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An adapted heat transfer model for engines with tumble motion

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HIGHLIGHTS

- An adapted heat transfer model for engines with tumble is presented.
- A theoretical CFD study in a specific high-tumble engine is performed.
- An innovative calibration methodology based on skip-fire tests is described.
- A sensitivity study focused on evaluating the model robustness is performed.

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ABSTRACT

In the last years, a growing interest about increasing the engine efficiency has led to the development of new engine technologies. The accurate determination of the heat transfer across the combustion chamber walls is highly relevant to perform a valid thermal balance while evaluating the potential of new engine concepts. Several works dealing with heat transfer correlations that consider the swirl motion are found in the literature; however, there is a lack of works dealing with heat transfer correlations which take into account the effect of the tumble movement. In this work, a heat transfer model accounting for the tumble motion is presented. A two stroke HSDI Diesel engine with high tumble and no swirl is used to perform the theoretical study, the model development and its final calibration. Initially, a theoretical analysis of the gas movement phenomena is carried out based on CFD results and then, a model is developed and calibrated based on a skip-fire testing technique. Finally, a sensitivity study focused on evaluating the model robustness is performed. The results confirm an average RMSE reduction of 70% with respect to the Woschni model, being this consistent improvement qualitatively evidenced in the instantaneous heat transfer evolution.

1. Introduction

The global awareness towards the greenhouse gases emissions has led to a more stringent ICE emissions legislation, thus focusing the automotive researchers and manufacturers attention on the development of cleaner and more efficient powertrains. In the last years, the efforts have been mainly focused on the reduction of the NO_x and soot emissions by means of different injection strategies [1], high pressure fuel injection systems [2], multiple injections [3], high boost pressure [4], exhaust gases recirculation (EGR) [5], variable valve timing [6], high swirl [7,8] and tumble ratios [9], new clean fuels [10,11] or after treatment systems [12]. Nowadays, there is an increasing interest towards the optimisation of the fuel consumption, and hence the reduction of the CO_2 emissions [13]. To comply with the upcoming requirements, new combustion concepts such as HCCI [14] and PCCI [15], and new automotive engine concepts such as downsizing [16,17], and two-stroke engines [18] are in the centre of the research. The air management is a common factor in these works, since it is a key issue to improve the air–fuel mixing process and achieve faster burning rates [19], and therefore modern ICE are designed to generate high vorticity and turbulence in the combustion chamber.

There are several methodologies aimed at the evaluation of specific engine technologies or operation strategies, being some of the most widespread the combustion diagnosis based on in-cylinder pressure evolution [20] and the energy balances [21]. The combustion diagnosis evaluates the combustion performance by analysing the Heat Release (HR), which is obtained by solving the first law of thermodynamics [22]. In this way, relationships between operating conditions (speed, load, injection setting, etc.) and engine outputs (emissions [15] and thermal efficiency [23]) may be established taking into account the combustion evolution.

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Nomenclature

A	area (m^2)
α	crank angle (°)
c_m	piston mean speed (m/s)
c_u	tangential vortex speed (m/s)
D	cylinder diameter (m)
ρ	density (kg/m^3)
$\Delta\alpha$	angular duration (°)
f_w	gas velocity dissipation function (–)
γ	adiabatic index (–)
h	heat transfer coefficient (W/m^{2}K)
HR	heat release (J)
η_{tr}	trapping ratio (–)
$imep$	indicated mean effective pressure (bar)
k	conductivity (W/mK)
$\dot{m}$	mass flow rate (kg/s)
n	polytropic index (–)
p	in-cylinder pressure (bar)
Q	accumulated heat transfer (kW)
$\dot{Q}$	heat transfer rate (J/°)
R	specific gas constant (J/kg K)
S	engine stroke (m)
T	temperature (K), (°C)
V	volume (m^3)
v	velocity (m/s)
μ	dynamic viscosity (Pa s)

Abbreviations

ATDC	After Top Dead Centre
BDC	Bottom Dead Centre
BTDC	before Top Dead Centre
CFD	Computational Fluid Dynamics
CI	Compression Ignition
EGR	Exhaust Gas Recirculation
HCCI	Homogeneous Charge Compression Ignition
HR	Heat Release
HSDI	High Speed Direct Injection
HT	Heat Transfer
ICE	Internal Combustion Engine
IGR	Internal Gas Recirculation
IVC	Intake Valve Closing
IVO	Intake Valve Opening
PCCI	Premixed Charge Compression Ignition
RMSE	Root Mean Square Error
RoHR	Rate of Heat Release
RTD	Resistance Temperature Detector
SI	Spark Ignition
TDC	Top Dead Centre
TR	Tumble Ratio

Subscripts

0	initial, motoring
a	air
CFD	calculated from CFD results
cyl	cylinder
d	displaced
eff	effective
f	final, fuel
g	in-cylinder gas
int	calculated at Intake
IVC	calculated at IVC
IVO	calculated at IVO
max	maximum
n	polytropic exponent
t	relative to tumble model
w	relative to the reference Woschni model

For a proper determination of the HR, the accurate determination of the Heat Transfer (HT) to the combustion chamber walls is a key issue. Moreover, chamber HT is also important to get relevant information for the engine thermal characterisation [24]. Experimental determination of heat flow to the chamber walls is a hard task that requires special instrumentation (thermocouples or RTDs), which is not usually available in a standard test bench [21]. Therefore, modelling becomes a suitable alternative approach, whose complexity and time consumption depends on the specific application.

Combustion diagnosis requires HT models with low computational effort (calculation time of seconds is usual). Thus, simple proposals dealing with the HT estimation in ICE can be found in the literature for both, compression ignition (CI) and spark ignition (SI) engines. Some of the most widespread correlations for HT coefficient calculation are those based on the well-known Woschni [25], Annand [26] and Hohenberg [27] works. To make these models suitable for a specific application, they must be adjusted based on different techniques such as CFD modelling [28], experimental measurements [29,30], or thermodynamic assumptions [31]. In general, these models correlate the HT coefficient with the thermodynamic state of the gases (pressure and temperature), the engine geometry (bore and stroke) and the gas movement (gas velocity and flow pattern), being this last parameter the most difficult to asses due to the unsteady nature of the gas motion, since it is a turbulent 3D flow with no clear symmetry of the gas properties along the chamber.

The main rotative macro structures that can be found in ICE are the swirl and tumble, being differentiated by their rotary axis (swirl rotates in the cylinder axis and tumble in the diametrical axis). Both are generated during the intake process and evolve in the compression-expansion stroke thanks to the engine geometry (particularly ports and combustion chamber configuration). The swirl movement is prompted by chamber configurations consisting of a shallow bowl engraved into the piston crown [19], whilst the tumble movement is enhanced by pentroof combustion chambers [32,33]. The swirl characteristics have been widely studied, and most of the HT correlations include a term accounting for its contribution to the characteristic gas velocity used to calculate the HT coefficient [25,28]. However, there is a lack of HT correlations dealing with the effect of the tumble characteristics on the HT coefficient. The tumble is usually evaluated by means of experimental techniques such as LDV and PIV [34,35], involving several engine modifications, or CFD modelling [36,37] leading to a long computational time. Alternatively, there are some quasi-dimensional models [32,38], which are faster than the CFD models, but require a detailed knowledge of the fluid motion pattern and also of the engine ports and combustion chamber geometry. This specific information is not usually available for combustion diagnosis, and hence leads to a lack of generality of the models for be applied to in different engines.

In this work, a generally applicable HT model that includes the gas velocity evolution produced by a high tumble movement is proposed. For the model development, a research CI two-stroke HSDI engine with high tumble motion and no swirl was experimentally characterised. The fluid motion analysis was carried out on the basis of CFD simulations, whereas the calibration of the model was performed in a specific experimental installation,