Coupling of 3D Eulerian and Lagrangian Spray Approaches in Industrial Combustion Engine Simulations

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Abstract: The Lagrangian DDM (discrete droplet model) is state-of-the-art for CFD (computational fluid dynamics) simulations of mixture formation and combustion in industrial engines. A commonly known drawback of the DDM approach is the attenuated validity in the dense spray, where the bulk liquid disintegrates into droplets. There the assumption of single droplets surrounded by a homogenous gas field is not reasonable. In this region, the Eulerian-Eulerian multi-phase approach performs better because instead of parcels the spray is represented by the volume fractions of one bulk liquid and several droplet size class phases. A further drawback of the DDM approach is that increasing the spatial resolution of the computational grid leads to a reduced statistical convergence, since the number of spray parcels per computational cell becomes smaller. It is desirable to combine the benefits of both spray approaches in coupled CFD simulations. Therefore, the dense spray region is simulated separately with the Eulerian spray approach on a highly resolved mesh covering only the region close to the nozzle orifice. The entire engine domain with combustion and emission models is simulated with the Eulerian-Lagrangian spray approach for the dilute spray region. The two simulations are coupled through exchange of boundary conditions and model source terms. An on-line coupling interface manages the data transfer between the two simulation clients, i.e., Eulerian spray and engine client. The aim of this work is to extend the coupled spray approach in terms of exchanging combustion related heat and species sources, and consequently creating the link between Eulerian spray and combustion models. The results show mixture formation and combustion in real-case engine simulations, and demonstrate the feasibility of spray model combination in engineering applications.

Key words: CFD, code coupling, combustion, Eulerian spray, Lagrangian spray, multi-fluid approach.

Nomenclature

c_p	Specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
D	Diameter (m)
h	Specific enthalpy ($\text{J}\cdot\text{kg}^{-1}$)
H	Enthalpy (J)
i	Time step counter (-)
m	Mass (kg)
n	Droplet counter (-)
N	Number of droplets (-)
N'	Droplet number density (m^{-3})
P	Momentum ($\text{N}\cdot\text{s}$)
s	Surface area (m^2)
t	Time (s)

T	Temperature (K)
u	Velocity ($\text{m}\cdot\text{s}^{-1}$)
μ	Volume fraction (-)
ρ	Density ($\text{kg}\cdot\text{m}^{-3}$)

Subscripts

ac	Accumulated
b	Boundary face
d	Disperse
par	Parcel
ref	Reference

1. Introduction

Reliable modelling of the mixture formation plays the key role for predictive simulation of combustion and emission in IC (internal combustion) engines.

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Therefore, the Eulerian-Lagrangian DDM (discrete droplet model) approach, described by Dukowicz [1] and others, has been applied for many years. A well known drawback of the DDM approach is the limited statistical convergence in the dense spray region meaning that the high spatial resolution of the computational grid required in this region leads to a reduced number of stochastic samples in every mesh cell. Furthermore, the DDM approach is based on the assumption of single (spherical) droplets surrounded by a homogenous gas field. In the dense spray where the transition from bulk liquid to individual droplets takes place, this assumption is not valid. Thus, for this region, an Eulerian spray model is the appropriate approach. Eulerian spray models are based on the Eulerian-Eulerian multi-phase approach obtained through the ensemble averaging process of the conservation equations, as summarized by Drew and Passman [2]. The first models for spray simulation within the Eulerian-Eulerian framework were proposed by Gosman et al. [3], Issa and Olivera [4], Lopez de Bertodano [5] and others. These models use two inter-penetrating phases and model the phase interactions between the continuous gas and dispersed liquid phase. The model of von Berg et al. [6] represents the droplet size PDF (probability density function) by discretization into several size classes assigned to independent phases for which the complete set of conservation equations are solved. Secondary break-up and droplet collisions determine the phase interactions between the liquid phases. This model was later extended by a primary break-up model, as described in Ref. [7], and determines the base of the Eulerian spray model applied in this work. Other Eulerian spray models apply different kinds of the MOM (method of moments), such as the DQMOM (direct quadrature method of moments), as described by Marchisio and Fox [8]. However, the main problem of all of the Eulerian spray models mentioned above is that for an adequate representation of the droplet size PDF in the dilute spray region a high number of size

classes and consequently a high number of transport equations for the moments and the balance equations are necessary. This leads to high computational effort in the CFD (computational fluid dynamics) simulations. Thus, for the dilute spray region, the DDM approach has a significant benefit, as the computational effort for additional spray parcels increasing the number of nodes in the droplet size PDF, is significantly smaller than that for additional droplet size classes in the Eulerian-Eulerian framework. Therefore, the combination of both approaches, the Eulerian and the Lagrangian spray, is reasonable. The ELSA (Euler-Lagrange spray atomisation) model first proposed by Vallet and Borghi [9] and later extended by Blokkeel [10] and Lebas [11] determines an efficient and practical approach for combining the benefits of the Eulerian and Lagrangian spray approaches in IC engine simulations. There, the dense region of the spray is treated as a single-phase flow composed of a liquid-gas mixture. To model the spray atomisation additional transport equations for the liquid mass fraction and the liquid surface density are solved. If the spray is dilute enough, Lagrangian spray parcels are initiated. However, segregation into droplet size classes is not performed.

The methodology applied in this work to combine the benefits of Eulerian and Lagrangian spray approaches is different. The dense spray is calculated with the Eulerian spray approach in a separate simulation client on a highly resolved computational grid. The Eulerian spray simulation is performed as multi-phase simulation with one gaseous phase, one bulk liquid phase, and several phases for the droplet classes representing the droplet size PDF. The engine client determines the second simulation client which applies the Lagrangian spray model in the dilute spray region. The computational grid of the engine client covers the entire simulation domain, including also the Eulerian spray region. This means that there is an overlapping region which is simulated on both clients. The interactions between the gaseous and the liquid

phases in the Eulerian spray simulation are transferred as source terms to the engine client simulation. The data transfer between the simulation clients is managed via the ACCI (AVL code coupling interface). This methodology of coupling sprays was applied first by Krueger [12] for a 1D Eulerian spray model, and extended for 3D simulations by Edelbauer et al. [13]. The benefit of this coupled methodology is that the computationally intensive Eulerian spray simulation is performed only in a limited region, but this region has a highly resolved and spray aligned computational mesh. The Eulerian spray as well as the engine simulation and the code coupling tool are performed with the commercial CFD code FIRE[®], further described in Ref. [14].

The paper is organized as follows: the following section discusses the spray and combustion models applied in the simulations; the next section deals with the code coupling procedure, and the interface between Eulerian and Lagrangian sprays is discussed in detail; the last section describes the numerical simulation set-up and discusses the simulation results.

2. Physical Models

Eulerian spray model:

In this model the different phases, gas and liquid, are represented as interpenetrating continua represented by their phase volume fractions. The liquid is divided into different droplet size classes; each represented by a separate droplet phase. Details about the Eulerian spray approach can be found in the publications of von Berg et al. [6, 7, 15] and Vujanovic et al. [16]. Table 1 shows the phase specification of the model. The first phase is always the gaseous phase determined as composition of the gas species required for evaporation and combustion. The gas species are transported by separate transport equations. Phases 2 to $n-1$ are liquid droplet phases sorted by ascending class diameters. For

Table 1 The phase specification of the Eulerian spray model.

Phase k	1	2, $n-1$	n
Content	Gas mixture	Droplets	Bulk liquid

every phase the droplet diameter is calculated from the transported moment's droplet number density and volume fraction. Phase n is the bulk liquid phase from the nozzle, which disintegrates into the droplet phases. The applied primary break-up model is based on the work of Bianchi et al. [17] considering two independent mechanisms, aerodynamic surface wave growth and internal stresses by injector flow turbulence. The secondary break-up causes mass transfer within the droplet phases 2 to $n-1$, and is modelled with the standard WAVE model formulated by Reitz [18]. The model of Abramzon and Sirignano [19] determines the evaporation model.

The Eulerian spray model applied in FIRE[®] has been intensively validated, as discussed in Refs. [15, 20]. Fig. 1 shows the comparison of measured and simulated penetration curves of the liquid and vapour spray tips. The rail pressure was 120 MPa, chamber pressure was 7.2 MPa, chamber temperature was 900 K, and the chamber gas was nitrogen. The corresponding experiments have been performed by Koenig [21] in the frame of the funded European I-LEVEL project. Although the vapour tip penetration is slightly underestimated, the comparison shows a good agreement between simulation and measurement demonstrating the reliability of the spray model.

Lagrangian spray model:

The Lagrangian DDM method solves the equation of motion for the spray parcels, which consists of a certain number of droplet or particles of similar properties. The motion of the parcels is determined by the forces acting on it, as there are drag, pressure, body and turbulent dispersion forces.

Fig. 1 Comparison of the calculated and measured liquid and vapour penetration.

The break-up and evaporation models are the same as for the Eulerian spray model. Model details can be found in Ref. [22].

Combustion model:

The ECFM-3Z (3-Zones Extended Coherent Flame Model) model developed by Colin and Benkenida [23] is the combustion model used in the coupled simulations. The implementation of the model into FIRE[®] and a comprehensive validation study is described by Priesching et al. [24]. The main advantage of the ECFM-3Z model is that it is a universal model applicable for gasoline as well as conventional and alternative diesel combustion modes, such as HCCI (homogeneous charge compression ignition). It takes into account the main regimes relevant in diesel combustion, namely premixed flame, auto-ignition and non-premixed, i.e., diffusion combustion. Therefore, the model distinguishes between three mixing zones as there are: unmixed fuel, mixed air and fuel, unmixed air and residual gases. Owing to the flame propagation every zone is further split into burned and unburned fractions. The premixed flame combustion takes place within the mixed air and fuel zone in the time between start-of-injection and auto-ignition onset. The ignition delay time is obtained from stored look-up tables depending on the local conditions of temperature, pressure, fuel/air equivalence ratio and amount of residual gas. Once the ignition criteria are fulfilled, the auto-ignition event is triggered and the premixed fuel is consumed. Diffusive combustion, where the reaction takes place in a thin zone which separates fuel and oxidizer, follows. It is assumed that the chemical time

in the reaction zone is much smaller than the time needed for the diffusion process.

3. Coupling of Spray Approaches

This section discusses the concept and the interfaces of the coupled simulations. A short summary about the main idea and the code coupling interface is given here, as details and first application examples have been already published in Ref. [13]. The ACCI server is further described in Ref. [26]. The interface managing the transition from Eulerian to Lagrangian spray is explicitly described.

Fig. 2 shows the concept of coupling Eulerian and Lagrangian spray approaches in engine simulations with combustion. The Eulerian spray and the engine simulations are clients of the ACCI server managing the exchange events, the spatial mapping, the complete data transfer and the time integration. For detailed investigation of mixture formation and combustion, a separate injector flow simulation taking into account the complete needle movement and cavitation effects, as demonstrated by Čaika et al. [25] can be performed. For certain discrete time steps, the flow data of the bulk liquid and the vapour phases at the nozzle orifice are stored on a data file providing the boundary conditions for the Eulerian spray simulation. For less detailed investigations, the injections rate simply determines the spray inlet boundary of the Eulerian spray client.

The coupled simulation starts with the computational initialization of both simulation clients which are registered at the ACCI server. The fluid properties are determined and the flow field of the engine

Fig. 2 The concept of coupling 3D-Eulerian spray model and 3D engine calculation.

client is initialized. Then the first exchange event takes place, since the initial gas flow field of the Eulerian spray client has to be fully determined by the initial flow field of the engine client. Therefore, the three velocity components, pressure, enthalpy, species mass fractions and turbulence transport quantities are mapped and transferred via the ACCI server. This exchange event takes place only once per simulation, at initialization. The other exchange events are determined by the simulation time steps of the clients. Since in general, the time steps of the Eulerian spray client are smaller than that of the engine client, the exchange events are triggered by the engine time steps.

Further data exchange from the engine to the Eulerian spray client is performed to obtain the flow field boundaries of the Eulerian spray simulation. Therefore, at every exchange event the 3D flow field of the engine client is mapped onto the 2D boundary faces of the Eulerian spray client. Data exchange in the other direction is required due to the interactions between droplets and gas described by exchange terms, the sources. For example, drag forces cause source terms in the momentum conservation equation, mass exchange from evaporation causes sources in the continuity and species transport equations. In the overlapping domain, the gas phase flow field is calculated on both simulation clients. Thus, the source (sink) terms from the phase interactions in momentum, mass and energy conservation equations as well as the sources from the species transport equations are transferred from the Eulerian spray to the engine client. This means that, although there is no liquid phase in the overlapping domain of the engine client, the gas phase is fully encountered by the interactions with the droplet phases. The data exchange due to the combustion model is contrariwise. Only the engine client calculates combustion and emission, the Eulerian spray client receives the sources. The ECFM-3Z model solves transport equations for the burned and unburned fuel species, and for the additional eleven gas species,

namely O_2 , N_2 , CO_2 , H_2O , CO , H_2 , O , N , OH , H and NO . The sources from all species and the chemical energy released during combustion as heat source are transferred from the engine to the Eulerian spray client. This methodology is not limited to the ECFM-3Z model. For other combustion models, the sources of the energy conservation equation and the required species are exchanged in a similar manner. The exchange of the combustion sources is very important, since without this exchange the Eulerian spray client would not recognize the rise of gas temperature caused by combustion. This exchange determines a significant improvement compared to the status of coupled spray-engine simulations presented by Suzzi et al. [27], where the back-coupling of the combustion sources was neglected.

Since the Eulerian spray approach is applied in the dense spray only, special attention has to be paid to the interface to the Lagrangian spray approach. The liquid droplets leaving the Eulerian spray client initiate the spray parcels at the engine client. Fig. 3 shows two different views of the transition from the Eulerian spray to the engine client. Conservation of liquid mass, momentum, energy and number of droplets are required criteria for the interface.

The algorithm for creating new parcels by fulfilling the conservation criteria is described here. The basic idea is that a new parcel is created, if the accumulated liquid mass of a droplet phase exceeds a certain mass threshold called m_{par} . In the current implementation, the preparation of new spray parcels is fully calculated by the Eulerian spray client. Via the ACCI server, the parcel initialization data is sent to the engine client where the new parcels are introduced. A loop over all droplet phases and over all open boundary faces is performed for every time step to check the droplet mass leaving the domain. The mass flow rate $dm_{d,i}/dt$ of the liquid mass through a boundary face at time step i is defined by the phase velocity vector $u_{d,i}$, the face area vector s_b , the density $\rho_{d,i}$ and the phase volume fraction $\alpha_{d,i}$ as defined by the equation:

Fig. 3 Transition of the liquid phase from Eulerian spray to Lagrangian spray approach.

$$\dot{m}_{d,i} = \vec{u}_{d,i} \cdot \vec{s}_b \cdot \rho_{d,i} \cdot \alpha_{d,i} \quad (1)$$

The number of droplets leaving the boundary phase per time $dN_{d,i}/dt$ is obtained from the mass flow rate, the droplet density and the droplet volume determined by the droplet class diameter $D_{d,i}$ as shown by the equation:

$$\dot{m}_{d,i} = \dot{N}_{d,i} \cdot \rho_{d,i} \cdot \frac{D_{d,i}^3 \cdot \pi}{6} \rightarrow \dot{N}_{d,i} = \frac{6 \cdot \dot{m}_{d,i}}{D_{d,i}^3 \cdot \rho_{d,i} \cdot \pi} \quad (2)$$

Accumulation over the simulation time steps has to be performed to determine the total mass which had left the Eulerian spray client through the boundary face, as described by:

$$m_{d,ac} = \sum_i^{n_{ac}} \dot{m}_{d,i} \cdot \Delta t_i \quad (3)$$

where, n_{ac} is the accumulated number of time steps Δt_i of the Eulerian spray client. Similar integrations are performed to obtain the accumulated number of droplets $N_{d,ac}$, momentum $P_{d,ac}$ and enthalpy $H_{d,ac}$ leaving the boundary face, as shown by the equations:

$$\begin{aligned} N_{d,ac} &= \sum_i^{n_{ac}} \dot{N}_{d,i} \cdot \Delta t_i \\ \vec{P}_{d,ac} &= \sum_i^{n_{ac}} \dot{m}_{d,i} \cdot \vec{u}_{d,i} \cdot \Delta t_i \\ H_{d,ac} &= \sum_i^{n_{ac}} \dot{m}_{d,i} \cdot (h_{d,i} - h_{d,ref}) \cdot \Delta t_i \end{aligned} \quad (4)$$

Every time step is checked, if the accumulated mass exceeds the minimum mass value m_{par} for creating a

new parcel. m_{par} is a simulation parameter which influences the total number of parcels in the simulation. The smaller the m_{par} the higher the number of parcels created and the better the statistical convergence but the higher the computational effort. If m_{par} exceeds $m_{d,ac}$, a new parcel is created and n_{ac} is reset, otherwise n_{ac} is incremented by one, as shown by:

$$m_{d,ac} \geq m_{par} = \begin{cases} \text{yes: } \text{new parcel } n_{ac} = 0 \\ \text{no: } n_{ac} = n_{ac} + 1 \end{cases} \quad (5)$$

The mass and the number of droplets of the new parcel are simply the accumulated droplet mass and number of droplets, as described by the equations:

$$\begin{aligned} m_{d,par} &= m_{d,ac} \\ N_{d,par} &= N_{d,ac} \end{aligned} \quad (6)$$

The density of the new parcel is set to the value of the droplet phase density at the time step for creating a new parcel, as shown by the equation:

$$\rho_{d,par} = \rho_{d,i=n_{ac}} \quad (7)$$

To conserve the droplet mass the droplet diameter assigned to the new parcel has to be calculated from the set parcel mass, the density and the number density, as described by the equation:

$$D_{d,par} = \left(\frac{6 \cdot m_{d,ac}}{N_{d,ac} \cdot \rho_{d,par} \cdot \pi} \right)^{\frac{1}{3}} \quad (8)$$

The parcel velocity and temperature are obtained from accumulated droplet momentum and enthalpy as described by the equations:

$$\vec{u}_{d,par} = \frac{\vec{P}_{d,ac}}{m_{d,ac}}$$

$$T_{d,par} = T_{d,ref} + \frac{1}{c_{p,d,i=n_{ac}}} \cdot \left(\frac{H_{d,ac}}{m_{d,ac}} - \frac{\vec{u}_{d,par} \cdot \vec{u}_{d,par}}{2} \right) \quad (9)$$

4. Results and Discussion

This section discusses the simulation set-up and the results of the coupled spray calculation. The chosen test cases demonstrate the feasibility of the methodology in typical industrial engine simulations. Two coupled simulations were performed, one without and one with engine swirl. For the latter case the cylinder axis is the swirl axis and the swirl number at initialization is 2.9. Fig. 4a shows the computational meshes of the two simulation clients. The engine client has moving diesel bowl geometry with a sector angle of 60°, since a six-hole injector with a nozzle orifice diameter of 137 µm is applied. The injected fuel mass is 8.5 mg per sector. On the side surfaces of the sector, periodic boundary conditions are applied. The engine stroke is 89.4 mm and the bore diameter is 81.4 mm. The spray client uses a structured and cone shaped computational mesh. The axis of the cone is in line with the spray axis and a cone length of 10 mm was chosen for the Eulerian spray domain. This length is open for discussion and the subject of further investigations, since the aim of the coupled simulation is to apply Eulerian spray in the dense spray only. It can be expected that the optimum length stays between 3 mm and 10 mm. The nozzle orifice is resolved by 15 cells

in diameter and 132 cells in total. This means that in the direction perpendicular to the spray axis, the mesh cells at the orifice have side lengths of approximately 10 µm. In the axial direction, the side lengths of the cells are longer, since higher cell aspect ratios are reasonable for spray axis aligned grids.

The engine speed is 4,200 rpm, SOI (start of injection) is at 703.4 °CA and EOI (end of injection) is at 738.2 °CA leading to an injection period of 1.38 ms. The diesel fuel is represented by the species C₁₃H₂₃. The injection rate curve is shown in Fig. 4b. The peaks of the orifice mean velocity reaches more than 600 m/s. The fuel temperature at the orifice is 373 K. The gas phase in both clients is represented by the fuel species and eleven additional species required for the ECFM-3Z combustion model. The Eulerian spray client uses six phases, where phases 2 to 5 are the droplet size class phases and phase 6 is the bulk liquid phase. The initial diameters of the liquid phases are 5, 10, 20, 40 and 137 µm. Primary break-up takes place at the Eulerian spray client only and leads to a mass transfer from the bulk liquid phase 6 to the droplet phases 2 to 5. Secondary break-up and evaporation models are active on both simulation clients. The standard WAVE model is applied for secondary break-up causing a mass transfer within the droplet phases. The evaporation model of Abramzon and Sirignano [19] calculates the mass transfer between liquid phases and the gaseous phase. The minimum mass for creating a new spray parcels m_{par} is set to 2.5×10^{-11} kg. The engine client starts the simulation at 630 °CA

Fig. 4 (a) Computational meshes of the Eulerian spray and the engine client, and (b) injection velocity.

with an initial pressure of 0.45 MPa and an initial temperature of 430 K. At SOI at 703.4 °CA the coupled simulation starts, and it is performed until the end of the simulation at 780 °CA. The maximum crank angle step of the Eulerian spray client is 0.0125 °CA which corresponds to a time step of approximately 0.5 μ s. During the injection period the crank angle step of the engine client is 0.025 °CA which is a multiple of the Eulerian spray time step and determines the time step for data exchange via the ACCI server. This means that at every second Eulerian spray time step the boundary conditions and the combustion sources are transferred from the engine client to the Eulerian spray client, and the spray sources are transferred from the Eulerian spray to the engine client. The time integration of the spray sources is performed by the ACCI server. On the lateral surface of the spray cone, a velocity boundary is applied and on the end face of the cone a static pressure boundary is applied. During the coupled simulation, these boundary conditions are determined by the 3D flow field of the engine client which is mapped and transferred via the ACCI server.

The following figures show representative results of the coupled simulations with and without engine swirl. Fig. 5a shows the velocity vector fields of both simulation clients viewed from the top. The swirl motion causes the counter-clockwise motion of the gas around the cylinder axis. One can observe that the gas motion is well proceeded across the boundary interface of the simulation clients. Fig. 5b shows the evolution of the spray in side and top views at different time steps after SOI. The plots show ISO-lines of the total liquid volume fraction defined as the sum of the volume fraction values over all liquid phases. The outermost iso-line indicates a total volume fraction of 10^{-3} and determines the spray contour. At approximately 712 °CA, auto-ignition takes place and the non-premixed combustion starts. This leads to a significant increase of the gas temperature and accelerates the evaporation. Thus, the angle of the liquid spray contour and the spray tip penetration at 715 °CA and 720 °CA are considerably smaller. From that time, only few spray parcels are initialized at the engine client. The swirl motion leads to a slight deflection

Fig. 5 (a) Gas velocity field in overlapping plots at 707.5 °CA and (b) evolution of the spray in side and top views between 704.5 °CA and 720 °CA in the coupled simulation with engine swirl.

of the spray which is clearly visible in the top views of Fig. 5b.

Fig. 6 shows the phase droplet diameters of the Eulerian spray client in side and top views, but in the simulation without engine swirl. By assuming spherical droplets the phase droplet diameter is simply obtained from the transported moments of phase volume fraction α_d and droplet number density N' by using the equation $d_d = (6 \cdot \alpha_d / \pi / N')^{1/3}$. The cuts on the left-hand side show the phase diameters at 710 °CA before ignition was triggered, and the cuts on the right-hand side show the diameters at 720 °CA during combustion. The diameters are plot for cells where the phase volume fraction exceeds 10^{-5} . Thus, the diameter fields of the bulk liquid phase 6 are quite small, since a few millimetres away from the nozzle orifice the phase mass is fully disintegrated due to primary break-up. To have a better illustration, the scales of the colour-bars are flexible for every phase and every crank angle step. Owing to break-up and evaporation there is a continuous decrease of the droplet diameter in every phase. It is remarkable that the maximum values of the phase droplet diameters, visible at the colour-bars, are

higher than the initial values of 5, 10, 20, 40 and 137 μm . The reason for this is the thermal expansion, meaning that in certain regions the diameter increase owing to thermal expansion is faster than the diameter decrease from evaporation. The temperature increase during combustion amplifies this effect.

The gas temperature fields of the engine and spray clients in the coupled simulations without engine swirl before and during combustion are shown in Fig. 7. In the overlapping domain, the gas flow field is calculated on both clients, and one can observe a good agreement of the gas temperature. Before ignition at 710 °CA, only cooling is visible, since the energy required for evaporation is provided by the gaseous phase. Heat sources (sinks) from evaporation are transferred from the Eulerian spray to the engine client causing the cooling effect. Since the Eulerian spray client has the finer computational mesh, this effect is resolved there in more detail. The ignition and combustion models are calculated at the engine client only. Later at 720 °CA combustion has been started, and heat and species sources are transferred from the engine to the Eulerian spray client. This leads to the temperature increase of

Fig. 6 Droplet phase diameters in side and top views at 710 °CA (left) and 720 °CA (right) in the simulation without engine swirl.

Fig. 7 Gas temperatures in spray and engine clients in side (left) and top views (right) before ignition at 710 °CA (top) and during combustion at 720 °CA (bottom) in the simulation without engine swirl.

the gaseous phase in the periphery of the spray. Consequently, the evaporation is faster and the spray angle becomes smaller. Without exchange of the combustion sources, the Eulerian spray simulation would not resolve this effect.

5. Conclusions

The presented methodology offers a promising simulation tool for detailed mixture formation and combustion. Eulerian spray and DDM approaches are applied in the regions where they are beneficial: Eulerian spray in the dense and DDM in the dilute spray region. This study shows the feasibility of the methodology in industrial applications. The spray approaches are applied in separate CFD simulations, the Eulerian spray and the engine simulation. They are coupled through boundary conditions and source term

exchange. A code coupling interface manages the data transfer between the simulation clients. Special attention has to be paid to the transition between Eulerian and Lagrangian spray formulation. The presented interface guarantees conservation of droplet mass, droplet number, momentum and enthalpy. Furthermore, the transfer of the combustion related heat and species sources from the engine to the Eulerian spray client determines a significant improvement compared to the status of the coupled simulations achieved in Refs. [13, 27]. The next steps will include detailed comparisons with standalone DDM simulations, mesh variations to determine the optimum length of the Eulerian spray cone, development of an interface taking into account spray parcels re-entering the Eulerian spray region, and coupling with injector flow.

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