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Research Paper

Fast algorithms for generating thermal boundary conditions in combustion chambers

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HIGHLIGHTS

- A model for thermal boundary conditions in engine combustion chambers is proposed.
- The method only uses integrated quantities without in-cylinder pressure data.
- The model is valid for variations in the air-fuel ratio and the boost pressure.
- Highly non-uniform pressure changes in ignition time variations are underestimated.

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ABSTRACT

The focus of this paper is the fast determination of thermal boundary conditions in engine combustion chambers. In contrast with many other studies, only cycle integrated quantities like the induced torque are needed as input variables, which means that no crank angle resolved in-cylinder pressure data are required.

Changes in the engine mapping like variations in ignition time and boost pressure or various lambda strategies are studied concerning component temperatures, and not to crank angle resolved heat fluxes, as it was often the case in previous published works. It is demonstrated that variations of cycle averaged solid temperatures can be predicted with the proposed identification method for thermal boundary conditions. The limit of the model for highly non-uniform pressure changes, as it is the case in ignition time variations, is well discussed.

A variety of thermal boundary conditions is tested within a CFD-CHT simulation in order to get component temperatures. The new calculation algorithm combines proven models according to Woschni with a statistical method, which takes pressure fluctuations into account. Probability density functions and realisations of chosen random variables, like heat transfer coefficients, are transformed according to different engine operating conditions. For model validation, engine temperature measurements are conducted.

1. Introduction

1.1. State of the art

In the area of engine heat transfer, various calculation methods with varying model depth can be found. Early works addressed the problem with dimensional analysis and pronounced experimental studies: [1–3]. Based on these more phenomenological results, improved physical models are suggested with simple global turbulence modeling: In [4] a characteristic gas velocity is contained which includes the turbulent kinetic energy. Similarly, [5] developed a complete heat transfer model with a Reynolds-Colburn analogy. For the determination of heat transfer coefficients, a global k-ε model was used. In contrast, there also exist many works which uses detailed CFD in-cylinder flow simulations, including heat transfer processes: [6–8]. In [9], a method is proposed which couples detailed CFD techniques with a simplified engine working process analysis in order to ensure the overall heat transfer rate: much better results can be obtained in comparison with state-of-the-art wall function heat-transfer models. Regarding heat transfer, the dependence on different engine settings, like ignition time, air-fuel ratio or boost pressure, is of great interest. An excellent review about such sensitivities, in motored and fired engine operation, can be found in [10]. In this context, a design of experiments method is applied in [11]: Various engine settings like, e.g., ignition timing, air-fuel ratio, fuel or

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Nomenclature

A	realisation of random variable α, W/(m^2 K)
c_p	specific heat at constant pressure, J/(kg K)
c_v	specific heat at constant volume, J/(kg K)
l	characteristic length, m
m	Re exponent, dimensionless
m_{air}	mass flow of air, mg/stroke
m_{fuel}	mass flow of fuel, mg/stroke
$\underline{M}$	five-dimensional engine state matrix of outer boundary conditions, various
$\underline{M}_1$	five-dimensional engine state matrix: Given reference state (full load), various
$\underline{M}_2$	five-dimensional engine state matrix: Given state (part load), various
n	Pr exponent, dimensionless
n_{engine}	engine speed, rounds per minute [rpm]
$\boldsymbol{n}$	boundary normal vector, dimensionless
N	amount of substance, mol
Nu	Nusselt number, dimensionless
p	static pressure, Pa
p_m	motored cylinder pressure, Pa
p_{cmb}	cylinder pressure due to combustion, Pa
p_{int}	boost pressure, mbar
p_α	probability density function on α, dimensionless
$p_{\alpha\|\underline{M}}$	conditional probability density function on α with regard to $\underline{M}$, dimensionless
Pr	Prandtl number, dimensionless
$\boldsymbol{q}$	heat flux vector, W/m^2
R	universal gas constant, J/(mol K)
Re	Reynolds number, dimensionless
t_{int}	inlet temperature of air, K
t_{amb}	ambient temperature of air, K
$t_{waterin}$	inlet water temperature, K
t_{oilin}	inlet oil temperature, K
T_{ref}	reference temperature, K
$\overline{T}_g$	cylinder-average gas temperature, K
T_s	solid temperature, K
T_i	indicated torque by combustion, N m
U	arbitrary random variable, various
u	realisation of random variable U, various
v	characteristic velocity, m/s
v_{c1}	part one of characteristic velocity according to Woschni, m/s
v_{c2}	part two of characteristic velocity according to Woschni, m/s
v_{piston}	mean piston speed, m/s
V	volume, m^3
V_d	displaced volume, m^3
Y	arbitrary random variable, various
y	realisation of random variable Y, various

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
α_1	realisation of α in the state $\underline{M}_1$, W/(m^2 K)
α_2	realisation of α in the state $\underline{M}_2$, W/(m^2 K)
α_{cr}	crank angle, °CA
α_{ign}	ignition crank angle, °CA
β	transformation coefficient, dimensionless
γ	ratio of heat capacities, dimensionless
κ	isentropic exponent, dimensionless
λ	thermal conductivity, W/(mK)
λ_{cmb}	ratio between actual air mass and stoichiometric air mass, dimensionless

Abbreviations

ACT	**A**verage **C**ylinder **T**emperature
CFD	**C**omputational **F**luid **D**ynamics
CHT	**C**onjugate **H**eat **T**ransfer
ECU	**E**lectronic **C**ontrol **U**nit
EGR	**E**xhaust **G**as **R**ecirculation
HTC	**H**eat **T**ransfer **C**oefficient
IVC	**I**nlet **V**alve **C**losing
PDF	**P**robability **D**ensity **F**unction
TDC	**T**op **D**ead **C**enter

compression ratio, are investigated. In a more fundamental manner, the Polhausen equation is verified in seven different operating regimes. Many works address the dependence on engine settings, including experimental measurements of heat fluxes and the prediction accuracy of different models: [12–17]. As an example, [18] investigated heat fluxes as a function of ignition timing, air-fuel ratio and mixture preparation.

Nevertheless, the questions that arise in this context relate to resulting component temperatures. As an example, the underlying thermomechanical fatigue mechanisms are very sensitive to temperature changes. As an example, aluminium alloys like wrought alloy 2618A show a great temperature dependence of its high cycle fatigue resistance [19]. There are few studies on this topic. Most of the previous works investigated only crank angle resolved temperature curves: [20–23] or [24]. The influence of different engine settings on the cycle averaged component temperatures are not studied there. It is rare to find publications like [25] or [26]. The first one investigated experimentally averaged cylinder liner temperatures of a diesel engine as a function of ignition time and engine speed, whereas the second one measured cylinder head and piston mean temperatures of a SI engine in dependence of engine speed and load. Additionally, in [27], the cylinder head mean temperature is experimentally investigated with regard to three different air-fuel ratios. In all three references, it can be seen that the cycle averaged mean temperatures reacted more sensitively to engine settings, in contrast to the corresponding temperature swings. In the context of mean temperatures, only highly unique components like nozzle tips are sufficiently represented in literature: [28–30]. However, a general calculation method is missing. In particular, according to inverse problems, the fast and efficient identification of suitable thermal boundary conditions which can account for different engine settings is challenging. That is exactly the focus of the present paper.

1.2. Outline of the paper

One of the goals of the present paper is the fast generation of thermal boundary conditions in combustion chambers under fired engine states. The research question can be formulated as follows: With regard to crank angle averaged solid temperatures, knowing full well that in-cylinder heat transfer is a highly complex problem, is it possible to identify accurate enough thermal boundary conditions only with cycle integrated quantities as model input variables? In particular, for the purposes of engineering applications, can the conflict of objective between the calculation time, model input variables and the sensitivity to diverse engine settings be solved with an expedient modeling?

Starting from a reference operating point, for which heat transfer coefficients and the average gas temperature are known, relative changes in these quantities are calculated. Using pressure indication measurements and the model according to Woschni [2], thermal