OPPOSED-PISTON ENGINES: THE FUTURE OF INTERNAL COMBUSTION ENGINES?*

Jakub KALKE, Marcin OPALIŃSKI, Mateusz SZCZECIŃSKI†

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Abstract: This paper presents the advantages of opposed-piston engines, paying particular attention to the thermodynamic benefits, multifuel potential (petroleum, gasoline, methane, biogas in one engine), lower maintenance and production cost. We indicate current challenges connected with such machines like: high thermal load, piston ring wearing and effective ways of changing pistons linear to shaft’s rotary motion. We also include a short historical review together with a presentation of the current situation. The proposed future application utilizing the full potential of power-to-bulk ratio, efficiency and simplicity (like distributed power generation, range-extenders, military applications) are likely to lead to the renaissance of the opposed-piston, which probably has already began.

1. Introduction – what is an opposed-piston engine

In opposed-piston engines (OP) pistons are arranged in such a way that two pistons are reciprocating opposite to each other, both working in one cylinder. Most often such machines work as 2-stroke engines. A combustion chamber is formed between pistons near the top dead centre. There are no classical poppet valves, scavenging (the process of pushing fumes out of the cylinder and taking in a fresh charge) is usually controlled by piston-ported valves.

2. Why opposed piston

The classical 4-stroke engine with a crankshaft has been used and developed for more than 130 years—which proves its universality and timelessness. Why would one change such a well-tested design? In this section we would like to point out the most significant advantages of the classical engines.

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†Warsaw University of Technology
2.1. No cylinder head

Cylinder head heat losses are significant due to the necessity of cooling the mechanical parts such as poppet valves and camshafts. Eliminating head simply eliminates these loses, which improves thermodynamic efficiency. Moreover, it means reducing the emission of unburned hydrocarbons and carbon monoxide, mainly formed at the cold walls of the head, where the flame is quenched.

Fig. 1. 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).

2.2. Combustion chamber

Heat is generated proportionally to the volume (V) of the combustion chamber, while heat loses are proportional to the surface area (SA). The SA/V factor is nearly twice lower in OP engines than in conventional ones, leading to higher thermal efficiency. Moreover, simpler shape (cylindrical, no valves, only an injector and a spark plug inside) means higher pressure and thermal loads.

2.3. Uniflow scavenging

Most OP engines work as 2-stroke, which eliminates the 2 strokes used only for scavenging the cylinder. Induction and exhaust strokes are overlapped, which makes minimizing fresh air loses crucial. The main scavenging methods according to Niewiarowski (1983) are:

- cross flow scavenging with a vertical flow pattern. Currently not used due to a complicated piston, which gives poor SA/V ratio to the combustion chamber;
- loop (backflow) scavenging, with a horizontal loop pattern, used in smaller engines;
- uniflow scavenging, where fresh gases enter from one side of the cylinder and push out fumes through the exhaust on the other side. Widely used in large two-stroke diesels.
Uniflow scavenging gives the best trapping efficiency and scavenging efficiency indicators, maximizing the use of the engine displacement filled with a fresh charge. If there is no opposed piston valves in the cylinder head need to be used, for an opposed-piston engine uniflow scavenging is a natural decision.

Fig. 2. Scavenging methods from the left: cross flow, loop, uniflow with poppet valves, uniflow in opposed piston.

2.4. No poppet valves
Eliminating poppet valves reduces the cost of engine (fewer parts), improves the serviceability (fewer moving parts) and improves mechanical efficiency (no need to propel the camshafts). Moreover, the volumetric efficiency is improved, because pressure losses in the inlet and outlet are reduced by larger cross-sections.

Fig. 3. A schematic view of the opposed-piston engine during scavenging. Blue is inlet-side piston, red is exhaust-side piston. 1 – air chamber, 2 – inlet canals, 3 – exhaust canals, 4 – exhaust manifold.

2.5. Possible high stroke/bore ratio
High stroke to bore ratio is an indicator of efficiency. Engines with higher S/B have smaller surface area exposed to combustion gases, which, as mentioned before, improves thermal efficiency. Mechanical efficiency is also affected: when decreasing S/B
factor bearing friction increases proportionally to larger forces (larger piston area, same pressure). In OP engines the stroke is split between two pistons, which gives high S/B without increasing mean piston speed (the lower the speed, the better the efficiency).

2.6. Multifuel technology
Multifuel engines are particularly interesting for the military in case of main fuel shortage, but there is also a wide potential in non-military usage like distributed generation or emergency power generators. To be able to run on multiple fuels the engine must meet two basic conditions:

- Variable Compression Ratio (VCR), permits firing fuel with the highest octane rating;
- it must be strengthened to withstand widely changing working conditions (the temperature from burning biogas is different from one from aviation fuel).

Both of these 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. Also, fewer moving parts, simple combustion chamber shape and a more compact design make them more robust and durable.

2.7. High power-to-bulk ratio, high reliability and low maintenance
Fewer moving parts mean fewer potential failures, and that means lower maintenance cost. System weight and cost comparison between standard constructions and an opposed-piston engine in various configurations according to Pirault and Flint (2010):

| Tab. 1. 2-Stroke Boxer vs. 2-Stroke OP (8 kW one cylinder). |
|-----------------|-----------------|-----------------|
| **Aerial Vehicle Engine 8kW** | **2-Stroke Boxer** | **2-Stroke OP** |
| Weight [kg] | 7.17 | 6.84 |
| Cost [$USD @ 500 unit per year] | 1086 | 1027 |
| kW/kg | 1.12 | 1.17 |
| $US/kW | 136 | 128 |

| Tab. 2. 4-Stroke vs. 2-Stroke OP (32 kW). |
|-----------------|-----------------|-----------------|
| **Utility engine 32 kW** | **4-Stroke** | **2-Stroke OP** |
| Weight [kg] | 174 | 113 |
| Cost [$USD @ 500 unit per year] | 2306 | 1853 |
| kW/kg | 0.18 | 0.28 |
| $US/kW | 72 | 58 |
### Tab. 3. 4-Stroke vs. 2-Stroke OP (400 kW).

<table>
<thead>
<tr>
<th></th>
<th>Heavy-Duty Truck 400 kW</th>
<th>4-Stroke</th>
<th>2-Stroke OP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight [kg]</td>
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<td>945</td>
<td></td>
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<tr>
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<td>kW/kg</td>
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<tr>
<td>$US/kW</td>
<td>29.28</td>
<td>25.79</td>
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#### 2.8. Possibility of full engine symmetry

With an opposed-piston barrel type engine there is a possibility to achieve a full engine symmetry which leads to:

- cheaper parts – turning is faster and cheaper than milling;
- simple, axi-symmetric pistons (no need for a piston pin), which can rotate during work – wear occurs evenly over the entire circumference of the piston;
- spherical bearings with high capacity (proven by Sulzer’s practice);
- every cylinder has the same working conditions (crucial for Controlled Auto Ignition – burning with reduced fuel consumption and emissions);
- perfect engine balancing;
- lower vibration level.

![Fig. 4. 5-cylinder opposed-piston barrel engine (wobble plate blocked by bevel gear).](image)

#### 2.9. Possibility of lowering friction losses

Losses due to piston side force are responsible for even up to 40% of mechanical losses. Changing a classical crank system into a wobble plate mechanisms (in barrel engines),
when properly designed, can greatly increase mechanical efficiency by reducing piston-cylinder side force by 50 – 80%.

3. Challenges connected with opposed piston

As opposed-piston engines are a relatively fresh idea and still not fully explored, there are still non-trivial problems to be solved.

3.1. High thermal load

2-stroke engines have no additional 2 strokes to exchange the charge (during which the engine is 'cooled'). Also, high power concentration leads to problems with exhaust ports durability (they have to be water cooled) and piston head wear.

3.2. Changing linear to rotary motion

Classic engines inherently have one shaft. The problem with OP is to take the power from 2 pistons and put it on one shaft. Below the most popular ways of changing the reciprocating motion of the pistons into the rotation of the output shaft presented together with existing examples (Pirault and Flint, 2010):

- crankless free piston (GM Hyprex),
- single crankshaft (Atkinson, Doxford, Zoller, Trojan, Puch, M.A.P, Boxer OPOC),
- double crankshaft (Jumo 204, 205,207, Witzky),
- multi crankshafts (Napier Deltic, Tekon Stellar, Juno 223, GE Orion),
- rotary (Mukherjee, Tschudi),
- barrel engines (after (Mazuro et al., 2007)):
  - crank mechanisms coupled with bevel gear (Wherry, Cleveland),
  - swash plate (mostly Stirling engines, but also torpedoes),
  - cam driven (Alfaro 167),
  - wobble plate:
    - blocked by piston (Aero 35),
    - blocked by crosshead (Trebert, Statax),
    - blocked by bevel gear (Brzeski engine).

There is a variety of choices. According to P. Mazuro’s doctoral dissertation the wobble plate mechanism blocked by bevel gear has the highest possible mechanical efficiency and a great potential for further research, but its advantages can be fully utilized only in multi-cylinder barrel engines.

3.3. Need for better materials

Modern engines are supposed to have high efficiency which is inextricably linked to the temperature of the upper heat source. Cylinders have to be made from high-quality steel or cast iron to withstand demanding work conditions. Unfortunately, heat resistance and creep resistance do not go hand in hand with good tribological parameters like oil wettability or low piston-cylinder friction. There is a great potential in the development of various surface coating to improve piston work quality.
3.4. Possibility of increased piston ring wearing

Operational practice shows that piston porting leads to faster piston ring wear due to local bending and distortion. Piston rings must be specially treated; moreover, ports cannot be too big. Some examples can be found in Pirault and Flint (2010). Moreover, rings are heavily loaded as there is no ‘cooling’ stroke and no load reversal.

3.5. Oil losses

2-strokes are traditionally identified with high oil consumption which leads to two main problems. The first problem is of course the cost of oil. The second problem, even more costly nowadays, is increased particulate emissions. One solution is to 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.

3.6. Side injection

In OP engines injection is made perpendicularly to the piston motion in comparison to standard symmetrical central injection 4-stroke. Such injectors have problems with even fuel distribution in the combustion chamber and can lead to inefficient combustion. Moreover, there is a risk of cylinder liner/piston rings fuel impingement, which results in non-uniform charges and generates local high thermal loads. What is even worse, such fuel impingement can destroy the lubricant film, leading to increased emission, oil consumption, and faster piston-cylinder wear.

![Fig. 5. Examples of barrel engines.](image-url)
3.7. Numerical modeling

To the best of our knowledge there are three major 1D engine simulation computer programs (GT Power, AVL Boost and Ricardo WAVE), which have build-in standard 4-stroke and 2-stroke engines. Unfortunately, none of them has a module capable of simulating a true opposed-piston engine. Only Diesel RK has an opposed-piston uniflow scavenging system module, but being more a 0D and much less flexible software (concerning geometry and adding additional parts) it is not very useful in the design process.

General purpose 3D CFD software like Ansys Fluent or AVL Fire is of course capable of modeling opposed-piston engines, but calculation time is the factor limiting the usefulness of such tools. Giving rough numbers: one cycle (2 strokes) calculation time is about one day on a high-end PC with 0D combustion and no heat-transfer (such simulation can give some insight into scavenging parameters); we need to calculate about 4-5 cycles to get reproducible results from cycle to cycle (according to AVL). After 5 days we have results from a single configuration, while in 1D software it is possible to test one conception (this or that compressor, another turbine, another boost pressure etc.) every 5 min. Adding 3D combustion and heat transfer increases the CFD computation time by orders of magnitude.

There are some analytical models of scavenging in OP engines which give some general knowledge of the phenomenon, but also indicate a number of differences and disparities both from 3D CFD and engine dyno; a good overview is presented by Merker and Gerstle (1997); Sher (1989). More sophisticated models give better results, but they need from one even up to five empirical parameters, which are very hard to get even from an existing engine. After significant modification it is necessary to measure them once again, so such models are not universal. As Merker and Gerstle (1997) say, „here is an enormous potential for further research work and improvement”.

4. The Past: A short history of OP

The great history review can be found in Pirault and Flint (2010), here there are only the most important milestones:

-Probably the very first OP engine was made by Wittig in 1878, Germany.
-1900 – 1915 – land and marine diesel opposed-piston engines are introduced.
-1910 Vieckers of Newcastle – common rail injection system.
-WW1 – Doxford engine tested as a submarine drive unit.
-1920 Doxford Oil reaches brake thermal efficiency 32 %.
-1929 exhaust waste heat recovery begins.
-First highly boosted (6 bar) and turbocompound engines were seen in 1941.
-WW2 Junkers Juno Aeronautical Engines.
-1946 Sulzer 8G18 Series achieves 39.5 % BTE.

5. The Present: What is currently developed

Currently, there are several companies which develop an opposed-piston engine:
5.1. FairDiesel

A UK company established in 2000 is developing an opposed-piston, barrel engine. The linear-to-rotary motion is possible by using a non-sinusoidal cam mechanism. Their main aim is to produce engines for industrial and aviation use. According to Diesel (2010) they are designing from a 2-cylinder up to a 32-cylinder version (120 kW – 24 MW).

5.2. OPOCTM EcoMotorsTM

EcoMotors, a company founded in 2008, is (currently) commercializing an opposed-piston, opposed cylinder (OPOC) engine for cars and light trucks. What is worth mentioning: the main investors are Khosla Ventures (venture capital focused i.a. on clean technology) and Bill Gates. EcoMotors Inc., who is the developer of “efficient, clean, lightweight and powerful opposed-piston opposed-cylinder (opoc§) engine” informed on 13 March 2014 that they established a joint research and development center with Huhan University (HNU) in Changsha EcoMotors (2014). The main market for EcoMotor is supposed to be China, so the reason for creating an R&D unit there is to adapt the technology and the engine to the local reality. Moreover, in April 2013 they have announced that they will be cooperating with Chinese auto parts giant Zhongding Power, who will build a $200 million factory in China. Planned production volume is 150 000/year, production launch is expected in 2014 (Fehrenbacher, 2013).

5.3. Pinnacle Engines

A start-up with an idea of commercializing a 4-stroke, SI, opposed-engine. Using sleeve valves can enable a 4-stroke work – a possible way to reduce emission in OP engines. Their industrial partner is FEV (design and development company). Pinnacle engines are mainly sold to the developing countries, with natural aspiration, fixed-compression-ratio, fixed-valve-timing – reducing fuel consumption and emission without increasing vehicle cost. According to Engines (2014) it uses ‘Cleeves’ cycle, changing constant volume combustion to constant pressure combustion depending on the operating conditions. Production of 110cc scooter engines will be launched in Asia in 2014.

5.4. AchatesPower

A USA company founded in 2004, started engine testing in 2005, received a DARPA contract to design a light-weight, compact UAV engine in 2007, in 2014 reached 5000 hours of dynamometer testing. They are developing a 2-stroke, 3-cylinder, OP diesel engine (205 kW power). What is interesting, they have a single cylinder engine on dyno and using a GT-Power interface simulate a 3-cylinder engine response (Power, 2014).

6. The Future: Proposed application

We believe there are three main areas where opposed piston can win the competition.
6.1. Range Extenders

Growing popularity of hybrids has made a place for highly efficient small engines. Opposed-piston engines with a good power-to-weight (and power-to-bulk) ratio, together with simplicity and potentially higher fuel efficiency can be a good alternative to conventional engines. Probably the biggest problem of this implementation is related to (still) significant level of emission, and in small engines installation of additional filters is pointless.

6.2. Distributed power generation

Same as before, good power-to-weight ratio, simplicity, easier maintenance, and a more robust construction give broad perspectives. In comparison to small range extenders controlling emissions is easier. Additionally, thanks to a variable compression ratio, there is a possibility of introducing a controlled auto ignition on a variety of fuels.

6.3. Highly flexible piston power plant

Piston engines are much more flexible than turbines. Their start-up time (from 0 to 100 % load) is 5 min, while turbines need 25 min, and CHP systems 25 – 50 min. Moreover, piston engines have higher efficiency under partial loads. A power plant consisting of opposed-piston engines with variable compression ratio would be able to work efficient on one, main fuel, and, if needed, switch to another. For example, the main fuel could be biogas from local farms. In case of a need for additional power some engines could switch to natural gas or even petroleum.

References

Diesel, Fair (2010), ‘http://www.fairdiesel.co.uk/’.