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Numerical simulation of non-reacting diesel fuel sprays under low temperature late injection operating condition

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Abstract

Accurate simulations on combustion and emission characteristics of direct injection diesel engines are highly dependent on detailed prediction of equivalence ratio distribution inside the combustion chamber. In this study, Open-FOAM and Lib-ICE multi-dimensional CFD frameworks were used in order to model engine flow, liquid diesel fuel spray, break-up, evaporation and mixing. Simulations were conducted on the basis of experimental data from SANDIA optical engine. Initial simulation results showed tangible discrepancy with the experimental equivalence ratio data in distribution of fuel-rich zones. Investigations on three different injection angles in three different combustion chamber bowl geometries showed that cavitation phenomenon was most probably occurred in injector nozzle during the experiments. Onset of cavitation in injector nozzle internal flow can noticeably change the spray break-up length and cause asymmetric spray angle later inside the combustion chamber. Taking cavitation effects into account, simulations were performed by corrected values of spray break-up length and injection angle based on experimental injection pressure and nozzle orifice dimensions. Final spray simulations showed better agreement with experimental results for all of three bowl geometries. This enhanced accuracy of numerical prediction without unacceptable tuning of spray sub-model parameters.

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Keywords: Low temperature; diesel fuel spray; OpenFOAM; cavitation

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Nomenclature

ATDC	After Top Dead Center	NO_x	Nitrogen Oxides
BDC	Bottom Dead Center	PCCI	Premixed Charge Compression Ignition
CAD	Crank Angle Degree	PM	Particulate Matter
CFD	Computational Fluid Dynamics	PPCI	Partially Premixed Compression Ignition
DI	Direct Injection	SOI	Start of Injection
DOI	Duration of Injection	PRF	Primary Reference Fuel
HCCI	Homogeneous Charge Compression Ignition	UHC	Un-burnt Hydro Carbons

1. Introduction

Recent optimizations on diesel engines were mainly focused on further reducing PM, NOx, and UHC emissions. Although for more than two decades limiting regulations of these pollutant emissions in 2013 were reduced down to respectively 2%, 3-12%, and 6-12% of their levels in 1990, further reductions would be inevitable mainly for light-duty diesel engines [1]. Low-temperature combustion (LTC) has been on the focal point of diesel engine investigations mainly due to its potential to simultaneously reduce PM and NOx emissions [2]. There has been proposed numerous LTC strategies such as HCCI, PPCI, PCCI, and so forth [1]. PCCI combustion for instance, was achieved by suppressing combustion temperatures and premixing fuel with the in-cylinder charge before the ignition. The main requirement of this combustion mode was injection and mixing of the fuel early in the compression stroke [3]. Late injection combustion, as an alternative combustion mode, was favorable where combustion was more closely coupled to the injection event offering more direct control over combustion phasing compared to the PCCI mode. Nonetheless, if injected fuel in the late injection combustion mode was not mix rapidly, fuel rich regions would be created leading to higher levels of soot emission. Genzale et al [4] investigated The impact of spray targeting on the mixture evolution and combustion of a late-injection heavy-duty diesel engine under low temperature combustion operating conditions. Laser sheets were used to illuminate thin layers in the combustion chamber and optical access was provided to SANDIA diesel engine. Unique jet–wall and jet–jet interactions were resulted by applying three different injector nozzles angles. They concluded that weaker jet–wall and jet–jet interactions were achieved with a wide injection angle which may cause bulk flows to stagnate and hinder late-cycle mixing processes. By contrast, in narrow-angle injection the jet momentum was redirected up along the bowl-wall suppressing the formation of rich regions due to jet–jet interaction. This reduced soot formation and enhanced bulk-flow mixing late in the combustion cycle. Diesel engine multi-dimensional simulations of low temperature late injection combustion was conducted also by Genzale et al [5] on SANIDA optical engine. Numerical results show that the spray-targeting strategy can significantly alter the jet interactions with the jet-bowl and with neighboring jets, influencing the entire combustion. In the present work extensive numerical simulations were conducted based on experiments of Genzale et al [2]. Initial simulation results showed notable discrepancy with the experiments. Taking effects of cavitation into account more acceptable results in case of equivalence ratio distributions within the combustion chamber were resulted.

2. Experimental setup, combustion chamber meshes and initial conditions

A single-cylinder optically-accessible heavy-duty DI engine was used to perform the experiments by Genzale et al [2, 4]. Specifications of the SANDIA engine were summarized in table 1. Three piston designs were considered in the experiments with piston bowl diameters of 60%, 70% and 80% of the cylinder bore where for each bowl design, the injector spray angle was selected so that the nominal spray axis intersected the vertical midpoint of the bowl wall with the piston at TDC. For the 60%, 70%, and 80% piston bowls, the spray included angles were 140°, 152°, and 160°, respectively. Experiments were conducted for reacting and non-reacting conditions where non-reacting conditions were achieved by using pure N_2 in the intake charge. PRF29 was used in the experiments and addition of 1% of toluene by volume provided a tracer for the direct measurement of fuel concentration. Laser sheets were used to capture images of the tracer enabling equivalence ratio measurements during the non-reacting experiments. Three different horizontal laser sheets were considered as it is depicted in figure 1 and experiments of different bowl geometries were performed for the initial conditions of table 2. Computational mesh generation was carried out for