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Definition of a CFD Methodology to Evaluate the Cylinder Temperature Distribution in Two-Stroke Air Cooled Engines

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Abstract

On the basis of the operating cooling fluid, internal combustion engine cooling systems can be classified in two macro areas: air-cooling system and liquid-cooling system.

In four-stroke engines, liquid-cooling system is generally preferred to the air-cooling system because of its efficiency in the engine heat dissipation. However, thanks to its simplicity, today the engine air-cooling system is still widely used in the engine market, especially on two-stroke engine applications like small motorbike, light aircraft, and handheld products.

To assure the necessary heat waste in air-cooled engines, the key point is the optimization of the air flow over the cylinder external surface. Air flow separation from cylinder external surface can result in high temperature gradients inside the cylinder volume causing destructive heat problem for the engine. It can be avoided only by a fine optimization of the cylinder fin design placed externally to the cylinder surface. To fulfil this need, the definition of specific methodology to evaluate the air-cooling effect on the engine is mandatory.

In the present paper, the authors present a 3D-CFD simulation methodology designed to perform a detailed evaluation of two-stroke air-cooled engines. The methodology was applied on two different engines equipping handheld brush-cutter machines. The optimization of the air-cooling system of such a machine is a very challenging task because the machine design must be very compact forcing all the engine parts to remain quite close each other. The simulation results are compared to experimental evidences in order to verify the validity of the proposed approach.

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1. Introduction

In internal combustion engines, the cylinder cooling plays a fundamental role on the engine overall efficiency and engine lifetime. To assure an adequate cooling effectiveness to an engine cylinder, its cooling system must be carefully tailored considering the comprehensive engine performance and the application for which the engine is designed. In general, from the internal combustion engine point of view, the cooling system can be subdivided into two main categories: liquid-cooling system and air-cooling system.

The liquid-cooling system is characterized by a high efficiency in heat transfer and its application is mainly oriented to high performance engines or to stationary engines adopted, for example, as power generator systems.

The air-cooling system is characterized by a simplified layout that allows containing the engine cost and the engine weight. In reason of its simplicity, in terms of heat transfer efficiency the air-cooling approach is poorer than the liquid-cooling system. However, still today the air-cooling system is considered the most effective way to assure the cooling in two-stroke engines applied on small motorbikes (from 50 to 150cc), small planes, and on almost all the handheld products like blowers, brush-cutters, and chainsaws.

Focusing the attention on the air-cooled engines, in those cases the heat produced by the combustion is wasted toward the ambient surrounding the engine by a series of fins distributed over the external cylinder surface and licked by the air stream flowing externally to the cylinder itself (Figure 1). Generally, the fins are not symmetrically distributed respecting to the cylinder. This design strategy is necessary to try to compensate the non-uniform distribution of the air flow around the cylinder surface [1,2].

Among all the possible applications of the air-cooling systems to two-stroke engines, surely the handheld products are representing one of the most challenging task because in those cases the engine layout must be necessary very compact. Therefore, the machine designers are forced to maintain the hottest components (muffler and cylinder) quite close each other. It can produce engine cooling problems resulting in unexpected cylinder deformation, increased blow-by gas, and high lubricant oil consumption [3-10].

In the present paper, the air-cooling system performance of two handheld machines designed by EMAK company were evaluated by adopting a 3D-CFD simulation methodology suitable to predict the most critical aspects limiting the engine cooling efficiency. First results obtained by the proposed simulation methodology were presented in [11]. The methodology was based on the Conjugated Heat Transfer (CHT) approach and was validated against experimental data available for both the considered machines.

All the presented simulations were run by using the 3D CFD StarCCM+ solver [12].

The paper is organized in three main sections. Firstly, the machine layouts are presented. Secondly, the defined simulation methodology is presented together with its validation on experimental data. Lastly, a complete thermo-flow analysis of the considered brush-cutter machine layout is presented over the operating engine speed range.



Fig. 1. Two-stroke air-cooling system: generic layout characterized by fins distributed over the cylinder surface.

2. Handheld machine layouts

In the present work, two handheld machines were considered: a brush-cutter machine and an edge-trimmer machine. Both these machines are equipped with a two-stroke air-cooled engine where the air flow was guaranteed by a fan directly connected to main crankshaft. The main engine characteristics are summarized in Table 1.

Despite the similarity shared by the two considered machines, the different relative positions among the fan, the cylinder, and the muffler resulted in a quite different temperature distribution over their external cylinder surfaces. For this reason, the application of the proposed simulation methodology to both these machine layouts was considered as a good test-bench for the methodology itself.

In the brush-cutter machine (Figure 2-a), the cylinder fins were placed orthogonally to the cylinder axis and characterized by a constant thickness/pitch equal to 1.5mm/5.3mm respectively. The external cylinder area available for the heat exchange with air was close to 0.095m². The air flow entering in the engine case was also devoted to cool the ignition coil but not the catalytic muffler separated from the cylinder by a L-shape metal sheet. Even if the cylinder air volume and the muffle air volume were physically separated, the huge temperature level (~500°C) reached by the catalytic muffler resulted in an extra heat load on the cylinder rear side.

In the edge-trimmer machine (Figure 2-b), the fins were sloped of about 15° respecting to the cylinder axis. The fin thickness was variable between 1.3mm and 2.4mm while the fin pitch was set to 5mm. The edge-trimmer fin layout resulted in an external cylinder area available for the heat exchange close to 0.05m². Similarly to the brush-cutter machine, also in the edge-trimmer machine the air flow was also devoted to cool the ignition coil. Differently to the brush-cutter machine, in the edge-trimmer machine the air stream was forced to flow also over the muffler surface before to leave the plastic engine carter. The edge-trimmer muffler was not catalytic, therefore its mean temperature was expected to be closer to the engine exhaust gas temperature (~250°C).

Table 1. Brush-Cutter and Edge-Trimmer machine main characteristics.

Machine type		Brush-Cutter	Edge-Trimmer
Displacement volume	[cc]	44	22
Engine max power	[kW]	1.8 (@7500)	(1.53@6000)
Stroke	[mm]	32	27
Bore	[mm]	42	32
Connecting rod	[mm]	57	57

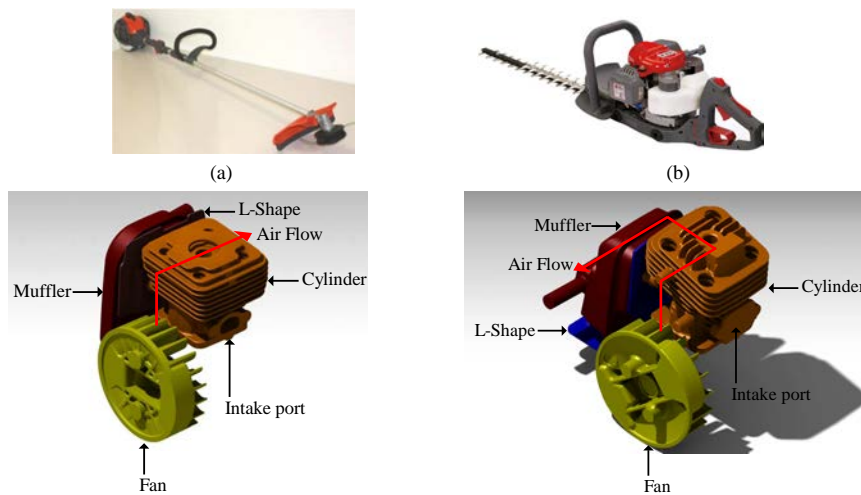


Fig. 2. Brush-cutter (a) and edge-Trimmer (b) machine layouts.

3. Simulation set-up

3.1. Computational domain subdivision and mesh generation

To perform the desired CHT simulations, the first step was the definition of the computational domain and its subdivision in different sub-volumes. Considering the similitudes between the two machines, for both cases the following macro domain partition was adopted (Figure 3):

- Cylinder solid volume
- Spark solid volume
- Main fluid volumes surrounding the cylinder, the coil connected to the cylinder, the rotor, the carted, and the muffler
- Rotor fluid volume representing the air volume trapped between the fan blades

All the sub-volumes were properly interfaced each other from both fluid and thermal point of views and discretized by StarCCM+ polyhedral mesh generator [12]. The necessary resolution level close to the walls was assured by the introduction of prismatic layers generated over all surfaces on both fluid and solid sides. Figure 4 shows a detail of the mesh structure at cylinder-to-air interface. The final mesh size was equal to 4.1 million of cells for the brush-cutter machine and 4 million of cells for the edge-trimmer machine.

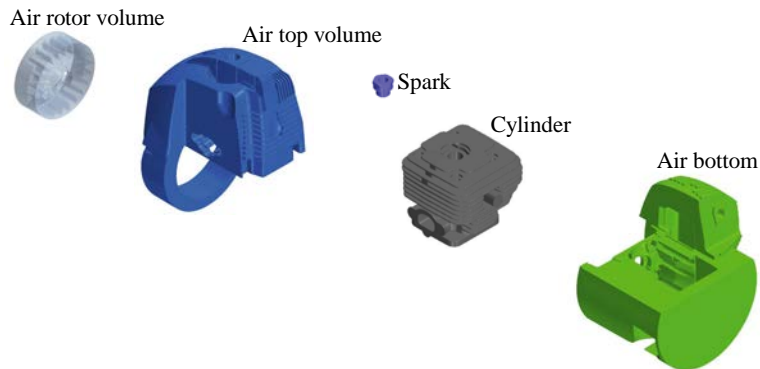


Fig. 3. Macro domain repartition adopted for both brush-cutter and edge-trimmer machines.

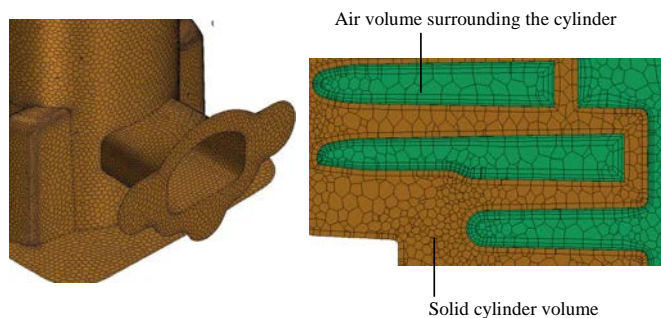


Fig. 4. Polyhedral mesh distribution adopted over the cylinder surface and at air-cylinder interface.

3.2. Fluid dynamic and thermal boundary conditions

The inlet/outlet sections defined on the machine fluid volumes were set as showed in Figure 5. On all these sections, the pressure was fixed at 0bar (relative to atmospheric pressure) and the temperature was fixed at 39°C consistently to the experimental condition described in the simulation result section. The temperature value fixed on the outlet sections must be considered as the backflow temperature.

To impose the desired thermal load to the engine cylinder, a similar surface repartition was adopted for both the machines (Figure 6). The heat release associated to the two engines was by GT-Power 1D models validated by EMAK against experimental data (Table 3). The total thermal load associated to the cylinder was identified as the 30% of the total generated thermal power. Of such an energy budget, the 70% was applied to the head and liner surfaces while the remaining 30% was dissipated through scavenging ports, the intake/exhaust ports, and the crank case by imposing on these surfaces the thermal conditions summarized in Table 4.

On all the surfaces connected to the machine external plastic cases (gray surface of Figure 5) a natural convection thermal condition was applied in order to reproduce natural convection in stagnating air (T_{bulk} 39°C and HTC 7W/m/K). The thermal effect of the catalytic muffler was modeled by imposing a constant temperature over its external surface. The constant muffler temperature value was set equal to 500°C for the brush-cutter machine (catalytic muffler) and equal to 250°C for the edge-trimmer machine (no-catalytic muffler).

About the ignition coil, in both cases the main coil body temperature was set to 75°C while the coil laminated iron core temperature was set to 90°C.

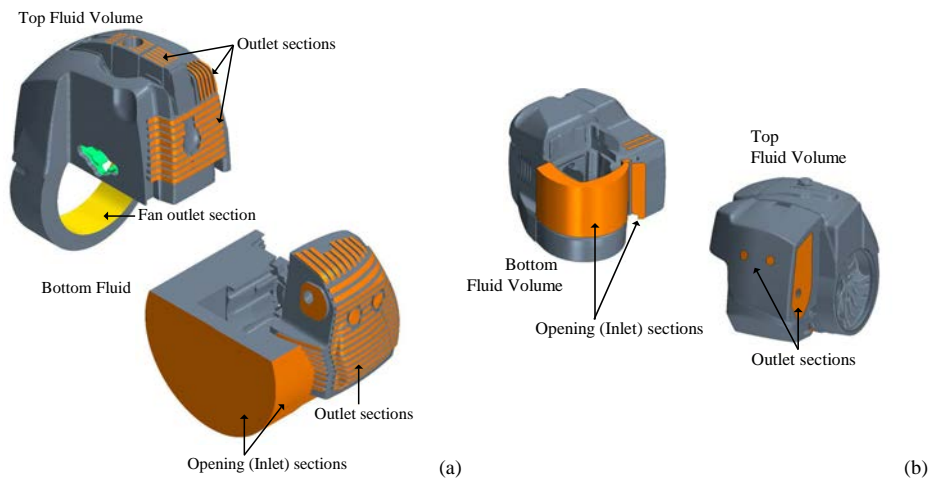


Fig. 5. Opening surfaces set on the fluid volumes surrounding the brush-cutter (a) and edge-trimmer (b) cylinders.

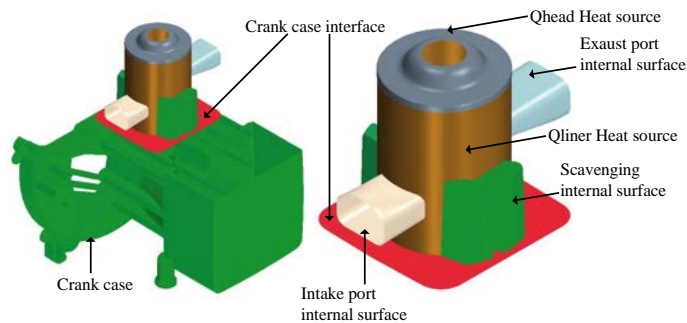


Fig. 6. Subdivision of the cylinder and crank internal surfaces to impose the desired heat flux and thermal conditions.

Table 3. Brush-cutter and Edge-trimmer machines: characteristic engine power levels.

Machine type: Brush-Cutter/Edge-Trimmer				
RPM	Thermal power [kW]	Driving power [kW]	Thermal load [kW]	Exhaust gas [kW]
6000	4.45/1.53	1.40/0.48	1.33/0.48	1.72/0.57
8000	5.42/1.48	1.63/0.44	1.55/0.44	2.24/0.60
10000	5.75/1.47	1.53/0.39	1.70/0.44	2.52/0.64

Table 4. Brush-cutter and Edge-trimmer machines: thermal conditions imposed on the internal surfaces.

Machine type: Brush-Cutter/Edge-Trimmer				
Surface	Thermal condition	T_{bulk} [°C]	HTC [W/m/K]	Surface
Intake port	Convection	40	100	Intake port
Exhaust port	Convection	580	100	Exhaust port
Scavenging port	Convection	60>120(*)	90	Scavenging port

(*) the T_{bulk} over the scavenging port internal surfaces was increased over the cylinder axial direction moving from the crank case to the head surface.

3.3. Numerical set-up

All the simulations presented in this paper were made by using the StarCCM+ v8 code [12]. To reproduce the fan rotation, the Moving Reference Frame approach (MRF) was adopted [12]. It allowed maintaining the relative reference frame associated to the rotor in a fixed position respecting to the stationary frame. Even if by the MRF was not possible to model the transient effects at the frame change interface, it can be considered an helpful approach to reproduce the interaction effects between stationary and rotating components at an affordable computational cost.

Turbulence was modelled by the RNG $k-\varepsilon$ model [13] coupled with the two-layer wall function approach [13]. Pressure, momentum, energy, and turbulence equations were discretized by using second-order schemes [13].

4. Result analysis

4.1. Brush Cutter machine: simulation results

For the brush-cutter machine, EMAK performed experimental tests to extract the mean cylinder temperature values at 6 locations positioned all around the cylinder surface (Figure 7-a). The tests were performed at 8500rpm.

The first simulation step performed on the brush-cutter machine was devoted to the comparison between experimental and numerical data. At this purpose, the authors started to consider the total thermal load at 8500rpm (1.57kW). Only the 70% of the estimated total thermal load was applied directly as heat flux on the liner and head surfaces. The rest of the thermal power budget was introduced into the system by the crank case, scavenging ports, and inlet/outlet ports.

In detail, the thermal power budget associated to liner/head was subdivided as 57% to the head surface (~0.63kW) and 43% to the liner surface (~0.47kW). This subdivision was proposed to take into account the extra thermal load on the head produced by the combustion process.

Figure 7-b depicts the comparison between the experimental and computational temperature values recorded at the thermocouple positions. Numerically, the mean temperatures on the cylinder surface were evaluated by considering spherical volumes having a radius equal to 1mm and centered on the thermocouple experimental positions. The match between the temperature profiles was pretty good in terms of both temperature magnitude and overall trend suggesting that:

- The total thermal load and its subdivision imposed on the engine was compatible with the expected real engine thermal behaviour
- The flow field surrounding the cylinder was well predicted by the computation. The maximum cylinder

temperature (T4) was located in the rear part of the cylinder where the flow was detached from its surface (Figure 8). On the contrary, the temperature values recorded at T2, T3, and T5 resulted well bounded because the flow stream remained quite close to the fins and cylinder external surfaces

Thanks to the results obtained at 8500rpm, the simulation methodology was considered as a valid tool to reproduce at least the overall thermal behaviour of the considered brush-cutter layout on the operating engine range (from 6000rpm to 10000rpm).

Figure 9-a shows the cylinder temperature profiles obtained at thermocouple locations over the considered operating range (from 6000 to 10000rpm). Changing the engine velocity the overall cooling characteristic associated to the cylinder remained almost the same. The T4 value remained always the higher one and its gap respecting the T2/T3 values did not change significantly. It suggested that the flow detachment condition located in the rear part of the cylinder (Figure 8) did not change significantly over the engine speed. Respecting to the T2-T4 values the engine speed influence on the T6 value was quite evident. Passing from 6000 to 10000rpm the reduction of the T6 magnitude was evident because the increased engine speed was promoting the air flow toward the exhaust duct.

By the comparison between the temperature trends showed in Figure 9-a, it was possible to appreciate as the gain in temperature reduction at each thermocouple progressively increased over the engine speed. It was due to the relation between the cooling mass flow increment and the total thermal load increment versus the engine speed. Referring to the 6000rpm case, the $\Delta\%$ associated to the cooling mass flow rate over the engine speed was higher than the engine thermal load gradient allowing to improve the air-cooling effect on the cylinder surface (Figure 9-b).

Passing to the 3D temperature distribution over the cylinder surface, Figure 10 clearly shows the reduction of the high temperature zone extensions and of the differences in air cooling efficiency between the front/rear cylinder sides over the engine speed.

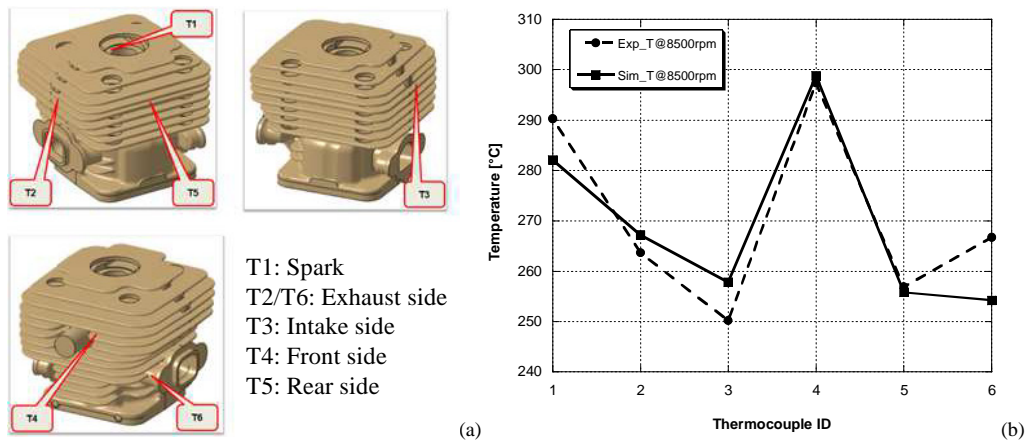


Fig. 7. Brush-cutter machine: comparison between numerical and experimental temperature profiles at 8500rpm.

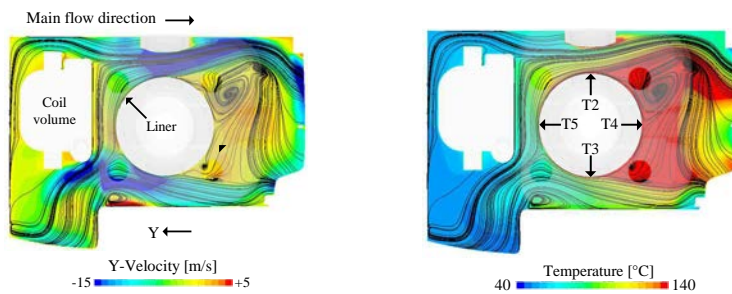


Fig. 8. Brush-cutter machine: flow and temperature fields recorded over a plane positioned orthogonally to the cylinder axis at 8500rpm.

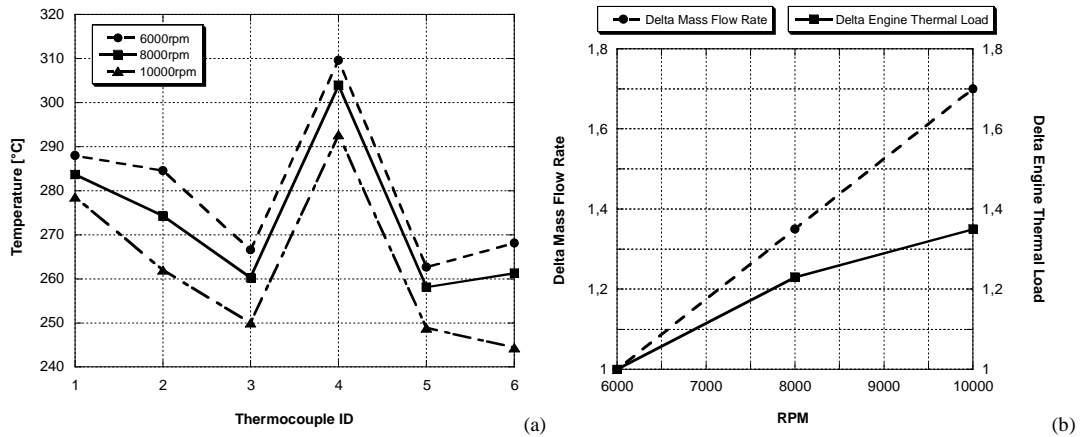


Fig. 9. Brush-cutter machine: (a) temperature trends at thermocouple locations versus the engine speed, (b) mass flow and thermal load variations over the engine speed.

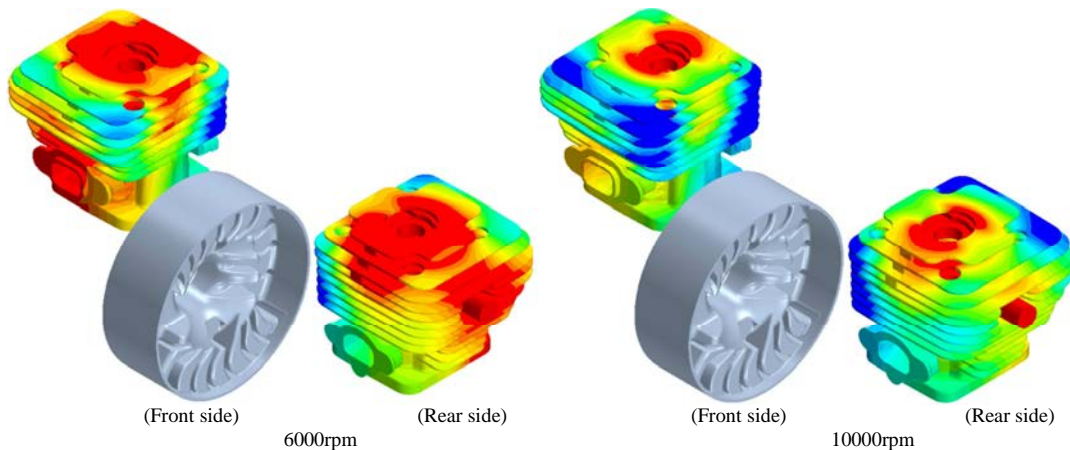


Fig. 10. Brush-cutter machine: 3D temperature maps (150°C-250°C) on the front/rear cylinder surface over the engine operating range.

4.2. Edge trimmer machine: simulation results

The same simulation methodology adopted to study the brush-cutter machine was adopted to reproduce the edge-trimmer machine thermal behavior over the same operating range (from 6000 to 10000rpm). The analysis of the edge-trimmer machine was useful to evaluate the methodology capability in reproducing the thermal behavior of an engine similar to the previous one but characterized by a quite different flow field and distribution of the main components around the cylinder. Respect to the brush-cutter machine, to perform the simulations on the edge-trimmer machine only the total thermal budget dissipated by the engine was updated according to the data summarized in Table 3.

For the edge-trimmer machine, experimental temperature data were recorded over the cylinder surface by 6 thermocouples (Figure 11-a). In this case, the experimental data were available at two different engine speeds: 8000 and 10000 rpm.

Figure 11-b depicts the comparison between the experimental and numerical temperature trends at 8000 and 10000 rpm. By the obtained results, it was possible to appreciate the pretty good capability of the proposed simulation method in reproducing the overall cylinder thermal behavior over the operating range. Differently from

the brush-cutter, for the edge-trimmer the highest temperature value was located on the muffler side. It was due to the flow path around the cylinder that was not promoting, as happened in brush-cutter, a direct air flow toward the cylinder exhaust side. Moreover, in the edge-trimmer machine the cylinder and the muffler were located inside the same air volume. Therefore, respecting to the brush-cutter, despite the lower muffler temperature (catalytic/non-catalytic mufflers), the extra thermal load produced by the muffler toward the cylinder was sensibly higher than before.

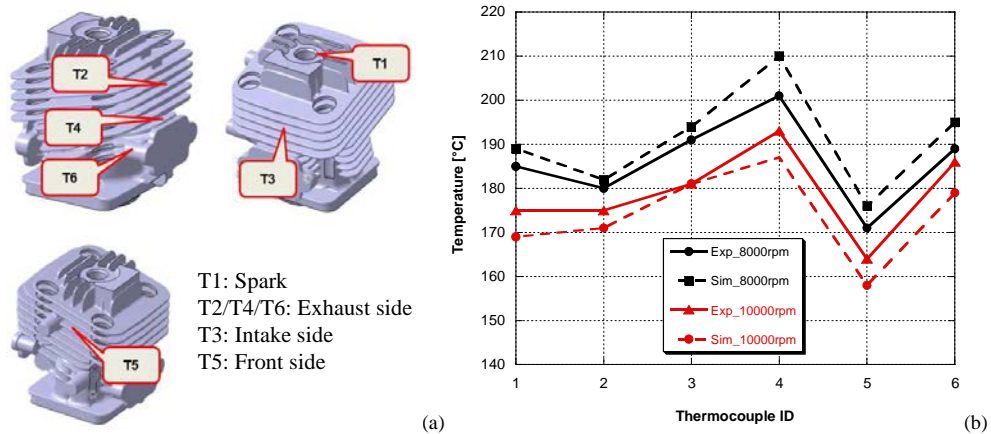


Fig. 11. Edge-trimmer machine: comparison between numerical and experimental temperature profiles at 8000 and 10000rpm.

5. Conclusion

This work was aimed to define a CFD simulation methodology to evaluate the overall thermal behaviour of air-cooled two-stroke engines. At this purpose, two engines were considered. The first one was equipping a brush-cutter machine. The second one was equipping an edge-trimmer machine.

Both the considered hand held machines were made by EMAK company. The proposed simulation methodology was based on the CHT approach while the rotor motion was managed by the MRF approach. To evaluate the simulation methodology reliability, the numerical temperature distributions recorded over the cylinder surfaces were compared to experimental data available for both the considered machines.

By the performed numerical/experimental temperature comparisons it was possible to appreciate the pretty good capability of the proposed simulation methodology to reproduce the cylinder thermal behaviours over the considered operating range. In detail, for both the machines, characterized by a quite different flow path across the cylinder external surface, the numerical results allowed to correctly locate over the cylinder surfaces the highest temperature zones and the temperature gradients among the cylinder sides.

For the brush-cutter machine, the highest temperature values were identified on the cylinder side opposite to the fan. It was due to the detachment conditions characterizing such a cylinder zone.

Differently from the brush-cutter machine, the simulation methodology allowed to correctly identify the edge-trimmer highest temperature on the muffler side. It was due to the primary effect produced by the muffler over the cylinder.

Authors future works will be devoted to adopt the proposed simulation methodology in improving the cylinder design to increase the air flow cooling efficiency.

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