

UMOTOR - PERFORMANCE EVALUATION OF A SMALL OVER-EXPANDED ENGINE USING 3D-CFD AND 1D ENGINE MODELS

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Resumo: *An innovative over-expansion small Internal Combustion Engine was developed in the pursuit of ultimate efficiency to power a super-mileage (Shell Eco-Marathon) car, the EconomicUM. The previous engine was based on a Honda 50cc fitted with an over-expanded cycle enabled by Early Intake Valve Closure (EIVC). A peak fuel economy of 1560 km/L was attained during a competition at the Rockingham race-track, in Britain. The new engine is a native over-expansion engine using an expansion ratio of 1.7:1 provided by a hypo-trochoid mechanism integrated within the crankshaft. With it, the expansion and exhaust strokes are 1.7 times longer than the intake and compression strokes. This enables a higher thermal efficiency, as the exhaust gases are further expanded into the cylinder before being expelled to the atmosphere. But the engine has further features that enable higher efficiencies to be achieved.*

As mechanical losses increase with the square of the engine speed, this engine was designed to run efficiently at low speeds, so it needs to attain fast burning rates at low rpm. Therefore, turbulence is enhanced in terms of added swirl and squish, and two spark-plugs are used to increase the initial burn rate. The intake duct was specifically developed to produce swirl and the combustion chamber, although with a hemispherical design, has a shape enabling squish to be created as the piston reaches TDC.

The present work shows the first theoretical performance analysis of the UMotor engine using two different, but complementary, engine modelling tools. The burning rate and in-cylinder heat transfer were evaluated using a 3D-CFD software. These results were then used as an input for a 1D engine model reproducing the full engine and valve flow paths. This software coupling strategy allowed for an initial performance evaluation and optimization prior to testing the engine. One of the major issues with native over-expansion engines is the higher mechanical losses resulting from the more complicated crankshaft. Although the indicated cycle results of the over-expanded engine are much better than those from a conventional Otto cycled engine, the higher mechanical power required to run the hypo-trochoid mechanism will limit the improvements gained with the thermodynamic cycle improvements. Nonetheless, it was possible to minimize the overall mechanical losses by the verticalization of the connecting rod during expansion enabled by the hypo-trochoidal mechanism.

Palavras-chave: *Engine Modeling, Over-Expansion, Fast Combustion, High Efficiency Engine*

1. INTRODUCTION

With the aim of participating in the Shell Eco-marathon contest, in which the objective is to achieve the lowest possible consumption per km, the Department of Mechanical engineering of the University of Minho, is developing a high efficiency small engine the UMotor (Figure 1). Previous numerical analyses of this concept have shown promising indicated efficiency figures (37%) for such a small engine, with a 23% improvement over an equivalent Otto cycle engine [1], working at wide open throttle (WOT) for the same amount of injected fuel.



Figure 1. EconomicUM prototype vehicle in representation of University of Minho and the full CAD assembly of the UMotor.

The present work shows the first full predictive theoretical performance analysis of the engine using two different, but complementary, engine models. The burning rate and in-cylinder heat transfer were evaluated using a 3D-CFD software. Details about the 3D-CFD model configuration can be found in other publications by the authors [2][3]. These results were used as input to the 1D engine model. This software coupling strategy allowed for a first full performance evaluation and optimization prior to the testing of the engine.

Firstly, details about the engine are presented which include piston motion and engine head characteristics developed to promote a faster combustion. In the results section, the improvements in combustion that can be attained using 2 spark plugs and a high swirl intake port developed previously are evaluated using the 3D-CFD model for a specific engine operation point. Secondly, the overall performance of the engine is compared with a conventional engine for the full range of engine speed operation using the 1D model.

2. UMOTOR ENGINE DETAILS

The crank mechanism implemented in the UMotor consists of an hypotrochoidal gear set, featuring two fixed annular gears and two corresponding interior spur gears (planetary gears) (Figure 2). This crank mechanism enables an expansion ratio (ratio between expansion and compression strokes) of 1.7:1. With this mechanism the 4-strokes of the engine have different lengths, the intake and compression strokes display almost half of the length of the expansion and exhaust strokes. The engine runs between a top dead centre (TDC) and two bottom dead centers (BDCs), as displayed in Figure 3.

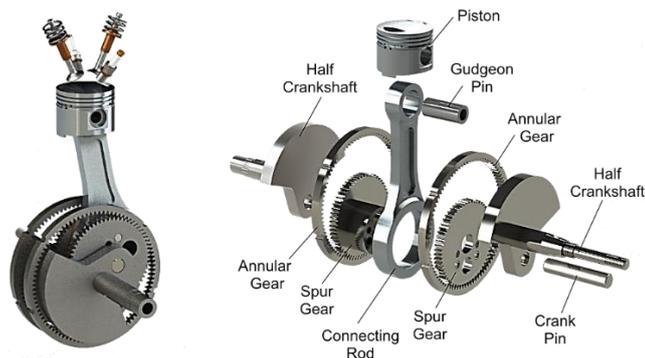


Figure 2. Internal components of the UMotor engine.

Figure 3 shows the piston position curve throughout the entire engine cycle, alongside with a representation of the crank system position along the different TDCs and BDCs with the aforementioned trajectories, as well as the different intake and expansion strokes. It is evident in Figure 3 that during the expansion stroke the connecting rod is almost vertical, consequently reducing the piston-liner forces and the overall engine friction.

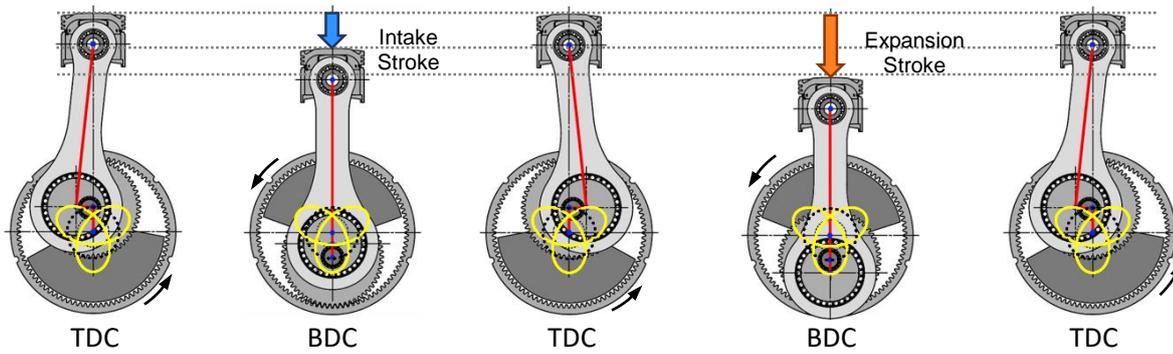


Figure 3. Hypotrochoidal mechanism and corresponding crank system position along one engine cycle. Dashed lines represent the location of the top and bottom dead centres.

3. UMotor COMBUSTION CHAMBER AND PORT DESIGN FOR FASTER COMBUSTION

Small engines suffer inherently from high combustion chamber area/volume ratios. Consequently, in order to minimize the heat transfer from hot burning gases to the combustion chamber walls, a hemispherical combustion chamber was chosen (Figure 4). With the limited space available and without the requirement for high power output, just one intake and one exhaust valves were used, disposed at 50 degrees between their sliding axes. Without the possibility of including one central spark plug in the combustion chamber, two small diameter spark plugs were used (Figure 4). This is also beneficial for burn rate and knock reduction since the travel of the flame front is shorter. Additionally, turbulence induction features, such as a squish area (Figure 4) and a high swirl rate helical intake port (Figure 4) were developed with detail. The positioning of the spark plugs was optimized for the swirl intake channel, with one of the spark plugs located near the exhaust valve and deflected from the central axis of the combustion chamber.

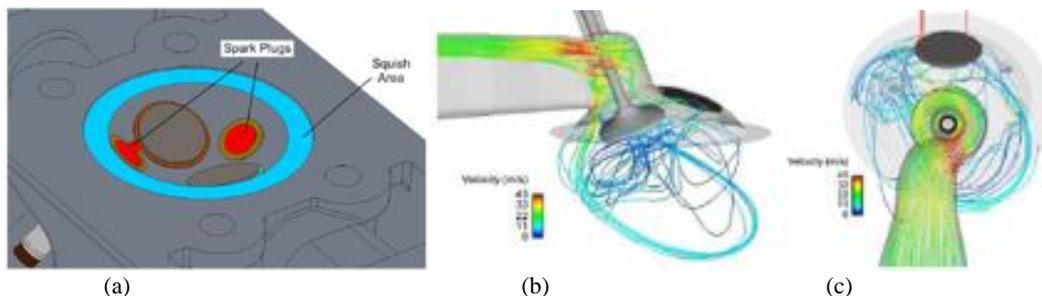


Figure 4. (a) representation of the UMotor combustion chamber with twin sprak plugs (in red) and a squish area (in blue); (b) Lateral an (c) top view of the path lines from the flow through the high swirl intake port.

4. ENGINE COMPARISON SPECIFICATIONS

Table 1 lists the main specifications of the UMotor engine and a conventional engine used as comparison, which uses a conventional crankshaft. The full displacement of the conventional engine was set so that the maximum output power would be roughly the same for both engines. The combustion chamber volume of each engine was adjusted to match the same compression ratio. The 6000 rpm limit was selected to reduce engine mechanical losses and the combustion chamber and intake track were optimized for this relatively low speed.

Table 1. List of the relevant engine specifications for both the UMotor and conventional engines.

		UMotor	Conventional
Engine type		4 stroke OHC single-cylinder spark-ignition	
Bore (mm)		39.0	39.0
Stroke (mm)	Intake and compression	21.5	24.0
	Expansion and exhaust	37.5	
Displacement (cm ³)	Intake and compression	25.7	28.7

	Expansion and exhaust	44.8	
Compression ratio		11.0	11.0
Expansion ratio		18.4	
Fuel	Gasoline		
Air-fuel ratio	Stoichiometric		

Figure 5 shows the piston position for both engines along a whole cycle. Unlike the conventional engine the valve overlap TDC of the UMotor occurs at 345 crank angle (CA) degrees while the both BDCs occur at 172.5 and 532.5 CA degrees. Therefore, the intake and compression strokes have a duration of 172.5 CA degrees while the expansion and exhaust stroke have 187.5 CA degrees.

The differences in stroke durations between the UMotor and the conventional engines were accounted for the valve timings, so both engines have equal intake and exhaust valves opening and closing durations, as can be seen in Figure 5. Piston position along one engine cycle for both the UMotor and the conventional engines.

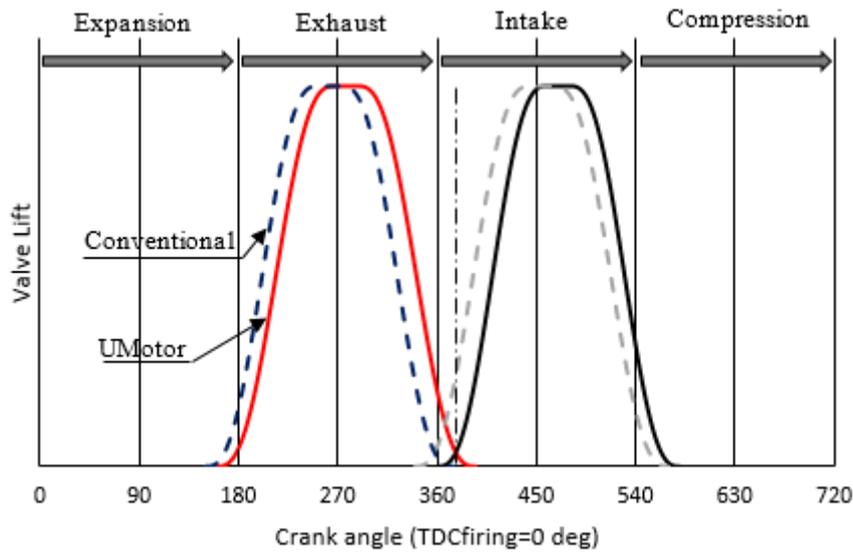


Figure 6.

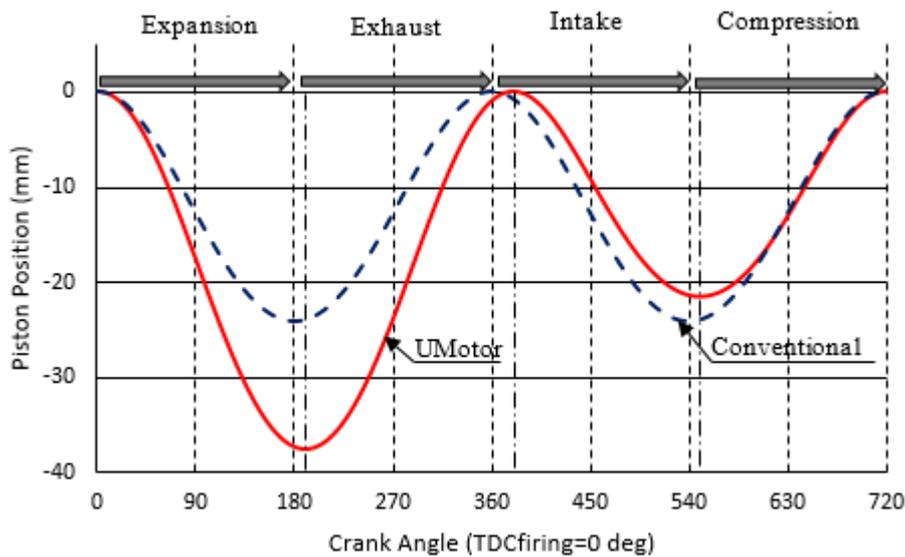


Figure 5. Piston position along one engine cycle for both the UMotor and the conventional engines.

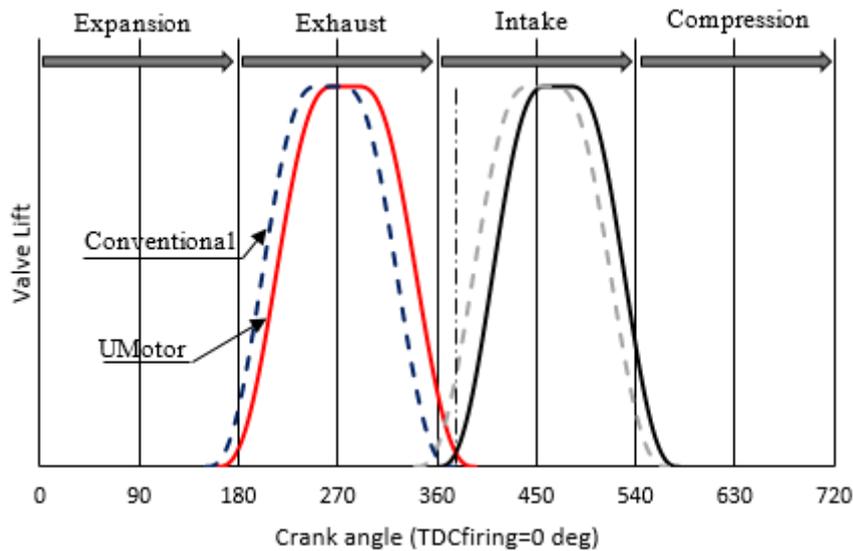


Figure 6. Comparison between valve lifts for both the UMotor and the conventional engine.

5. RESULTS

5.1. Combustion Improvement

The improvements in combustion that can be attained using 2 spark plugs and the high swirl intake port developed for the UMotor were evaluated using the 3D-CFD model for the peak indicated power engine operation point (6000 rpm), of the conventional 4-stroke engine. The mass fraction burned (MFB) is compared in Figure 7 to evaluate the differences between engine head configurations. These include: (1) normal intake port using 1 spark plug; (2) normal intake port using 2 spark plugs; (3) high swirl production intake port using 2 spark plugs. The same relative location for start of combustion was considered for all cases.

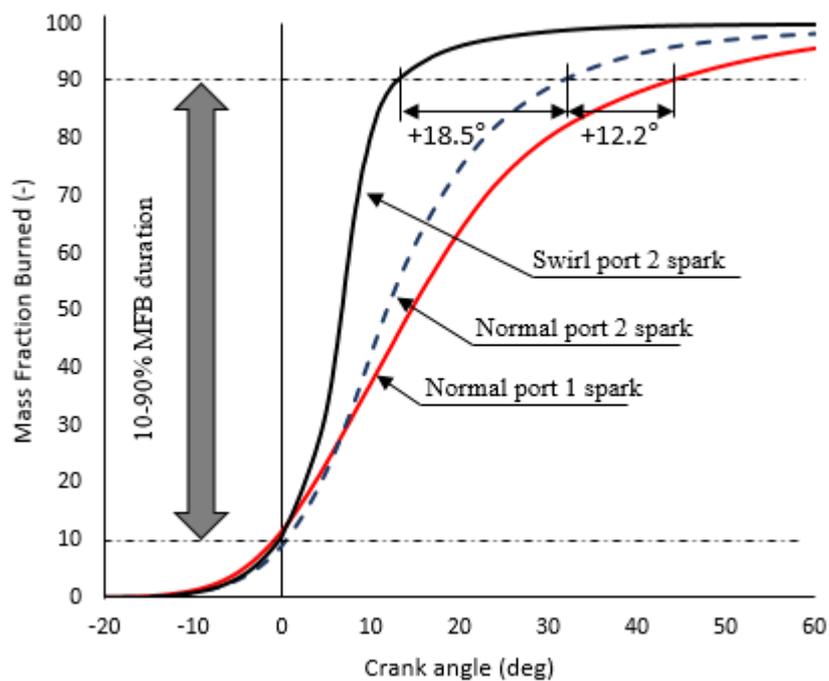


Figure 7. Mass fraction burned for 3 engine head configurations: (1) normal intake port using 1 spark plug; (2) normal intake port using 2 spark plugs; (3) high swirl production intake port using 2 spark plugs.

All configurations behave similarly at the initial stage of the combustion (MFB below 10%). By adding a second spark plug it may be seen that the combustion duration is reduced during the main combustion stage (10 to 90% MFB) by 12.2°. The use of the high swirl port is able to further reduce the combustion duration by 18.5°. In terms of performance, adding a second spark plug to the combustion chamber can increase engine indicated efficiency from 29.5% to 30.4%. By adding the high swirl intake port the conventional engine can attain a peak indicated efficiency of 31.2%. The combined effect of these two techniques enabled the enhancement of the efficiency in almost 6% (1.7 points).

Despite the significant improvements in combustion attained by the high swirl intake port, this feature will create a bigger flow restriction compared to a more common intake port with constant cross section as the one modelled here. Table 2 shows the work loss induced by the two intake port configurations along with the resulting change in volumetric efficiency. The work loss difference is relatively small, also expressed in the small difference in volumetric efficiency. This indicates that the intake port displays a good balance between combustion improvement and flow restriction losses for the selected engine speed.

Table 2. Indicated work loss and volumetric efficiency comparison between the normal and swirl intake ports

	Normal Port	Swirl Port
Work Loss during intake (J)	-1.4	-2.4
Volumetric efficiency Real BDC (%)	78.8	78.4

The configuration using the high swirl intake port and 2 spark plugs is the actual configuration implemented in the UMotor. The combustion and heat transfer 3D-CFD results obtained for this configuration were used in the overall engine performance comparison as a direct input in the 1D engine model for both engine configurations.

5.2. Overall Engine Performance Comparison

The overall trend in indicated efficiency can be seen in Figure 8 for the full RPM range of the engine operating at wide open throttle (WOT). Peak indicated efficiency occurs at 6000 rpm for both engines, with 31.2% for the conventional engine and 35.9% for the UMotor. This represents a 22% gain of the UMotor over the basic conventional engine (with 29.5% efficiency).

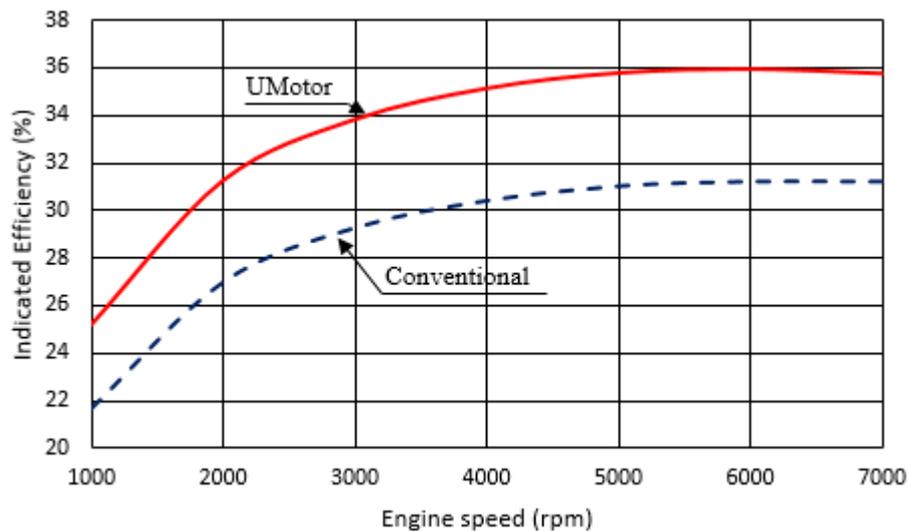


Figure 8. Indicated efficiency for the full RPM range at WOT for the UMotor and conventional engines.

The partial indicated work of each stroke during operation with WOT were compared for the UMotor and conventional engine to verify the effects of over-expansion in increasing the indicated thermal efficiency. Table 3 shows the results, at 6000 RPM where peak indicated efficiency occurs for both engines. The results include the amount of heat supplied per cycle and the respective indicated thermal efficiency achieved.

Table 3. Partial indicated work produced per stroke at 6000 rpm WOT.

		UMotor	Conventional
Indicated work	Intake	-2.4	-2.6

per stroke (J/stroke)	Compression	-10.8	-12.1
	Expansion	46.9	45.2
	Exhaust	-5.7	-4.0
Total work (J/cycle)		28.0	26.5
Supplied Energy (J/cycle)		78.0	84.9
Indicated Efficiency (net)		35.9 %	31.2 %

The total amount of work per cycle is approximately the same for both engines, but less heat is supplied to the UMotor. The indicated thermal efficiency of the UMotor is 35.9%, which is an increase of 4.7 points over the 31.2% for the conventional engine (improvement of 15% as a result to over-expansion alone). Focusing on the losses within the cycle, the exhaust stroke loss of the UMotor decreased by 1.7 J compared to that of the conventional engine. The same trend can be seen for the intake and compression strokes, due to their shorter durations compared to the conventional engine. On the other hand, during the exhaust stroke the UMotor loses more energy. This is caused by the lower pressure at exhaust valve opening for the UMotor, taking less advantaged of the blowdown compared to the conventional engine. Figure 9 shows the LogP-LogV diagrams for both engines at the same engine conditions.

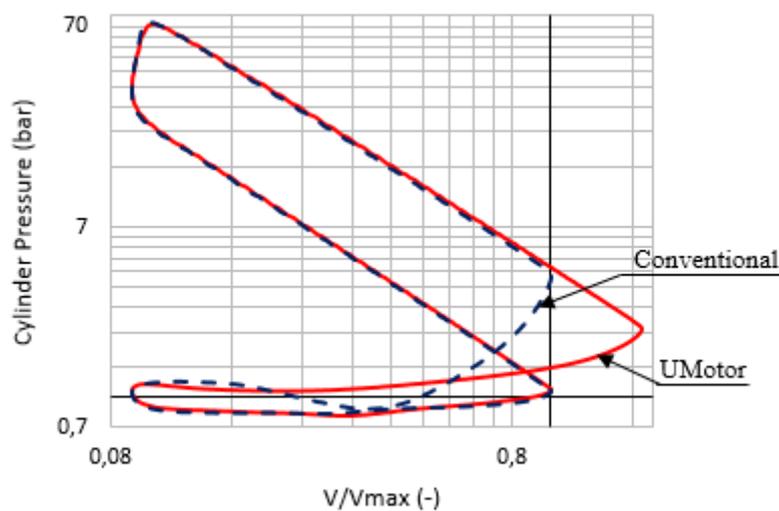


Figure 9. P-V and LogP-LogV diagrams for both engines at 6000 rpm WOT.

As can be seen in Figure 10, besides a reduction in exhaust energy accomplished using over-expansion, the UMotor also shows reduced heat losses compared to the conventional engine. This is due to the bigger intake displacement of the conventional engine, having larger surface area exposed to the exhaust gases near TDC where heat transfer is higher.

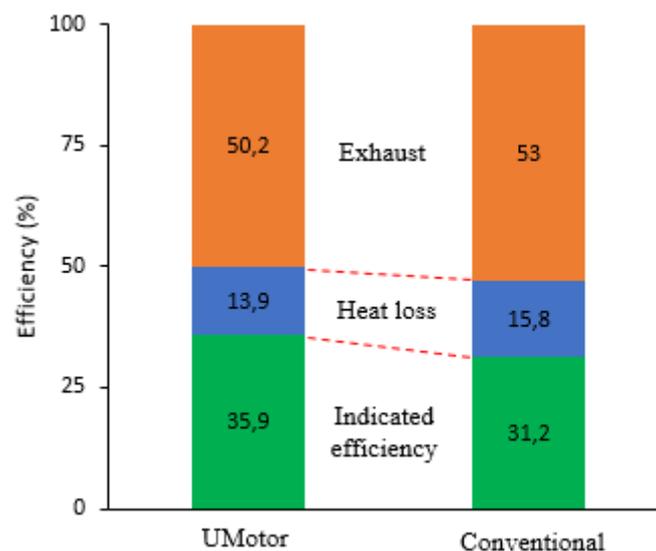


Figure 10. Comparison of the energy distribution for both engines at 6000 rpm WOT.

6. CONCLUSIONS

The present work performs the first theoretical performance analysis of the UMotor engine, a small efficiency-oriented engine incorporating native over-expansion through a custom crank mechanism. This mechanism allows to implement an expansion stroke which is longer than the intake stroke. Furthermore, the way that the mechanism is implemented causes the connecting rod to be nearly vertical during the whole power stroke. The reduction of the piston skirt friction resulting from this may compensate for the friction added by the crank mechanism.

The analysis was performed through two different, but complementary, engine models. Firstly, the burning rate and in-cylinder heat transfer were evaluated using a 3D-CFD software. Heat release rate results computed by the CFD software were then used as an input for a 1D engine model reproducing the full engine and valve flow paths. This model was used to predict and compare the overall performance of the UMotor with a conventional engine with similar indicated power. This software coupling strategy allowed for a first performance evaluation and optimization prior to the testing of the engine.

The use of a high swirl intake port and two spark plugs in the combustion chamber was proven to provide a faster combustion rate, a shorter combustion duration and an increase in indicated efficiency from 29.5% to 31.2% when implemented in the conventional engine.

Results show a peak indicated efficiency of 35.9% at 6000 RPM at WOT against 31.2% attained by the conventional engine. The difference in performance is related to the lower exhaust and cooling energy losses of the UMotor compared to the conventional engine. This efficiency improvement is a result of the use of an over expanded cycle in the UMotor, where the expansion and exhaust strokes are geometrically longer than the intake and compression strokes, providing a more effective conversion of the enthalpy of the gases into useful work by the engine.

Even though the UMotor displays a higher surface area at the end of the expansion stroke due to the bigger displacement, it showed lower overall heat transfer losses than the conventional engine. A reason for this might be that the surface area near the top dead centre (which is frequently called the combustion chamber region), where heat transfer losses are maximum, is higher for the conventional engine (the conventional engine has a slightly higher displacement).

The results obtained allow to conclude that the UMotor concept seems to have a good potential as a small efficiency-oriented engine. The absolute values for the efficiencies obtained are of course limited by the fact that these are very small engines, which are intrinsically lower in efficiency than bigger engines. However, the nearly 6% absolute increase in efficiency from the base engine to the over-expanded engine incorporating the twin spark plug and the swirl-inducing intake port actually represents a relative improvement in efficiency close to 20%.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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