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An advanced real-time capable mixture controlled combustion model

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A R T I C L E I N F O

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The paper presents an innovative and advanced MCC (mixture controlled combustion). The MCC model is coupled to the innovative mechanistically based 0D spray model presented in a companion paper [1] that provides inputs on fuel mass distribution. Advanced MCC model is embedded into a 2-zone combustion modeling framework. Advanced MCC predicts ROHR (Rate-Of-Heat-Release) as the combination of the premixed and two diffusion parts, which correspond to rich and lean spray region. It also calculates the amount of fuel available for premixed combustion based on the duration of the ignition delay period. In addition, it reduces the reaction rate based on the oxygen availability using mechanistic basis, based on evaporation rate and based on mechanistically determined fuel amount that has reached the walls. High level of model predictability was confirmed by good agreement between the simulated and the measured ROHR traces over very broad operating range of the engine by using fixed parameters of the advanced MCC model and the spray model. Moreover, the applied modeling framework with embedded innovative spray and advanced MCC model features HiL (Hardware-in-the-Loop) compatible computational times.

1. Introduction

Global concerns on sustainable energy use and environmental protection are a continuous driving force of innovative ICE (internal combustion engine) technologies. Diesel engines feature high effective efficiency, whereas further optimization of diesel engines with the aim to increase specific power and efficiency and in particular to lower exhaust emissions is required for reaching environmental objectives and customer acceptance. One of the main scopes of this optimization is a further optimization of the combustion processes. This inherently calls for advanced and powerful simulation tolls where besides the tools dedicated to detailed analyses, advanced system level tools are also of utmost importance for the virtual development process or the virtually assisted development process.

As addressed in Ref. [1], system level simulations are generally aimed to support the development process in two stages. First, system level models are indispensable for efficient exploration of the design space and pinpointing most promising design during the concept development and during the powertrain design phase. Second, efficient system engineering simulation models are also applicable as plant models for MiL (Model-in-the-Loop), SiL (Software-in-the-Loop) and HiL (Hardware-in-the-Loop) activities in the validation and calibration phase. To efficiently support these tasks system engineering simulation models have to feature high level of accuracy and predictability as well as very fast computational times, whereas in HiL environments it is mandatory to strictly fulfil the real-time constraints [2,3].

In addition, general applicability of the models, which on one side covers the ability to model a wide range of engines and operating conditions and on the other side relates to the ability of a single model to support various stages of the development process, is of utmost importance. It reduces model calibration workload and ensures high level of consistency throughout the development process. To efficiently comply with the objectives on high level of accuracy and predictability, very fast computational times and general applicability of the models a careful selection of the appropriate physical depth of the model is required.

It was presented in Refs. [4,5] that 0D filling and emptying modeling approach with an optimized interaction of the cylinder and the gas path domains complies with the real-time constraint imposed by HiL systems on a single core processor. Furthermore, in Ref. [6] this modeling approach was extended with 2-zone combustion modeling framework presented in Ref. [7] and coupled with a MCC (mixture-controlled-combustion) model presented in Ref. [8]. It was presented in Ref. [6] that such a modeling approach also complies with a real-time constraint on a single core processor

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Nomenclature

C	model constant (−)
d_{nozzle}	injection nozzle diameter (m)
F	rate multiplication factor (−)
H_{LHV}	lower heating value (J/kg)
id	ignition delay (−)
k	constant in the Gaussian profile (−), turbulent kinetic energy density (m^2/s^2)
k_A	model constant (−)
L_{st}	stoichiometric air fuel ratio (−)
$\dot{M}$	momentum flux (N)
dQ/dt	burn rate (W)
R	ratio (−)
r	radial distance from the center line of the spray (m)
s_{tip}	spray tip penetration (m)
s_1	spray origin or tail (m)
T	temperature (K)
T_A	activation temperature (K)
t	time (s)
x	distance from the nozzle and (m)
V	volume (m^3)
λ	excess air ratio (−)
ρ	density (kg/m^3)
ϑ	spray cone angle (deg)
τ	characteristic time (s)

Subscripts and abbreviations

A	available
air	air
B	burned
BMEP	brake mean effective pressure
BZ	burned zone
$comb$	combustion
CP	combustion products
cyl	cylinder
$diff$	diffusive
EOI	end of injection
$evap$	evaporated
f	fuel
FV	fuel vapor
G	gross
ign	ignition
inj	injected
pre	premixed
ROHR	Rate-Of-Heat-Release
ROI	Rate-Of-Injection
SOI	start of injection
sp	spray
U	unburned
$unevap$	unevaporated
UZ	unburned zone
$wall$	combustion chamber wall

while modeling turbocharged multi-cylinder high-speed low-swept volume engine. Simulating such an engine type is demanding in terms of compliancy with the real-time constraint as small volumes call for small integration time steps and as high engine speed requires simulation of many cycles per unit of time, whereas turbocharging inherently results in more complex gas path topologies featuring large number of elements. Findings showing similar trends are also presented in Ref. [9], where authors report that a model that combines a mean-value modeling approach for the engine periphery with a 2-zone combustion modeling framework coupled with a fully empirical Vibe combustion model complies with the real-time constraint when run on a quad core processor. The latter indicates more computational operations per engine cycle in the model presented in Ref. [9] compared to the models presented in Refs. [4–6].

The basic mixture controlled combustion model was presented in Ref. [10]. It relies on two hypothesis influencing the ROHR (Rate-Of-Heat-Release) calculation. First, it considers that ROHR is proportional to the fuel quantity available for combustion at the moment of consideration [10]. Second, it considers that in a Diesel engine the rate of fuel oxidation is determined by the rate of mixing of fuel vapor and fresh air/charge and thus by the local density of the turbulent kinetic energy [10]. MCC model from Ref. [10] was in Ref. [11] extended in a way that in addition to the burn rate for the diffusion part of combustion, it also addressed the ignition lag and the premixed part. The reason for this extension lies manly in the fact that in part-load conditions the premixed portion of the rate of heat release contributes significantly to the overall burn rate [11]. An additional extension of the model presented in Ref. [11], is presented in Refs. [8,12–14] where ROHR is based on the separate description of both the primary processes closely related to the fuel jet as well as the following combustion of the fuel mass remaining after the end of injection. The new features of the ROHR model prove to be necessary to describe the effects of modern high-pressure fuel injection systems on the combustion process regarding the strong influence of the injection rate on the burn rate.

Refs. [15–17] present an alternative quasi-dimensional CI model where the spray is axially discretized in slices. These slices propagate through the combustion chamber in the direction of injection and as they propagate the admixture of combustion chamber gas to the slices is stipulated by means of an empirical distribution of the excess air ratio [16]. The excess air ratio distribution of the spray has a direct impact on the diffusion combustion as the model relies on three excess air ratio zones: the extremely rich zone that is unable to burn, the zone of diffusion combustion, which also contains the stoichiometric excess air ratio, and the very lean zone [16]. The diffusion combustion considers contributions of the last two zones, where a damping function using empirical inputs is used in Ref. [15] to account for the oxygen deficiency.

According to Ref. [15] and also according to author's experience models that discretize the injection jet in the axial and radial direction in numerous parcels do not comply with the real-time constraint. Moreover, according to the data on computational speeds presented in Ref. [6] (that used a 0D spray model) there is also not sufficient margin in computational speed that would allow for introduction of discretized spray models while still complying with the real-time constraint. This is reasoned by two facts. First, some margin in computational speed is required to support modeling of engines with a large number of cylinders and/or with complex gas path topologies operating at high engine speed, which is of particular importance for ensuring general applicability of the models. Second, higher level of discretization inherently leads to an increased number of variables and in general also calls for smaller integration time steps as stiffness of the system commonly increases with increased spatial resolution.

To comply with the real-time requirements on computational speed of the entire engine model, an innovative 0D spray modeling framework that allows for calculation of fuel mass and mass of in-