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Modelling spray and combustion processes in diesel engine by using the coupled Eulerian–Eulerian and Eulerian–Lagrangian method

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ABSTRACT

The focus of this paper is to demonstrate that the existing and developed models, within the coupled approach, are capable for describing spray, combustion and pollutant formation processes. The Eulerian–Eulerian (EE) method, multi-continuum model, is used for spray modelling including the fuel jet disintegration and droplet evaporation processes. The combustion process is modelled by employing the Eulerian–Lagrangian (EL) discrete droplet model (DDM). The EE–EL coupling has been performed by running simultaneous simulations on a separate computational domains with constantly exchanging mass, enthalpy and momentum sources. The calculated results were compared to the available experimental data and to the previously published results. It is concluded that the pressure and temperature traces, energy conversion and the emission trends are well described and a good agreement to the experimental data is observed. The advantage of the presented approach is retaining a high CPU efficiency, characteristic for the EL method, with an increased solution accuracy in the near-nozzle region characteristic for the EE method.

1. Introduction

A vast amount of CO_2 is released into the environment by combusting fossil fuels [1], and a rapid emission reduction (up to 85%) has to be achieved by 2050 [2]. Powering diesel engines and fossil fuel combustion lead to an increase in the pollutant emissions concentrations. However, due to the better diesel engine energy conversion, compared to the spark ignition engines [3], diesel engines are still a favourable choice on the transportation vehicle market in the European countries. A significant contributors to the pollutant emissions are carbon monoxide, unburnt hydrocarbons, nitric oxides and carbonaceous particles. The regulation of these pollutants has been a hot topic for several decades and a rigorous regulations are planned in the future. These regulations include the European emission standards arising from one of the governmental policies as an option for accomplishing cleaner production [4]. There are several factors why a constant development of the internal combustion (IC) diesel engine is important. One is the fact that the European Union promote the use of biofuels [5] and second is more often use of the effective hybrid technology [3,6]. In order to remain the most widely used transportation vehicle powering system, diesel engines must meet higher efficiency standards [7]. A huge scientific effort and research time are being dedicated to determine how various factors and fuel energy conversion influence the IC engine emission production. Detailed understanding of such processes is limited in experimental investigations and therefore, the Computational Fluid Dynamics (CFD) tools can be employed. Furthermore, the uncertainties arising from experimental investigations can be figured out by use of such tools [8].

Numerous studies about spray processes have helped engineers establish the criteria needed to design and develop more efficient combustion devices while minimizing the pollutant emissions [9–11]. The understanding of fuel spray complex nature formed by the mostly used high pressure injectors [12] in experimental research is limited and this understanding can be significantly improved by use of numerical simulations. Numerical modelling of spray process, which represent a multi-phase flow, is a very challenging task as compared to a single-phase flow modelling. The challenges arise due to the interaction between phases, and property variations across the phase interfaces. Thus, spray models demand a complicated techniques to couple the dynamics of the liquid droplets with the carrier gas. A variety of strategies have been formulated during the last years in order to address this problem. In general, most of these strategies fall into two basic formulation methods that are commonly used to couple the

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Nomenclature

Roman	*Description (Unit)*
k, l	Eulerian class index
∇p	pressure gradient (Pa/m)
$\mathbf{f}$	body force vector (N/m^3)
h	specific enthalpy (J/kg)
H_{kl}	enthalpy exchange term between phase k and l (W/m^3)
$\mathbf{M}_{kl}$	momentum exchange term between phase k and l (N/m^3)
$\boldsymbol{q}$	heat flux vector (W/m^2)
t	time (s)
$\mathbf{v}$	velocity vector (m/s)
$\mathbf{v}_{\text{int}}$	interface velocity vector (m/s)
dt	calculation time step (s)
wf	weighting factor

Greek	*Description (Unit)*
ε	turbulence dissipation rate (m^2/s^3)
θ	enthalpy volumetric source (W/kg)
$\boldsymbol{\tau}$	shear stress tensor (N/m^2)
Γ_{kl}	mass exchange term between phase k and l (kg/(m^3 s))
α	volume fraction (–)
ρ	density (kg/m^3)

Subscripts	*Description*
k	phase index
ex	extensive property
in	intensive property

Superscripts	*Description*
t	turbulent index

Abbreviations	*Description*
CFD	computational fluid dynamics
IC	internal combustion
DDM	discrete droplet method
ACCI	AVL code coupling interface
CV	control volume
rpm	revolves per minute
EHVA	electro hydraulic valve actuation
SOI	start of injection
EOI	end of injection
EGR	exhaust gas residuals
TDC	top dead centre
BDC	bottom dead centre
CA	crank angle

dynamics of the liquid and the gas phase: the EL and the EE method.

The EL method has been firstly used in [13–16] and is the most used method in the various engineering applications. In this method, spray is represented by a finite numbers of grouped droplets called parcels. The assumption is that all droplets placed within one parcel are similar in size and physical properties. The transport of each parcel through the flow field is solved by using the Lagrangian formulation, whilst the continuous gas phase is described by solving the Eulerian conservation equations. The phase coupling is performed by introducing the source terms for interfacial mass, momentum and energy exchange. The EL method has severe limitations as it is very sensitive to the numerical grid resolution in the near nozzle region [17]. The limitations on grid size also affect the modelling of heat transfer, momentum exchange, etc. Therefore, the numerical resolution is important in reproducing the structure of sprays [18]. This results in inadequate description of dense spray region in the vicinity of the nozzle. However, Lagrangian method is suitable for calculating the diluted region where a lower liquid phase volume fraction is encountered. Other drawbacks of the EL formulation are the increase of computational costs with higher number of introduced parcels and the parallelization issues. The EL method also suffers from the statistical convergence problems, as discussed in [19,20].

Spray process can be modelled by employing the numerical methods used for tracking the liquid–gas interface such as VOF and level-set methods. The authors in [21] examined the jet breakup (injection velocity 100 m/s) on a 2.1 mm computational domain consisting of over 14 million control volumes by employing the level set/VOF/ghost fluid method. The authors in [22] used the level set method to solve the disintegration of fluid jet on a 2 mm computational domain, also consisting of high number of control volumes. The authors in [23] presented the modelling of primary atomization process by employing the refined level set grid method. They pointed out extremely high memory requirements (10 GB data of every 50 ns of simulation) of such simulations. More detailed description of sharp interface techniques for multi-fluid flow modelling can be found in [24]. Based upon the literature review, despite their accuracy, such models are highly computationally expensive and are not considered in our simulation of the real IC engine.

To overcome the disadvantages of the EL method the EE multi-continuum method can be employed. Here, both phases are treated as continuum and conservation equations are solved for each phase separately by using the similar numerical techniques. The EE method was firstly addressed by [25] and has been adopted and applied for numerical simulation, e.g., [26–28] and others. Compared to the EL method, the EE method is fairly efficient for calculation of flows with higher droplet concentration, whilst the EL method show feasible solution for calculation of the diluted spray region. Driven by those facts, the EL and EE methods can be used in combination to overcome disadvantages inherent for both methods and to improve the accuracy of spray modelling. In this work, the coupling concept was presented where the previously validated EE method [29] was used together with the EL DDM method. This concept was applied for coupled simulation of the real IC engine, which is particularly challenging. The spray process is calculated by employing the EE method in a fine, non-moving, mesh that covers only a small part of the engine domain. The EE simulation is coupled with the EL engine simulation performed on the coarser mesh.

Coupling of the EE spray simulation with EL DDM engine simulation was performed using the AVL FIRE® Code Coupling Interface (ACCI) [30]. Coupling of two simulations means that the calculated results of both simulations are used either as boundary condition values or source/sink terms for the other simulation. The results from the engine calculation are used as boundary condition for the Eulerian spray simulation. In order to synchronise the flow field the source terms (mass, momentum and energy) between the liquid and the gas phase, calculated on the spray client, are transferred to the gas phase within the engine calculation.

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