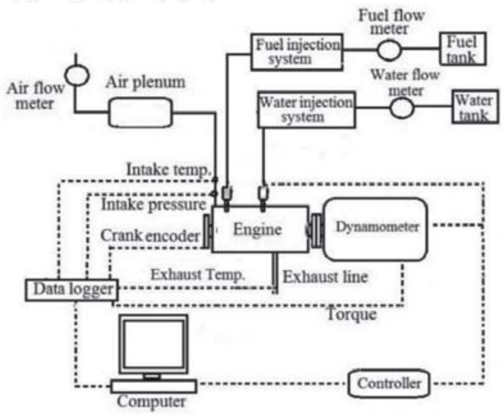


Fig. 1 Schematic diagram

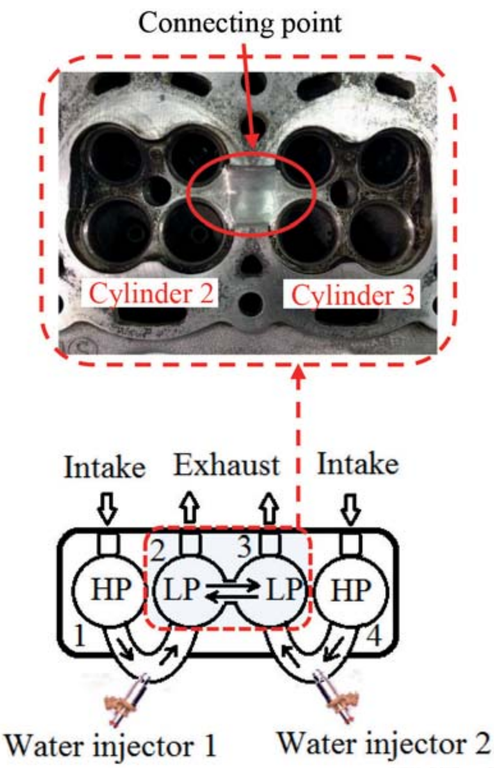


Fig. 2 The operating of modified 5-stroke SI engine with water injection

Fig. 3 The modified intake camshaft for 5-stroke engine

Fuel consumption was recorded by an in-house fuel flow meter. The intake air pressure and flow were measured by a manometer and orifice meter measurement, respectively, which were located at the air plenum. The engine speed was measured by crank encoder, and then brake specific fuel consumption (BSFC) and engine efficiency were obtained by the following equations.

$$BSFC = \frac{\dot{m}}{\dot{W}} = \frac{\dot{m}}{2\pi NT} \quad (1)$$

$$\text{Thermal efficiency} = \frac{\dot{m}}{\dot{W}} = \frac{2\pi NT}{\dot{m}\,(LHV)} \quad (2)$$

Where

$\dot{m}$ = Fuel flow rate (g/s)

$\dot{W}$ = Power output (kW)

N = Engine speed (rpm)

T = Torque (N.m)

LHV = Lower heating value (kJ/kg)

The temperatures of the intake air, water coolant, engine oil and exhaust gases were measured by K-type thermocouples. The equivalence ratio was measured by the oxygen sensor. The engine was operated for sufficient time to achieve thermal stability, which was checked by the temperatures of the coolant, engine oil and exhaust gas.

Table 1 Modified engine specification

Engine Parameters	Values
Engine type	In-line,4 cylinders
Displacement	1587 cm^3
Bore x Stroke	81x77 mm
Compression ratio	9.5:1
Ignition timing	10° BTDC
Combustion and 1st expansion	Cylinder 1 and 4
2nd expansion (5th stroke)	Cylinder 2 and 3 (connected to each other)
Valve timing of HP cylinder	IVO 6° BTDC IVC 214° ATDC EVO 144° ATDC EVC 6° ATDC
Valve timing of LP cylinder	EVO 132° ATDC EVC 8° BTDC

Ideal gas law is used to estimate the increase of in-cylinder pressure due to water expansion. The assumption was made following:

1. All injected water could be changed suddenly into steam.
2. Steam behaves like ideal gas.
3. Steam expands fully in 5th stroke, i.e. cylinder 2 and 3.

2.2 Experimental condition

In this study, the effect of varying water injection amount on performance of 5-stroke engine at different engine loads and speeds shown in **Table 2.** In addition, the effects of the use of water injection on lubricant is also observed.

Table 2 Operating conditions

Parameter	Value
Engine loads (%)	25, 50, 75
Engine Speeds (rpm)	1,500 – 3,500
Water injection (mg)	13 – 40

3. Results and Discussion

This part introduces the engine characteristics of 5-stroke engine without water injection then follow by the effect of water injection.

3.1 Characteristics of 5-stroke SI engine without water injection

Fig. 4 shows the performance curve of 5-stroke SI engine performed at engine load of 75%. The maximum torque is 57 N.m occurred at engine speed of 2,500 rpm, while the possible maximum power is 17.8 kW at engine speed of 3,500 rpm, where it is the limitation due to the modification of camshaft.

Fig. 5 (a), (b) and **(c)** shows that with increasing the engine load from 25% to 75% for all engine speeds, brake specific fuel consumption (BSFC) decreased during 34% to 46%, while efficiency increased by 5% to 7%.

This result is similar to Li et al. [1]. It could be explained that the higher cylinder and piston temperatures as estimated by the higher exhaust temperature at higher loads improve the level of combustion. This leads to reduce CO and THC but NO_x as shown in the previous work [22].

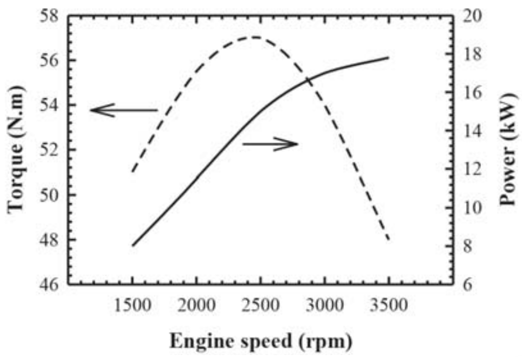
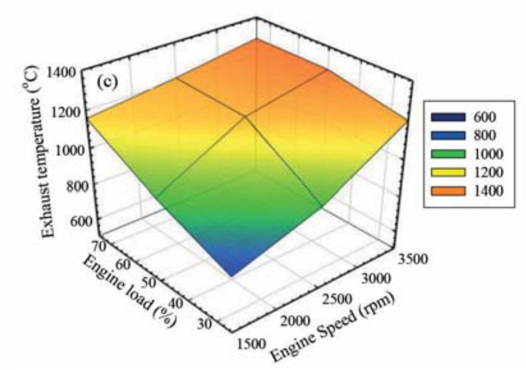


Fig. 4 Performance curve of 5-stroke SI engine at engine load of 75%



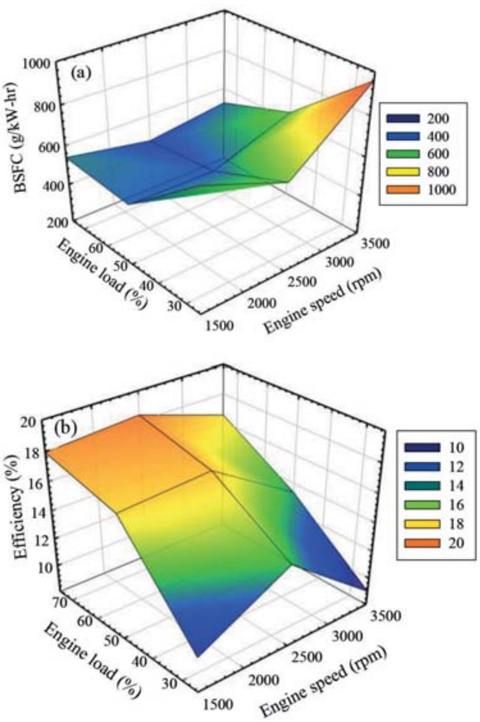


Fig. 5 Engine characteristics of 5-stroke SI engine: (a) Brake specific fuel consumption (BSCF); (b) Efficiency; (c) Exhaust gas temperature

It is clear that the engine characteristics of 5-stroke SI engine depends on engine load and speed. The optimum operating speed is 2,500 rpm for all loads.

3.2 Effect of water injection on 5-stroke SI engine characteristics

This part shows the effect of water injection on 5-stroke SI engine. The theoretical expectation of water injection used for heat recovery during 5th stroke is that the excess heat could convert the injected water to the expanded and pressurized steam which increases the in-cylinder pressure, as shown in **Fig. 6**, and it is possible to do more work resulting lower BSFC and higher efficiency.

Nevertheless, a large amount of water injection is not always useful as shown in **Fig. 7.** Increasing amounts of injection water show slightly effect on BSFC, efficiency and exhaust temperature for all loads at constant engine speed. It could be explained that the vaporizing rate of water controlling phase change and steam expansion is longer than the residence time in 5th stroke (Additional expansion stroke). A small amount of water could be vaporized to recover heat during 5th stroke, and the remained water is blown out with the exhaust gas. Therefore, higher amount of injected water makes slightly change in combustion characteristics at a constant engine speed for all engine loads.

In addition, engine characteristics become worst with increasing engine speed as shown in **Fig. 8** and **Fig. 9.** At engine speed of 3,500 rpm in **Fig. 8,** BSFC cannot be improved by water injection. In other words, the similar result is obtained by increasing the injected water amount from 13 mg to 40 mg at engine speed of 3,500 rpm.

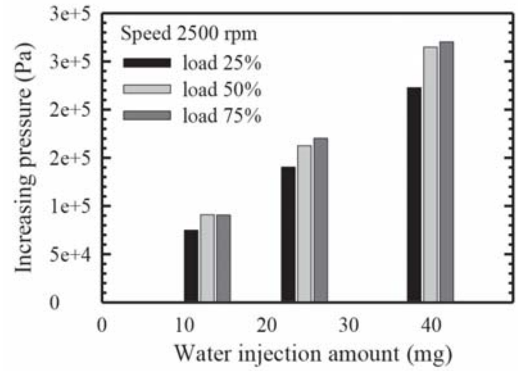


Fig. 6 The estimation of increase of the in-cylinder pressure in 5th stroke due to water expansion

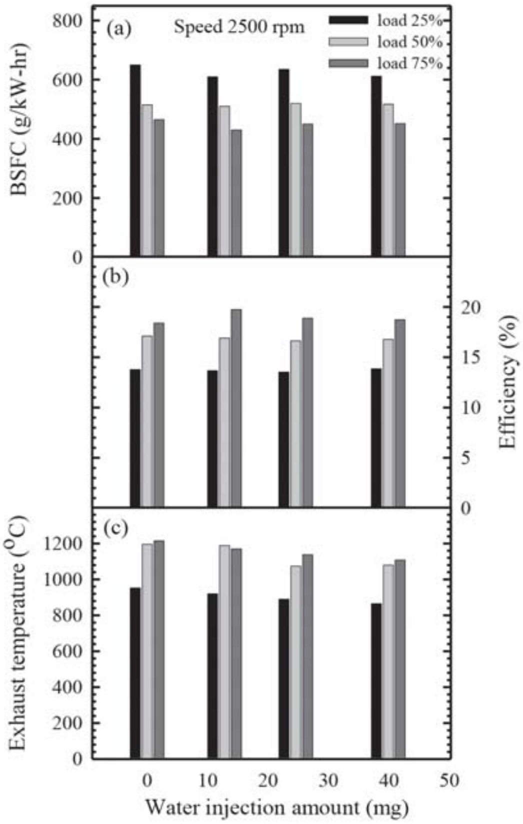


Fig. 7 (a) Brake specific fuel consumption (BSFC); (b) Efficiency; (c) Exhaust temperature of 5-stroke SI engine with water injection amount at constant engine speed of 2,500 rpm

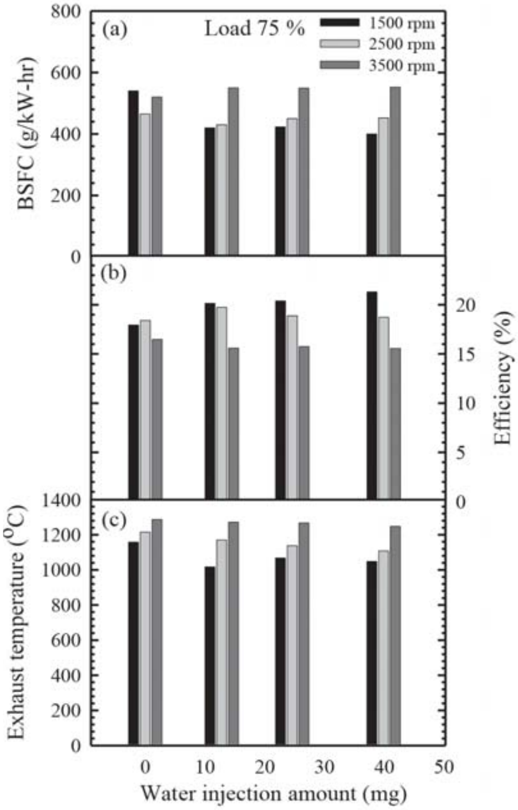


Fig. 8 (a) Brake specific fuel consumption (BSFC); (b) Efficiency; (c) Exhaust temperature of 5-stroke SI engine with water injection amount at constant engine load of 75%

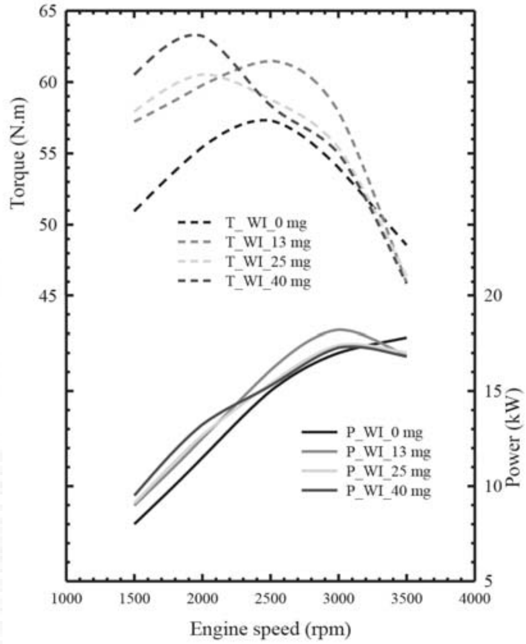


Fig. 9 Performance curves of 5-stroke SI engine with and without water injection at constant engine load of 75%

However, water injection during the 5th stroke significantly decreased BSFC by 22% to 26% at engine speed of 1,500 rpm. These relate with the efficiency. Water injection improves efficiency by 0.4% to 3.3% at engine speed of 1,500 and 2,500 rpm except 3,500 rpm. The results could be confirmed by exhaust temperature shown in **Fig. 8 (c)**. Increasing amount of injected water does reduce the exhaust temperature in case of engine speed of 1,500 and 2,500 rpm. This means that excess heat is recovered by vaporized water during 5th stroke. However, the exhaust temperature could not be quenched by water vaporization in case of higher engine speed (3,500 rpm) although water injection amount is increased, because it has short residence time.

The performance curve with and without water injection as shown in **Fig. 9** could also be used to confirm that water injection recovers efficiently the heat at engine speed below 2,500 rpm, because at low engine speed there is enough residence time for water vaporization.

3.3 Effect of water injection on engine oil

In this study, the 5-stroke SI engine with water injection was performed over 200 hours. The engine operated normally during the tests. However, there were some negative effects caused by the use of water injection on engine oil.

Engine oil deterioration was observed after testing. The injection of water provided an extreme water contaminant in the engine oil, which formed oil–water microemulsions resulting to the lubricity reduction. Therefore, the water injection for recovering heat loss in the 5-stroke engine may increase the possibility of lubricity failure for long term used. The increase of engine wear leading to shorter durability is expected as the drawback of water injection.The microemulsions can be easily detected by oil color change as shown in **Fig. 10.** This drawback is also detected by the other works that study effect of high water contents used on engine performances [18], [22] and [23]. It should be considered and have to be improved for the realistic use.

(a) Before testing (b) After testing

Fig. 10 Deteriorated engine oil caused by water injection

4. Conclusion

This study presents the effect of water injection on 5-stroke SI engine performance. The main conclusions from the experimental results are as follows.

- The finding obviously shows advantage of heat recovery by water injection, particularly at low engine speed, i.e. 1,500 rpm, but the advantage deteriorates with increasing engine speed. At engine speed over 2,500 rpm, increasing amounts of injection water show slightly effect on BSFC and efficiency for all loads.
- The BSFC and efficiency of 5-stroke SI engine strongly depend on engine speed and load rather than water injection amount.
- The water injection provided an extreme water contaminant in the engine oil and formed oil–water microemulsions that reduced the lubricity of oil.

5. Acknowledgement

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6. References

[1] T. Li, B. Wang and B. Zheng, "A comparison between Miller and five-stroke cycles for enabling deeply downsized, highly boosted, spark-ignition engines with ultra expansion," *Energy Conversion and Management*, vol. 123, pp. 140–152, June. 2016.

[2] E. Arabaci and Y. Içingür, "Thermodynamic investigation of experimental performance parameters of a water injection with exhaust heat recovery six-stroke engine," *Journal of the Energy Institute*, vol. 89, pp. 569-577, Jun. 2016.

[3] Y. Ge, L. Chen, F. Sun and C. Wu, "Effects of heat transfer and friction on the performance of an irreversible air-standard Miller cycle," *International Communications in Heat and Mass Transfer*, vol. 32, no. 8, pp. 1045–1056, 2005.

[4] S. Hou, "Comparison of performances of air standard Atkinson and Otto cycles with heat transfer considerations," *Energy Conversion Management*, vol. 48, no. 5, pp. 1683–1690, 2007.

[5] J. C. Lin and S. Hou, "Performance analysis of an air-standard Miller cycle with considerations of heat loss as a percentage of fuel's energy, friction and variable specific heats of working fluid," *International Journal of Thermal Sciences*, vol. 47, no. 2, pp.182–191, 2008.

[6] A. Al-Sarkhi, J.O. Jaber and S.D. Probert, "Efficiency of a Miller engine," *Applied Energy*, vol. 83, pp. 343–351, 2006.

[7] G. Schmitz, "Five-stroke internal combustion engine," Patent 6553977, USA, 2003.

[8] P.C. Pien, "Over expanded limited-temperature cycle two-stroke engines," Patent 6848416 B1, USA, 2005.

[9] Z. Yang, "Ultra-expansion four-stroke internal combustion engine," Patent 7438025 B2, USA, 2008.

[10] T. Rajeshkumar, E. Vignesh, R. Haridass, G. Chockalingam, "Analysis of five stroke internal combustion engine - A Review," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 6, no. 1, pp. 489-492, 2017.

[11] A. Kéromnès, B. Delaporte, G. Schmitz, L. Le Moyne, "Development and validation of a 5 stroke engine for range extenders application," *Energy Conversion and Management*, vol. 82, pp. 259–267, 2014.

[12] M. Noga and B. Sendyka, "New design of the five-stroke SI engine," *Journal of KONES*, vol. 20, no.1, pp. 239–246, 2013.

[13] M. Noga and B. Sendyka, "Increase of efficiency of SI engine through

the implementation of thermodynamic cycle with addition expansion," *Bulletin of the Polish Academy of Sciences*, vol. 62, no. 2, pp. 349–355, 2014.

[14] N. Nuntapap, J.Saikhao, T. Kareo, N. Banboo, S. Wangkitphaiboo, R. Munsin, and N. Chaiyat, "The effects of exhaust gas temperature on 5-stroke engine performance," in *Proceeding of the 9th International Conference on Sciences, Technology and Innovation for Sustainable Well-Being*, Kunming, China, 2017, pp. 104-109.

[15] Y. Lu and P. Pei, "Performance evaluation of 4-cylinder 5-stroke internal combustion engine," *Chinese Internal Combustion Engine Engineering*, vol. 36, no. 1, pp. 18–24, 2015.

[16] G. Gonca, "Effects of engine design and operating parameters on the performance of a spark ignition (SI) engine with steam injection method (SIM)," *Applied Mathematical Modelling*, vol. 44, pp. 655–675, 2017.

[17] C. Ailloud, B. Delaporte, G. Schmitz, A. Keromnes and L. L. Moyne, "Development and Validation of a Five Stroke Engine," SAE Technical Paper 2013-24-0095, 2013.

[18] W. Mingrui, N. T. Sa, R. F. Turkson, L. Jinping and G. Guanlun, "Water injection for higher engine performance and lower emissions," *Journal of the Energy Institute*, vol. 90, pp. 285-299, 2017.

[19] S. M. Shafee and M. Srinivas, "Improvement of fuel efficiency in a petrol engine by using water injection," *International Journal of Chemical Sciences*, vol. 15, no. 2, pp. 123-130, 2017.

[20] F. Bozza, V. De Bellis and L. Teodosio, "Potentials of cooled EGR and water injection for knock resistance and fuel consumption improvements of gasoline engines," *Applied Energy*, vol. 169, pp. 112–125, 2016.

[21] J. Saikhao, T. Kareo and W. Ainatakhamma, "The comparative study of engine performance of 5-stroke engine and 4-stroke engine," RMUTL's Academics Report, 2017.

[22] R. Munsin, Y. Laoonual, S. Jugjai, and Y. Imai, "An experimental study on performance and emissions of a small SI engine generator set fuelled by hydrous ethanol with high water contents up to 40%," *Fuel*, vol. 106, pp. 586–592, 2013.

[23] M. Boons, R. Van Den Bulk and T. King, "The impact of E85 use on lubricant performance," SAE Technical Paper 2008-01-1763, 2008.