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Thermodynamic simulation comparison of opposed two-stroke and conventional four-stroke engines

Today's technology leveraging allows OP2S (Opposed Piston 2-Stroke) engine to be considered as an alternative for the conventional four-stroke (4S) engines as mechanical drive in various applications, mainly in transportation. In general, OP2S engines are suited to compete with conventional 4-stroke engines where power-to-weight ratio, power-to-bulk volume ratio and fuel efficiency are requirements. This paper does present a brief advent, as well as the renaissance of OP2S engines and the novel technologies which have been used in the new approach.

Also precise thermodynamic benefits have been considered, to demonstrate the fundamental efficiency advantage of OP2S engines. Hence, simulations of two different engine configurations have been taken into consideration: a one-cylinder opposed piston engine and two-cylinder conventional piston four-stroke engine. In pursuance of fulfilling this goal, the engines have been simulated in AVL Boost™ platform which is one of the most accurate Virtual Engine Tools, to predict engine performance such as combustion optimization, emission and fuel consumption. To minimize the potential differences of friction losses, the bore and stroke per cylinder are taken as constant. The closed-cycle performance of the engine configurations is compared using a custom analysis tool that allows the sources of thermal efficiency differences to be identified and quantified. As a result, brake thermal efficiency, power and torque of OP2S engine have been improved compared to conventional engines while emission concern has been alleviated.

Key words: *opposed piston two-stroke engine, AVL Boost software, thermodynamic benefits, conventional crankshaft engines*

1. Introduction

With soaring demand of high-efficiency, fuel economy and emission pollutions, opposed piston (OP) engines have been offered as a solution for challenges facing the ICEs (internal combustion engines) in certain applications. However, to provide as economically sustainable solution, these technologies must increase efficiency without increasing cost.

The most promising solution to meet the current, and future, standards is the opposed piston engine. However, OP engines have inherently suffered from both high oil consumption and high thermal load.

In addition to a brief explanation of OP advent and also its inherent efficiency benefits, challenges facing OP engines have been investigated. Therefore, a single-cylinder OP engine has been simulated in AVL Boost to compare with a conventional four-stroke engine. Finally, the simulations have been considered in different cases to highlight the thermodynamic benefits of OP engines.

Computational aided engineering development enables the renaissance of ICEs, so that AVL Boost platform, as an advanced Virtual Engine Simulation tool, can model an accurate predicting of engine performance, power, torque regarding of the emission optimizing and fuel consumption. Besides, Boost provides an engine simulation tool applicable from the concept phase up to Engine Control Unit calibration.

2. History of opposed piston engines

Opposed piston two-stroke engines in appeared in public during 1890s in Germany by Witting [1]. Opposed piston engines are characterized by pairs of pistons operating in a single cylinder shown in Fig. 1, eliminating the need for cylinder head because two engines in reality have been combined into one engine by placing them top to top and joining the cylinders [1–4]. Gas exchange for two stroke versions is handled by piston-controlled ports on cylinder walls. They began to be used commercially around 1900 for numerous land, marine, and aviation purposes. Around 1900s, Oxford Company introduced a new OP engine used in marine application due to low speed crankshaft of engine. Then, Junker was a new OP using two crankshafts resulting with higher speeds during 1930s and they were used in light airplanes. They were developed because of high potential efficiency compared to its competitors [1, 4].

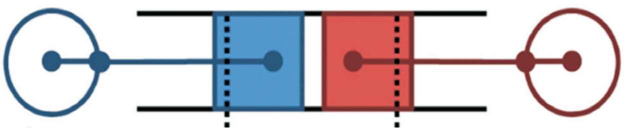

Fig. 1. Schematic of opposed piston two-stroke engine

Regardless of the field of application, OP (opposed piston) engines are getting popular due to the higher power-to-weight ratio, higher thermal efficiency, and more economic fuel consumption compared to the four stroke conventional crankshafts engines; however, they are facing many traditional two-stroke engines obstacles. Nevertheless, there are well established solutions [1].

After 2009, a renaissance of OP engines occurred by introducing Achates Power engine [1]. It has addressed the historical challenges with piston heat load that applies to all two stroke engines. The heat input due to combustion as well as heat rejection under piston's crown to cooling oil [1, 5–8].

The Achates Power OP2S diesel engine demonstrates significantly higher thermal efficiencies than comparable four stroke diesel engines with the same power [6–8]. Fair Diesel is another unique OP diesel engine introduced since 2000. It has combined two concepts of Barrel and OP engines. They are used in an exceptionally well-balanced lightweight diesel engine for wide range of applications. The use of shaped drive cams allow them to optimize the combustion cycle, resulting in higher thermal efficiency performance. The key feature of this patent is inertia force cancellation, resulting in a quiet engine with exceptionally low degrees of vibration [9]. Swash-Plate is used to transfer the reciprocating motion of the piston to rotational motion, although its brake efficiency decreases [9, 10].

Eco-Motors Company investigates on a new OPOC that each single opposed cylinder contains two pistons that move in opposite directions. The benefit of this architecture is significantly higher power density with smaller and lighter package [11] and commercially they have been used in light and medium vehicle applications [2, 11].

PAMAR-3 is another OP Barrel engine which transmits the reciprocating motion of the pistons into rotational motion by using Wobble plate. This engine is a prototype aeronautical engine built and designed by Pawel Mazuro [2]. Wobble plate mechanism blocked by gear which has been identified as the most promising for further analysis and research.

3. Advantages of OP engines

Generally, there are some advantages making the OP engines unique in comparison with the conventional crankshaft engines:

Absence of cylinder head; combination of two single cylinders from top to top eliminates the needs of cylinder head. Therefore the engine becomes lighter and more compact. Moreover, eliminating the cylinder head reduces the heat losses, which improves the thermal efficiency. Consequently, the emission of unburned hydrocarbons and carbon monoxide will be reduced [2]. Figure 2 shows various classifications of OP engines compared with classical crankshaft engines. The heat rejected to the cooling system of four OP engines is almost half the classical spark ignition engines.

Combustion chamber; OP engines can provide nearly twice lower SA/V than the conventional crankshaft engines, leading to higher thermal efficiency higher SA/V is of high importance due to the fact that Heat is generated proportionally to the volume (V) of the combustion chamber, while heat losses are proportional to the surface area (SA) [2]. Additionally, the amount of fuel injected in cylinder remains constant, but the volume is increased, resulting in leaner combustion and consequently it increases the specific heat ratio. Large volume combustion provides faster combustion duration at constant volume with same pressure rise rate [5].

Higher stroke to bore ratio; engines with higher stroke-to-bore ratio have smaller surface area exposed to combustion gases, leading to decreased heat transfer in-cylinder and consequently, it improves thermal efficiency. However, the mechanical efficiency is also affected [2, 4]. Also, higher S/B will increase SE (scavenging efficiency), resulting in lower pumping work. Besides, based on Achates Power for a fixed PCP, the crankshaft bearing friction decreases as the S/B increases, while the power-cylinder friction has the opposite effect. As a conclusion, both indicated thermal efficiency and pumping work benefit from a "longer S/B" [2, 4, 12–14].

Multi fuel technology; multi-fuel engine technologies are interested in both military applications due to fuel shortage and emission concern due to global climate contamination concern [2, 4].

These engines must meet two basic conditions to be able to run on multi-fuel bases. First, VCR (variable compression ratio), permits firing fuel with the highest octane rating; second, it must be strengthened to withstand widely changing working conditions (the temperature from burning biogas is different from one from aviation fuel).

Both aforementioned conditions are met in OP engines. VCR is incomparably easier to adapt in OP than in conventional engines, where a moving cylinder head or complicated shaft system must be adapted. Furthermore, fewer moving parts, simple combustion chamber shape and a more compact design make them more robust and durable [1, 2].

Uni-flow scavenging in OP2S engines gives higher effective flow area, resulting in reducing pumping work compared to 4-stroke or a single piston, 2-stroke uni-flow or loop scavenged engine [2, 5]. Besides, the scavenging ports are distributed all around the circumferences of the cylinder, resulting in trapping efficient air volume as well as increasing the volumetric efficiency.

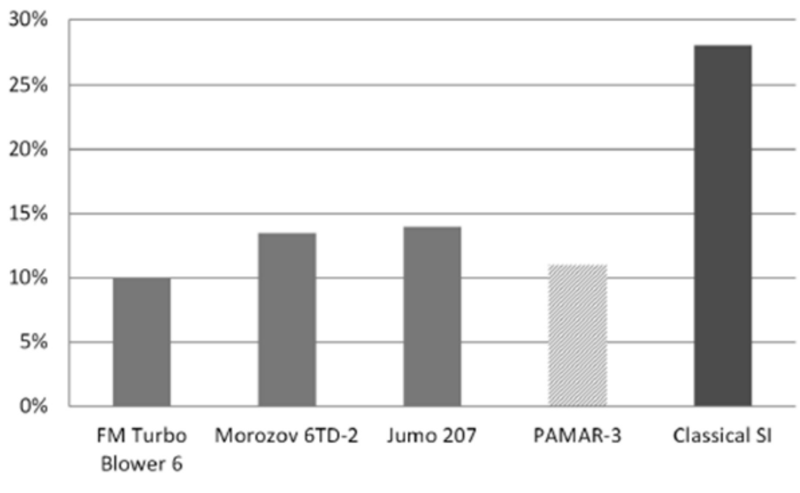

Fig. 2. Comparison of heat rejected to the cooling system of 4 OP engines and a classical spark ignition (PAMAR-3 is a prototype aeronautical engine built and designed by Paweł Mazuro)

Combustion of OP engines has been developed by Achates Power. This unique combustion system was composed of two identical pistons coming together to form an elongated ellipsoidal combustion volume where the injectors are located at the end of the long axis. This combustion system allows high turbulence, mixing and air utilization with both swirl and tumble charge motion. The ellipsoidal combustion chamber results in air entrainment into the spray stream from two sides with mid-cylinder penetration of fuel stream enabling larger $\lambda = 1$ iso-surfaces, excellent control at lower fuel flow rates because of two small injectors instead of one large one. Multiple injection events and optimization flexibility with strategies such as multiphase injection and rate-shaping [14]. All these factors result in minimal flame- wall interaction and no direct fuel spray impingement during the combustion. This improves performance and emissions [3] with fewer hot spots on the piston surfaces, enhancing piston thermal management and increasing engine durability [4]. As a result, Achates Power Technology has superior thermal efficiency and more fuel economy advantages.

4. Opposed piston challenges

OP engines are also facing some challenges such as high thermal load, changing linear to rotary motion, oil losses, side injection and numerical modelling are the worst issues [2, 5–7, 14] while some established solutions do exist [1]:

High thermal load; as the contiguous combustion takes place at the middle of the cylinder at the circumference, the maximum heat load is around there and also due to a longer stroke and also absence of long cooling induction stroke results in higher thermal loading of the piston crown and liner. Either air gap between the crown and piston skirt or side injection are used to isolate the piston crown, resulting in reducing the major negative feature of OP engines [1].

Oil consumption; higher oil consumption is a historical issue with two-stroke engines, while providing adequate lubrication to the piston pin and manage piston temperature. High oil consumption of the engines rises the running cost and additionally particulate emissions will increase. Some solutions have been established, one is design such interfaces (piston-liner and ring-liner) that can work with little oil by using special cylinder finishing, piston rings or cylinder materials. Another solution is effective oil impingement systems (an area, where marine engines are unsurpassed). The third direction of development is new synthetic oils [1].

Side injection; OP engine architecture does not allow to enjoy central fuel injection providing more homogeneous air-fuel mixing, and also due to lack of space the injector nozzles are preferred to be placed at the end of the cylinder. Therefore, the combustion system allows high turbulence, mixing and air utilization with both swirl and tumble charge motion, furthermore, the ellipsoidal combustion chamber developed by [15] Achates Power results in air entrainment into the spray plumes from two sides. Moreover, using multiple injection events alleviate the control of fuel flow at low ranges and optimize flexibility with strategies such as injector strategies and rate-shaping [14]. As a result, fuel spray does no longer impinge on the piston walls and also interaction between flame and wall would be getting minimal during the combustion. This technology would improve the performance and emissions [7, 14] with fewer hot spots on the piston surfaces, appending piston thermal management and enhancing engine durability [14, 16].

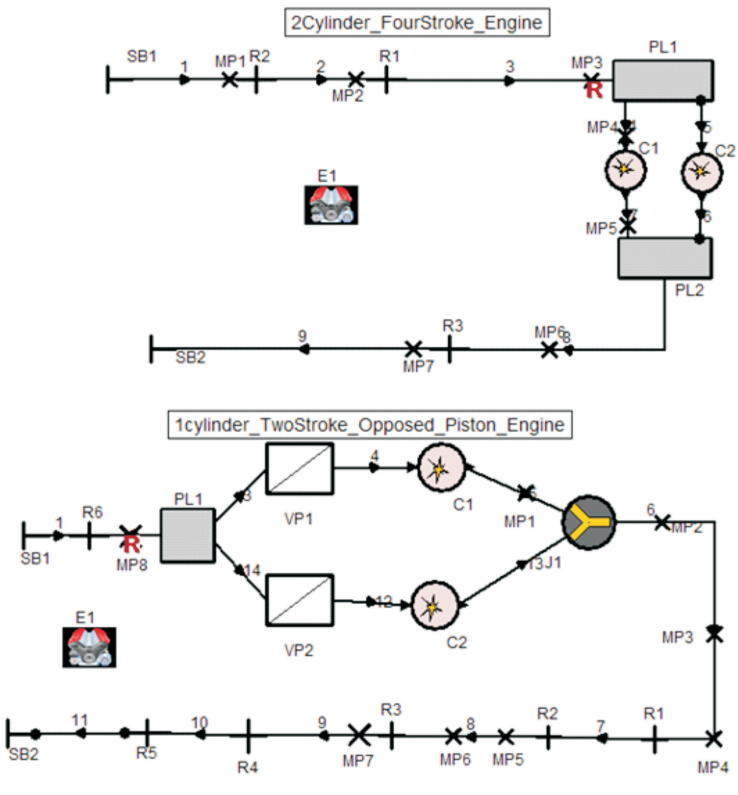

Fig. 3. Simulation model of 4-stroke and opposed piston 2-stroke engine in AVL Boost Platform

Linear motion transmission to rotational motion; two crankshafts are used to transfer the reciprocating motion into rotary motion, while one crankshaft was used in classic engines. Opposed piston engines are classified into different categories based on the crankshaft mechanism. An excellent summary of the propulsion transmission has been summarized in Pirault and Flint book [1]. According to the Mazuro's paper published in 2007, different crankshaft mechanism of barrel engines were compared to the conventional crankshaft engines, wobble-plate blocked by bevel gear mechanism conducted as the most promising mechanism of motion transmission due to higher mechanical efficiency than that of the crankshaft mechanism, favourable distribution of piston side thrust, resulting in smaller friction work [17].

Numerical modelling; several major 1D engine software platforms (GT Power, AVL Boost and Ricardo WAVE) have the capability to build up standard two-stroke and four-stroke engines characteristic. Unfortunately, none of them are able to simulate a true opposed piston engine. Only AVL Boost can build-up an OP engine by defining the relative piston motion profile. Meanwhile, Diesel RK known as 0D simulation software can model only an OP with uni-flow scavenging module, but it is less flexible and less useful in design process.

On the other hand, two 3D CFD software (Ansys Fluent and AVL Fire) have simulation OP module; however, for a simple OP simulation may take long time. Therefore, these software are useless in terms of time limitation [2].

5. Engine configurations

Two different engine configurations were taken into consideration in this paper: a two-cylinder four-stroke conventional crankshaft (4S) engine with standard architecture and fixed cylinder head and a hypothetical single cylinder opposed piston two-stroke (OP2S) engine (Fig. 3). The cylinder bore diameter and stroke per piston were held constant for each engine configuration to keep the friction work associated with each engine as similar as possible. First, the engines were compared at 4 different speeds to specify the importance of OP technology as an alternative for ICEs.

Second, the power output and engine speed were held constant for all thermodynamic comparisons at engine operation of range speed of 1500 rpm; however, the scavenging period of OP2S engine was varied by changing the engine architecture and valve/porting timings.

As an opposed piston engine is paired of two pistons in a cylinder, two classical four-stroke engines are specified to have the same stroke per piston as mentioned before.

For 4S engine, the total volume of the 4S engine is assumed 1.4 litre (0.65 l per cylinder). The engine power was specified to be 9.7 bar BMEP at a range of 1500 rpm. Additionally, the piston crowns and cylinder heads were flat and parallel, the intake valve closed 100° bTDC, the exhaust valve opened at 82° aTDC, and the data were taken from an Industrial six-cylinder 4-stroke engine released by AVL software company [18].

On the other hand, there are many different methods to simulate an OP engine; here a two-crankshaft mechanism has been picked up [12]. The simplicity and same individual piston motion for each engine configuration were the reason to choose this method.

To be more precise, by combining the two 2S engines from top and eliminating the cylinder head surfaces, an OP arrangement will appear.

The phase offset between two crankshafts was set to 13.5 degrees, so that intake port events are lagging with respect to exhaust events. As a result, not only there is more available time for burning gas, but also it avoids contamination of the fresh air caused by blowback.

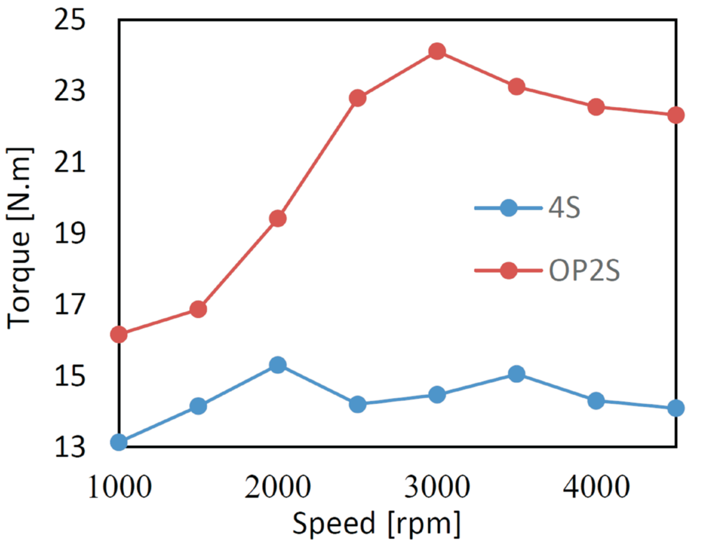

Fig. 4. Torque vs engine speed for 4S and OP2S simulated engines

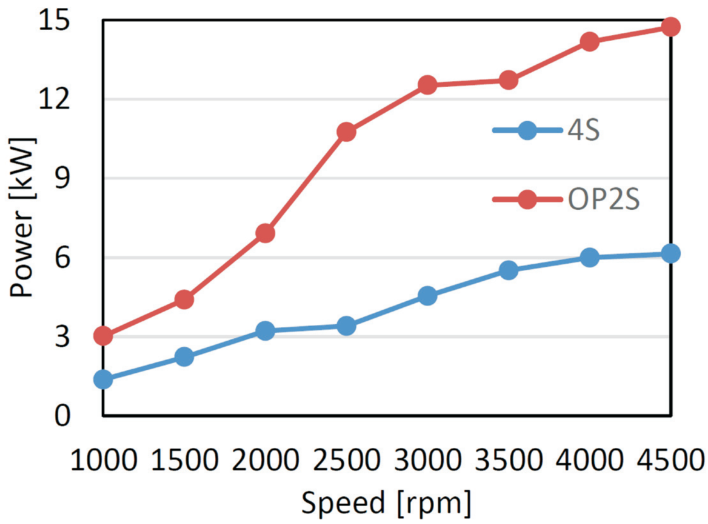

Fig. 5. Power vs engine speed for 4S and OP2S simulated engines

Table 1. Geometric characteristics of simulated engines

Engine	4S	OP2S
Cylinder number	2	1
Speed [rpm]	1500	1500
Bore [mm]	55	55
Stroke per piston [mm]	75	75×2
Connecting rod length [mm]	110	110
Trapped compression ratio	16:1	16:1
Crankshaft phase offset [deg]	---	13.5
Intake closing [deg. aTDC]	–100	–112
Exhaust opening [deg. aTDC]	82	81
Trapped volume [dm³/cyl.]	0.178	0.356

The intake ports were delayed 112° bTDC to be covered by the piston including the scavenging process needed for 2S engine operation. Moreover, the exhaust ports were advanced 81° aTDC to be opened. A summary of the

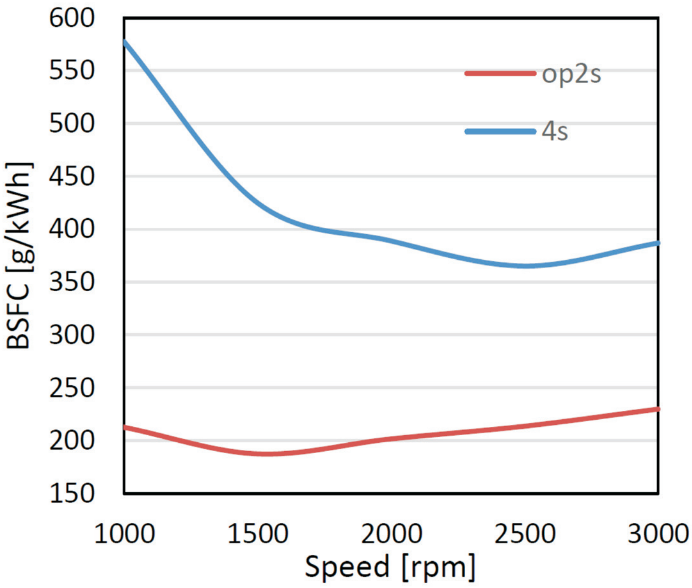

Fig. 6. BSFC vs engine speed comparison of 4S and OP2S simulated engines

Brake fuel consumptions of two simulated engines are shown in Fig. 6. BSFC is inversely proportional to the engine size, because lower amount of heat will be lost by transferring to cylinder wall. In addition, OP2S engine has more favourable surface-to-volume ratio rather than 4S engine. The BSFC also increases at lower engine speeds due to heat losses during longer time. Besides, BSFC rises at higher speeds due to increasing friction. Therefore, brake fuel consumption of OP2S engine will decrease.

The simulated pressure versus cylinder volume on logarithmic coordinates has been presented in Fig. 7 for both four-stroke (4S) and opposed piston two-stroke (OP2S) engines. Figures 7 and 8 show that in-cylinder pressure rises as fast as fuel gets burned near the end of compression stroke (minimum volume) and does not decrease due to absence of cylinder head and consequently lower surface area-to-volume ratio known as OP advantages.

geometric characteristics for three engine configurations is provided in Table 1.

6. Results

The process of increasing engine performance is of high importance. Therefore, power and torque versus different engine speeds have been represented in Figs 4 and 5. Figure 4 shows the trend of torque versus speed in OP engine is more desirable than that of the 4S engine, as it has been tried to flatten the curve in most of the modern automobiles.

Although power follows the torque curve due to the fact that power is torque multiplied by speed, as shown in Fig. 5, power will not increase linearly as friction increases at higher speeds. Engine power for OP2S continues increasing and resisting the slowing.

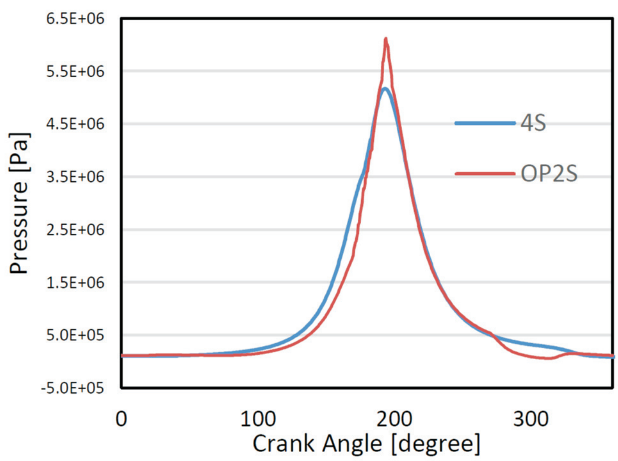

Fig. 8. Pressure rise profile of 4S and OP2S simulateed engines

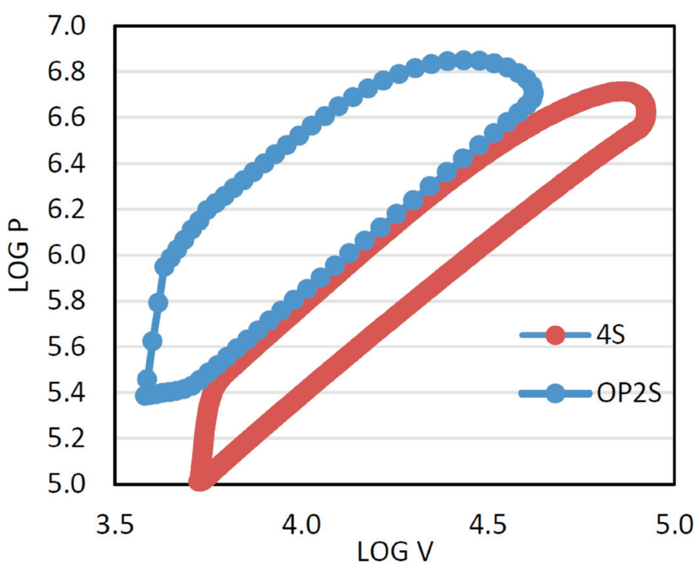

Fig. 7. Log P vs log V comparison of 4S and OP2S simulated engines

Additionally, the in-cylinder peak pressure is higher than conventional 4S engines. Figure 8 also compares the peak pressure of the simulation at the given operating conditions. OP engine has higher peak pressure value in comparison with 4S engine.

The combustion chamber geometry, piston motion and scavenging process for OP engine, valve/port timing, heat transfer analysis method and surface area and finally temperature taken by experimental measurements were inserted to interface model to simulate the combustion process (MFB, heat release,…) of the models. Inherently, the OP engines have lower heat losses; it obviously appears in heat release. Figure 9 shows the rate of heat release during combustion for both engines. OP2S engine has higher heat releases than its competitor.

The heat release rate as well as mass burn fraction is used in thermodynamic analysis. Heat release is

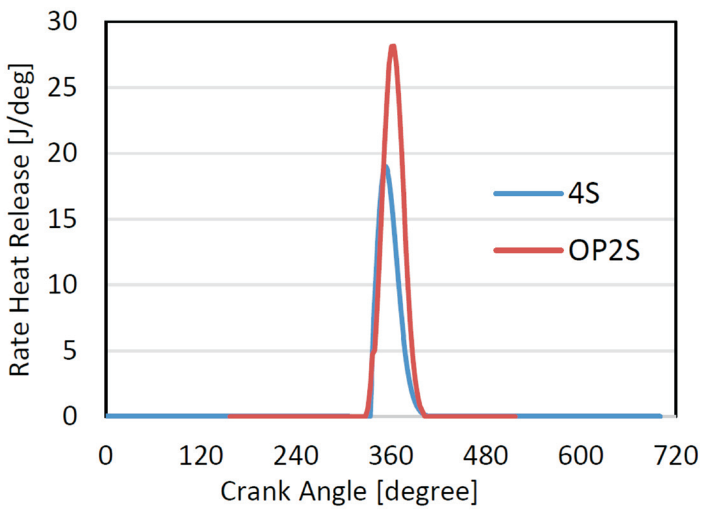

Fig. 9. Heat release rate of 4S and OP2S simulated engines

the result of the combustion of a fuel with oxygen in air; however, prediction of HRR is vital for hazardous fire.

Figure 9 shows the comparison of HRR traces versus crank angle for both OP and 4s engines. Higher HRR allows the higher energy to be transferred into the pistons, resulting in higher thermal efficiency. Additionally, due to the lower area-to-volume ratio of OP engine and removing the cylinder head by combining two two-stroke engines, heat transfer losses have been significantly decreased. As a result, lower fuel consumption is required to reach power target, resulting in less efficiency deduction.

The mass burn fractions are shown in Fig. 10. Amount of fuel injected into the cylinder is the same, but OP model has greater cylinder volume, thereby specific heat ratio increases during combustion and the work per unite of volume rises (eq. 1) – ideal engine efficiency:

$$\eta_{\text{ideal}} = 1 - \frac{1}{r_c^{\gamma-1}} \tag{1}$$

where: g – ratio of specific heats, r_c – compression ratio

Furthermore, that amount of fuel injected in-cylinder is allowing for shorter and also faster combustion duration as shown in Table 2. Therefore, combustion occurs at close condition to constant volume combustion, resulting in thermal efficiency improvement.

Table 2. Comparison of mass fraction burn of the fuel in 4S and OP2S simulated engine

Mass fraction burn	4S	OP2S
Mass fraction @ 5% [deg.]	6.8	1.84
Mass fraction @ 10% [deg.]	9.87	3.35
Mass fraction @ 50% [deg.]	22.3	9.5
Mass fraction @ 90% [deg.]	34.8	28.72
Combustion duration [deg.]	58.3	44.10

7. Conclusion

A brief history of advent of opposed piston engines has been described. The advantages and also challenges of OP engines have been outlined. Opposed piston engines have been considered as an alternative for conventional crankshaft engines where high power-to-weight ratio, high durability, easy manufacturing and compact arrangement are required. Opposed piston engines provide lower heat losses due to absence of cylinder head which can decreases to around 10–15% in comparison with conventional crankshaft engines. Further, high stroke-to-bore ratio decrease SA/V, resulting in improving thermal efficiency of OP engines. Despite OP engines face some challenges affecting the engines performance. High thermal load in the centre of cylinder, higher oil consumption, injection and air- fuel mixing can be considered as OP challenges.

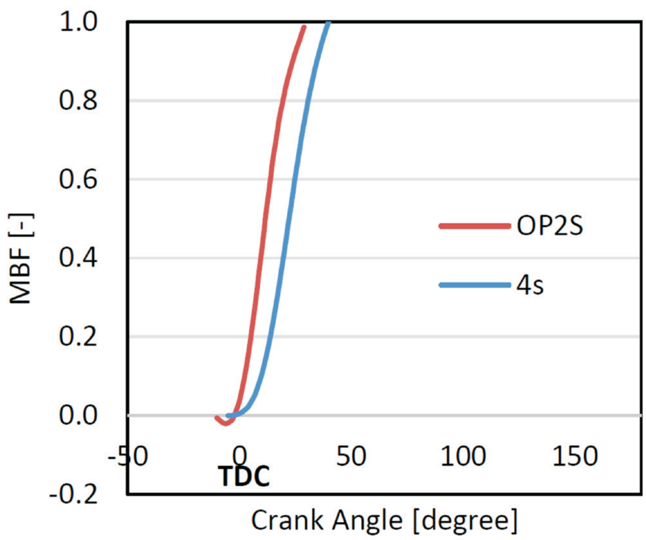

Fig. 10. Mass burn fraction of OP2S and 4S simulated engines

The thermodynamic analysis was performed to demonstrate superior advantages of an opposed piston two-stroke engine over a four-stroke conventional crankshaft engine. AVL Boost™, one-dimensional (1D) thermodynamic platform was used to simulate a 4S and a hypothetical OP2S engine. First, torque, power and BSFC of the engines were compared at four different engine speed rates to demonstrate preference of OP2S engines by considering that higher power and torque rates. In addition, fuel consumption of OP2S engines have been reduced compared to 4S engines.

On the other hand, both engines operated at the same engine speed rate of 1500 rpm to demonstrate thermodynamic advantages of OP2S engines rather than 4S engines. Opposed piston engines have larger combustion chamber volume than 4S engines. Hence, the combustion process of OP2S occurs in leaner condition against 4S engine, resulting in faster combustion and higher heat releases due to absence of cylinder head and also valve train.

Nomenclature

OP	opposed piston
OP2S	opposed piston two-stroke
4S	four-stroke
OPOC	opposed piston opposed cylinder
0D	zero-dimensional
SA/V	surface area-to-volume ratio
S/B	stroke-to-bore ratio
HRR	heat release rate
SE	scavenge ratio
VCR	variable compression ratio
BSFC	brake specific fuel consumption

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