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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 three bowl geometries in this study. Spray oriented meshes were generated, figure 2, and used in the spray simulations of this study.

Table 1- SANDIA optical engine specifications taken from [2]

Engine base type	Cummins N-14. DI diesel
Number of cylinders	1
Combustion chamber	Quiescent, DI
Swirl ratio	0.5
Bore × Stroke	13.97 × 15.24 [cm]
Bowl width × depth	9.78 × 1.55 [cm]
Displacement	2.34 [lit]
Connecting rod length	30.48 [cm]
Geometric compression ratio	11.2:1
Fuel injector, No. of holes	Common-rail, 8
Spray pattern included angle	152˚
Injection pressure	1200/1600 [bar]
Nozzle orifice diameter	0.196 [mm]
Nozzle orifice L/D	5

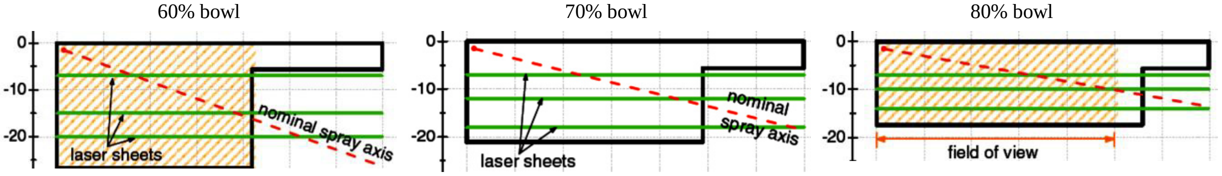
60% bowl
70% bowl
80% bowl

Figure 1- Laser sheet locations in three piston bowl geometries and injection angles in experiments of Genzale et al [2]

Table 2- Low temperature late injection case specifications [2]

Engine speed [rpm]	1200
Indicated mean effective pressure [bar]	4.1
Injection pressure [bar]	1600
Intake temperature [K]	343
BDC temperature [K]	351
Intake pressure [bar]	2.02
TDC motored temperature [K]	840
TDC motored density [kg/m^3]	22.5
SOI [˚ATDC]	0
DOI [CAD]	7
Injection quantity [mg/cycle]	56

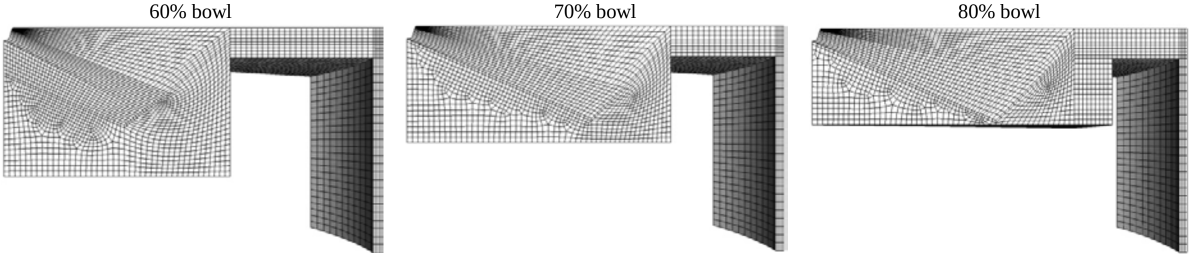
60% bowl
70% bowl
80% bowl

Figure 2- Spray oriented meshes generated for three bowl geometries of this study

3. Simulation tool

OpenFOAM® [6] open-source code and Lib-ICE [7] were used as multi-dimensional CFD simulation framework. Lagrangian droplet and Eulerian Flow approach was used in the spray simulations where for detailed descriptions of Eulerian and Lagrangian governing equations, their coupling, discretizations, and solution approaches the reader was referred to [8, 9]. Blob injector model was used in spray simulations and spray primary and secondary break-ups were modeled by hybrid KH-RT model with standard model coefficients [6].

4. Results and discussion

Simulation results was first conducted for engine base bowl geometry [2] of 70% and compared with experimental results in figure 3 for three laser sheets, 7mm, 12 mm, and 18 mm at 7 CAD ATDC. However, it can be seen that simulation results in case of location of the rich equivalence ratio regions and magnitude have considerable discrepancy with the experiments. As PRF29 is used in the experiments and injector had sharped edge configuration, it was possible that cavitation occurred during the injection process. Number of researches has been shown that cavitation can deviate spray shape and highly affect its break-up length and mixing with air [10, 11]. It has been also emphasized that occurrence of cavitation is highly depended on fuel local vapor pressure [12]. Figure 4 is a comparison of vapor pressure of components of PRF29 and heavier diesel fuels. It can be seen that under engine temperature operating conditions of the injector, there is a high possibility for cavitation in toluene, nHeptane, and iso-octane fuels to take place. Cavitation can then increase break-up length and change the fuel spray angle [13].

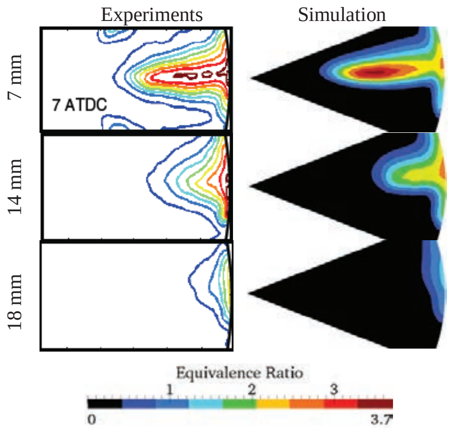

Figure 3- Comparison of equivalence ratio simulation results with experiments of 70% piston bowl geometry

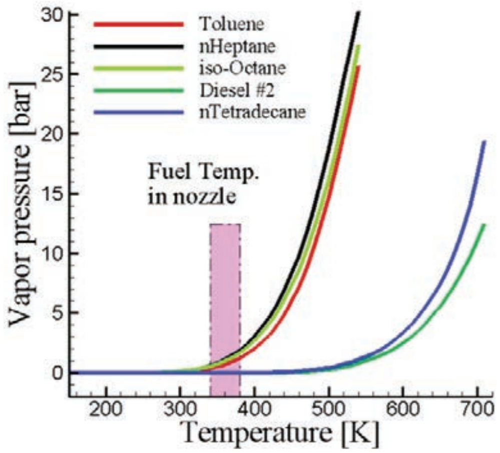

Figure 4- Vapor pressure versus temperature for PRF components and heavier surrogates of diesel fuel

Taking into account the cavitation phenomenon simulations were again conducted on 70% piston bowl geometry together with 60% and 80% bowls. It should be noted that injector nozzle internal flow simulations were not carried out and in order to represent cavitation phenomenon, experiments of Gannipa et al and Jia et al [13, 14] were used to correct break-up length constant and injection axis direction. Break-up length coefficient and spray axis directions of three piston bowl geometries were amended by evaluating the *Re* number based on injection pressure, injector nozzle dimensions, velocity profile and fuel density at the nozzle exit. Based on calculated maximum *Re* number and experimental results, break-up length coefficient in KH-RT model was almost doubled and injection angle due to cylinder fire deck was lowered. Results of simulations with corrected break-up length coefficient and injection axis directions were represented and validated by the experiments as below. Figure 5 shows the comparison between simulation results of equivalence ratio with the experiments of 70% piston bowl geometry for 7, 8, and 12 CAD ATDC. It can be seen that taking the effects of cavitation into account predictions of equivalence ratio distributions show noticeable enhancement. Comparing to figure 3, more accurate magnitudes and distributions of equivalence ratio were predicted after including the effects of cavitation. In order to further validate the new spray simulation setup with included cavitation effect, numerical calculations were conducted on 60% and 80% bowl geometries. Figures 6 and 7 show that simulations were able to capture acceptable equivalence ratio distributions within the combustion chamber for 60% and 80% piston bowls at three different crank angles. Results show that magnitude of equivalence ratio was noticeably reduced after 2 CAD for the cases which made higher angle with laser sheet planes. For instance, in 60% piston bowl geometry the rich region with equivalence ratio magnitude of 3.7 in middle of sector mesh was reduced to 1.3 during 2 CAD, whereas the same trend was not observed for 70% bowl case. Moreover, simulations were also captured experimental jet-jet interactions due to applying periodic faces where in 15 mm and 20 mm laser sheets of 60% piston bowl, it is well predicted by the calculations. Simulation results show that spray targeting and bowl geometry can lead to very different results in case of spray evolution, air-fuel mixing, equivalence ratio distributions and subsequent combustion if the reacting flow experimentation and simulation were conducted.

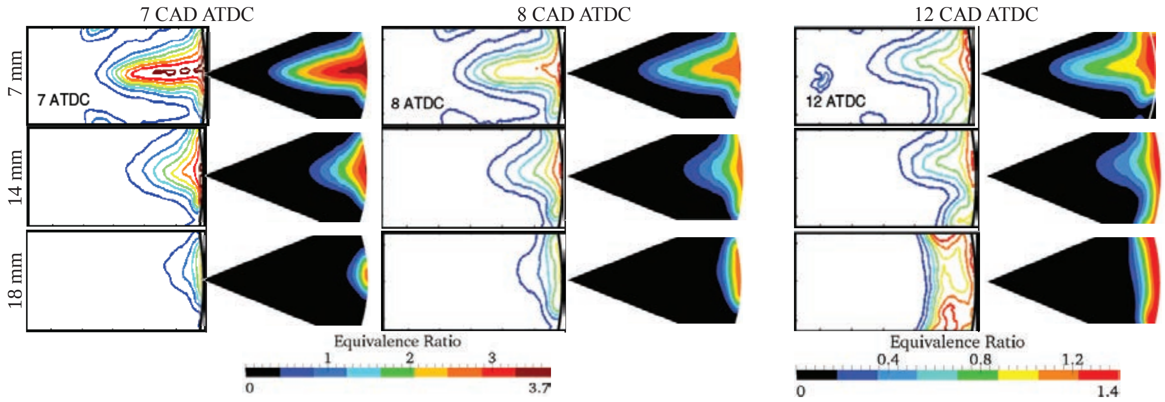

Figure 5- Comparisons of equivalence ratio distribution of three laser sheets of 70% piston bowl geometry at 7, 8, and 12 CAD ATDC

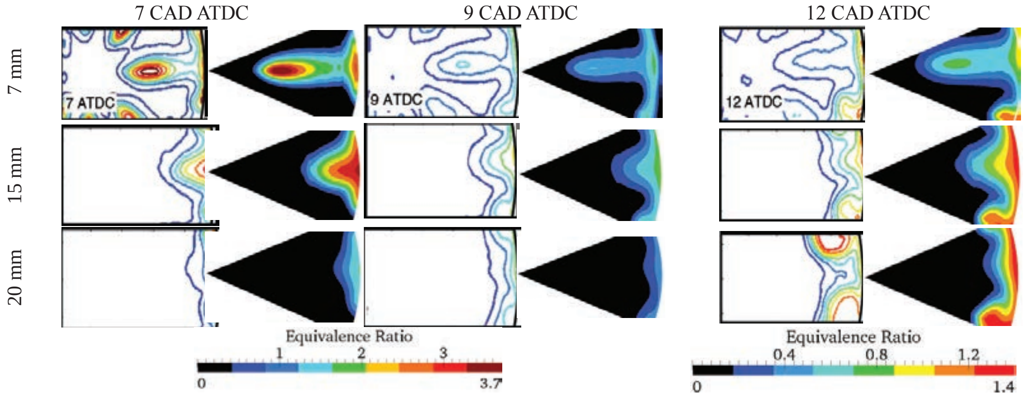

Figure 6- Comparisons of equivalence ratio distribution of three laser sheets of 60% piston bowl geometry at 7, 8, and 12 CAD ATDC

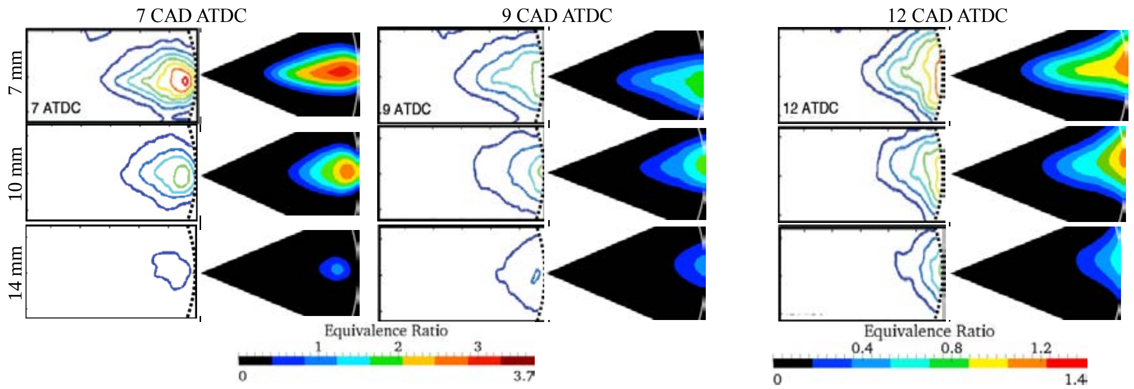

Figure 7- Comparisons of equivalence ratio distribution of three laser sheets of 70% piston bowl geometry at 7, 8, and 12 CAD ATDC

5. Conclusions

Multi-dimensional simulations were conducted on non-reacting low temperature late injection operating condition for an optically accessible DI diesel engine. Three different piston bowl geometries with specific spray targeting were considered. Initial simulation results showed noticeable disagreement with local rich equivalence ratio regions. By determining the *Re* number at the exit of the nozzle orifice simulations were then conducted by including the cavitation effect which was considered by increasing break-up length and shifting the spray axis direction towards cylinder fire deck. Numerical simulations by applying cavitation effects had more accuracy in the magnitudes and distributions of the local equivalence ratio within the combustion chamber. Results show that tangibly different air-fuel mixing and equivalence ratio distributions can be resulted in PCCI mode by applying different spray targeting techniques leading to different combustion behavior under reacting flow conditions.

6. References

[1] M.P.B. Musculus, P.C. Miles, L.M. Pickett, Conceptual models for partially premixed low-temperature diesel combustion (vol 39, pg 246, 2013), Prog Energ Combust, 41 (2014) 94-94.

[2] C.L. Genzale, Rolf D. Reitz, and Mark PB Musculus, Effects of piston bowl geometry on mixture development and late-injection low-temperature combustion in a heavy-duty diesel engine, SAE International Journal of Engines 1(1), (2009) 913-937.

[3] T. Kanda, Takazo Hakozaki, Tatsuya Uchimoto, Jyunichi Hatano, Naoto Kitayama, and Hiroshi Sono, PCCI operation with early injection of conventional diesel fuel, SAE transactions 114, no. 3, (2005) 584-593.

[4] C.L. Genzale, R.D. Reitz, M.P.B. Musculus, Effects of spray targeting on mixture development and emissions formation in late-injection low-temperature heavy-duty diesel combustion, P Combust Inst, 32 (2009) 2767-2774.

[5] C.L. Genzale, Reitz, R. D., Musculus, M. P. B. , Optical Diagnostics and Multi-Dimensional Modeling of Spray Targeting Effects in Late-Injection Low-Temperature Diesel Combustion, SAE paper 2009-01-2699, (2009).

[6] H.G. Weller, G. Tabor, H. Jasak, C. Fureby, A tensorial approach to computational continuum mechanics using object-oriented techniques, Comput Phys, 12 (1998) 620-631.

[7] G.D.E. T. Lucchini, F. Brusiani, G. M. Bianchi, A Finite-Element Based Mesh Motion Technique for Internal Combustion Engine Simulations, The Seventh International Symposium on Diagnostics and Modeling of Combustion, Sapporo, (2008).

[8] P.A. Nordin, Complex chemistry modeling of diesel spray combustion, Chalmers University of Technology, (2001).

[9] T. Lucchini, G. D'Errico, D. Ettorre, Numerical investigation of the spray-mesh-turbulence interactions for high-pressure, evaporating sprays at engine conditions, Int J Heat Fluid Fl, 32 (2011) 285-297.

[10] E. von Berg, W. Edelbauer, A. Alajbegovic, R. Tatschl, M. Volmajer, B. Kegl, L.C. Ganippa, Coupled simulations of nozzle flow, primary fuel jet breakup, and spray formation, J Eng Gas Turb Power, 127 (2005) 897-908.

[11] N. Mitroglou, M. Gavaises, J. M. Nouri, and C. Arcoumanis, Cavitation inside enlarged and real-size fully transparent injector nozzles and its effect on near nozzle spray formation, In Proceedings of the DIPSI Workshop 2011. Droplet Impact Phenomena & Spray Investigations, pp. 33-45. Dip. Ingegneria industriale. Università degli studi di Bergamo, (2011).

[12] E.V. Berg, A. Alajbegovic, D. Greif, A. Poredos, R. Tatschl, E. Winklhofer, and L. C. Ganippa., Primary break-up model for diesel jets based on locally resolved flow field in the injection hole, ILASS-Europe, Zaragoza 9 (2002): 11, (2002).

[13] L.C. Ganippa, G. Bark, S. Andersson, J. Chomiak, Cavitation: a contributory factor in the transition from symmetric to asymmetric jets in cross-flow nozzles, Exp Fluids, 36 (2004) 627-634.

[14] M. Jia, M.Z. Xie, H. Liu, W.H. Lam, T.Y. Wang, Numerical simulation of cavitation in the conical-spray nozzle for diesel premixed charge compression ignition engines, Fuel, 90 (2011) 2652-2661.