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Research Paper

A modified thermal wall function for the estimation of gas-to-wall heat fluxes in CFD in-cylinder simulations of high performance spark-ignition engines

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HIGHLIGHTS

- Engine thermal field evaluation helps reducing thermo-mechanical failures.
- Reliable gas-to-wall heat fluxes are needed to estimate engine thermal field.
- A modified heat transfer model is proposed for 3D-CFD in-cylinder simulations.
- The model is very effective for current production turbocharged SI engines.
- Validation based on experimental thermal surveys and thermocouple measures.

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ABSTRACT

Last generation spark ignition (SI) engines are characterized by a simultaneous reduction of the engine displacement and an increase of the brake power; such conflicting targets are achieved through the adoption of several techniques such as turbocharging, direct fuel injection, variable valve timing and variable port lengths. This design approach, referred to as "engine downsizing", leads to a remarkable increase in the thermal loads acting on the engine components facing the combustion chamber. Hence, an accurate evaluation of the thermal field is of primary importance in order to avoid thermo-mechanical failures. Moreover, the correct evaluation of the temperature distribution improves the prediction of point-wise abnormal combustion onset.

Due to the complexity of the experimental measurement of instantaneous gas-to-wall heat fluxes, 3D-CFD simulations of the in-cylinder processes are a fundamental tool to evaluate not only the global amount of heat transferred to the combustion chamber walls, but also its point-wise distribution. Several heat transfer models and thermal laws of the wall are available in literature, most of which were developed in the past decades and calibrated against experiments carried out in research laboratories at relatively low-load/low-speed engine operations. In the present paper two widely adopted heat transfer models are proved to be effective at such conditions to predict gas-to-wall heat flux, as demonstrated by their application to the well-known GM pancake engine test case. However, despite such comforting results, they manifest evident shortages when used for highly-charged/highly-downsized current production SI engines, since operated at specific thermal loads and engine speeds very different from the above experiments. In particular, overestimations of the wall heat transfer predicted by such thermal laws of the wall are pointed out thanks to experimental engine thermal surveys and temperature measurements on four current production engines.

Therefore an alternative heat transfer model is proposed by the authors and tested on such currently made turbocharged SI engines, operated at different conditions. Compared to the existing models differences are pointed out, especially in terms of law of the wall expression. Experimental engine thermal survey and point-wise temperature measurements are used to validate the numerical heat flux. In particular the increased predictive capabilities of the 3D-CFD gas-to-wall heat transfer simulations are revealed both in terms of global thermal balance and temperature distribution of the metal for all the investigated engines. In fact model adoption in a combined in-cylinder/CHT (Conjugate Heat Transfer) simulation loop leads to a correct characterization of the thermal status of all the analyzed engines. Finally, alternative

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model adoption for the investigated current production high specific power DISI turbocharged engines operated at full load and high revving speed is critically motivated adopting the “isothermicity parameter” ζ which represents an indication of the thermal state of the boundary layer, being a characteristic scale of the ratio between gas and wall temperatures.

Nomenclature

Definitions/Acronyms

B	bore
S	stroke
SI	spark ignition
DISI	direct injection spark ignition
BMEP	brake mean effective pressure
°CA	crank angle degree
aFTDC	after firing top dead center
bFTDC	before firing top dead center
BL	boundary layer
CHT	conjugate heat transfer
TKE (k)	turbulent kinetic energy
RTD	resistance temperature detector
θ^+, T^{+*}	non-isothermal dimensionless temperature (i.e. dimensionless temperature for non-isothermal boundary layer)
η^+, y^{+*}	non-isothermal dimensionless distance (i.e. dimensionless distance for non-isothermal boundary layer)
q_w	wall heat flux
ρ, ρ^*	density (local and mean of the inner zone)
ρ_w	density at the wall
ρ^+	dimensionless density
c_p, c_p^*	specific heat at constant pressure (local and mean of the inner zone)
u_τ, u_τ^*	friction velocity
T	temperature

T_w	wall temperature
T_τ, T_τ^*	characteristic temperature of the inner layer
T^+	dimensionless temperature
τ_w	wall shear stress
y	distance normal to the wall
y_τ, y_τ^*	characteristic length of the inner layer
y^+	dimensionless distance
υ, υ^*	kinematic viscosity (local and mean of the inner zone)
$\upsilon^+, \upsilon^{+*}$	dimensionless kinematic viscosity
υ_w	kinematic viscosity at the wall
υ_t	eddy kinematic viscosity
μ, μ^*	dynamic viscosity (local and mean of the inner zone)
μ_t	eddy viscosity
λ, λ^*	thermal conductivity (local and mean of the inner zone)
λ_t	eddy conductivity
Pr, Pr^*	Prandtl number
Pr_t, Pr_t^*	Turbulent Prandtl number
ζ	Isothermicity parameter
p	Pressure
γ	Ratio of specific heats
$\dot{Q}_{comb}$	In-cylinder gas-to-wall heat transfer
$\dot{Q}_{fric}$	Thermal power due to friction
$\dot{Q}_{surr}$	Thermal power due to surrounding components
$\dot{Q}_{coolant}$	Thermal power removed by coolant circuit
$\dot{Q}_{lubr}$	Thermal power removed by lubricant circuit
$\dot{Q}_{env}$	Thermal power lost to the environment

1. Introduction

New generation of internal combustion SI engines is characterized by high specific power. This is a consequence of more and more stringent laws that push engine manufacturers to lower fuel consumption and pollutant emissions. In order to meet such targets, automotive industry relies on several techniques such as turbocharging, engine downsizing and down-speeding, complex fuel injection strategies, variable valve timing, variable port length [1,2], innovative combustion modes (e.g. RCCI) and water a/o methanol injection [3,4]. Moreover, the possibility to hybridize vehicles cannot be neglected, which is an increasingly widespread solution. However, the increase of specific power thanks to downsizing and turbocharging is limited on one hand by the occurrence of abnormal combustions [5], on the other hand by the risk of thermo-mechanical failures. The raise of the thermal loads can significantly reduce the mechanical resistance of the engine components thus deeply reducing the engine reliability [6]. In order to avoid knock onset, the most diffused solution is the reduction of the engine spark advance (SA), thus lowering the engine performance.

In order to prevent thermo-mechanical damages, CFD-CHT and FE tools may be used to calculate the thermal field and thermo-mechanical stresses of the engine, reducing proficiently time- and cost-to market. For this purpose it is fundamental to estimate correctly the gas-to-wall heat transfer, which affects not only the thermal stresses, but also the overall engine efficiency and the exhaust emissions. As highlighted by Nijeweme et al. [7] the formation rate of NO_x is strictly dependent on temperature and a reduction of about 30 K in the peak combustion temperature can halve the NO_x emissions. Also wall temperatures are found to be important for emissions. In fact, Alkidas and Myers [8] show that, on one hand, NO_x emissions increase strongly with surface temperatures, on the other hand HC emissions decrease when coolant temperature raises. Furthermore, wall heat transfer should be correctly predicted to improve the accuracy of in-cylinder simulations, as it affects charge mixing and combustion.

A correct estimate of the gas-to-wall thermal loads is fundamental and it can be derived from either dedicated experiments or 1D/3D CFD simulations. The thermal power acting on the components facing the combustion chamber cannot be experimentally assessed without efforts. In fact, a direct evaluation of the instantaneous heat flux usually requires the adoption of complex, expensive and intrusive sensors [9,10], which cannot be used for moving parts (e.g. piston and valves). Otherwise, thanks to recent technological developments, particular thermocouples can be used to measure surface temperatures on engine components, even on the moving ones. Such fast response thermocouples, called Thin Film Gauges (TFG), can be placed on the valve face or even on the piston crown [11] to measure local surface temperatures