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A methodology to improve knock tendency prediction in high performance engines

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Abstract

The paper presents a comprehensive numerical methodology for the estimation of knock tendency in SI engines, based on the synergic use of different frameworks [1]. 3D-CFD in-cylinder analyses are used to simulate the combustion and to estimate the point-wise heat flux acting on engine components. The resulting heat fluxes are used in a conjugate heat transfer model in order to reconstruct the actual point-wise wall temperature distribution. An iterative loop is established between the two simulation realms. In order to evaluate the effect of temperature on knock, in-cylinder analyses are integrated with an accurate chemical description of the actual fuel.

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1. Introduction

The brake specific power of internal combustion engines, i.e. the power per displacement unit, is progressively increasing during the last 10 years. On the passenger car engine side, this is especially done through the use of the downsizing technique, which in turn mainly relies on the matching of a turbocharger to a reduced displacement engine; lower fuel consumption and pollutant emissions can be achieved without a substantial reduction of the engine performance [2]. On the high performance engine side, instead, the downsizing is a more recent approach, mainly because of the loss of appeal that could derive from the displacement reduction for the specific market. As a consequence, the need to increase the engine performance while complying with the progressively more stringent

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pollutant regulations is usually reached through the adoption of variable valve timing controls, variable length ports and gasoline direct injection.

For both engine classes, heat removal from the most stressed components plays a primary role both to avoid mechanical failures and to prevent the arise of abnormal combustions such as knock and/or surface ignition. The formers are in fact mainly due to the reduction of the material strength at high temperature, while the latters can be promoted by local temperature peaks within the unburnt mixture and/or on the walls facing the combustion chamber. This motivates the need to properly design the coolant circuit, which should be able to act over all the most thermally charged components in order to maximize the specific engine performance. For example, the effectiveness of the heat removal has a direct consequence on both the location of the spark advance and the boost pressure level, which in turn are responsible for the optimal location (timing) and magnitude of the in-cylinder pressure trace, and therefore for the amount of indicated work.

On the other side, however, an oversized coolant circuit reduces the thermodynamic efficiency of the engine and is responsible for increased pollutant emission, especially on the unburnt side due to the larger flame quenching thickness.

The accurate evaluation of the thermal field of the engine components under actual engine operations is something far beyond the possibility within the research and development industrial practice, and it is far from being a well-established practice even in highly-specialized research laboratories.

First of all, a relevant number of thermocouples should be distributed among the many components facing the combustion chamber in order to gain a comprehensive characterization of the thermal field within the engine. Then, despite the extremely high thermal gradients close to the combustion chamber would require sensors to be placed as close as possible to the gas-exposed surface, information are available at least a few millimeters within the components, in order to preserve the engine thermo-mechanical strength. Thermal gradients and surface temperatures can only be inferred by placing secondary thermocouples a few millimeters from the primary ones in the wall-orthogonal direction. Finally, thermocouples are usually placed only in the steady components, i.e. the engine head and block, while temperature measurements for the remaining ones (piston, valves, cylinder liners) can only be extrapolated from a-posteriori measurements such as residual hardness tests, unless very complex experimental equipment is used in highly specialized research laboratories.

The detailed reconstruction of the point-wise thermal field of the engine, and particularly of the combustion chamber walls, is particularly important to carefully estimate local events such as surface ignitions, knock and thermo-mechanical failures (due for example to both high-cycle and low-cycle fatigue crack initiations [3][4].

The increased in-cylinder pressure in SI engines has always been limited by the arising of abnormal combustion phenomena. In particular, the autoignition of gasoline-like fuel in the periphery of the combustion chamber induces a variety of damaging mechanisms that eventually lead to severe engine failures. These include removal of the lubricant film, increasing friction and wear, and large fluctuations of the heat flux to the combustion chamber walls, affecting the high cycle fatigue strength due to thermo-mechanical loadings . Knock still remains nowadays one of the most severe performance limiters in SI engines [5][6][7][8]. Therefore, the accurate detection of the combustion chamber's knock-favorable locations allows the designers to limit the risk of abnormal combustion onset and possibly increases the specific engine performance.

As for the thermal field, the experimental analysis of the knock-prone locations is far from being trivial, and qualitative information can only be gathered through expensive in-cylinder optical visualizations or a-posteriori wear or residual hardness analyses.

In view of the limitations of the experimental practice, the need to use CAE tools, and especially CFD simulations, emerges as a fundamental step, initially for a predictive approach and later for validation and/or for problem solving [4].

In the present paper, an extensive use of such CAE methodologies is proposed. Particularly, three different simulation frameworks are used to fully reconstruct the thermal field of a high performance SI engine and carefully address its knock-related behavior. Information from each of the tools are iteratively exchanged in order to reduce the numerical uncertainties and the number of assumptions. The methodology is successfully applied to evaluate the knock tendency of the engine under its full load, peak power engine speed operation, with two different SAs.