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ANALYSIS THE EFFECTS OF INJECTION STRATEGIES ON COMBUSTION CHARACTERISTICS AND POLLUTANT EMISSIONS IN A MULTIPLE DIRECT INJECTION DIESEL ENGINE

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Abstract: An advanced CFD simulation has been performed to explore different spray cone angles and multiple-fuel injection on combustion characteristics and emission formations in a DI-diesel engine. The in-cylinder pressure, temperature, heat release rate, combustion progresses and formation of emissions are simulated at different spray cone angles with AVL-FIRE code. An improved version of the ECFM-3Z combustion model has been applied and coupled with advanced Zeldovich and Kinetic models for NO and soot formation, respectively. After the validation of cylinder pressure and heat release rate experimental engine tests, further numerical simulations were performed to investigate the effects of spray cone angles. It has been determined that the cylinder peak pressure and heat release rate were slightly increased by 120° and 160° spray cone angles. The NO mass fraction is the lowest at a spray angle of 150°, while the soot mass fraction is the lowest at spray cone angles of 120° and 160°. Simulations of all configurations were subsequently performed to understand the effects of in-cylinder parameters during the combustion stroke. These results are significant enough to affect the combustion process and completely change the next generation of emissions.
Keywords: Multiple injections, Diesel combustion, Pollutant emissions, CFD simulation

ÇOK PÜSKÜRTMELİ DİREKT ENJEKSİYONLU DİZEL BİR MOTORDA ENJEKSİYON STRATEJİLERİNİN YANMA KARAKTERİSTİKLERİ VE KİRLETİCİ EMİSYONLAR ÜZERİNDEKİ ETKİLERİNİN ANALİZİ

Özet: Direk enjeksiyonlu dizel bir motorda çok püskürtmeli yakıt enjeksiyonu ve farklı püskürtme açılarının yanma karakteristikleri ve emisyon oluşumuna etkilerini açıklamak amacıyla gelişmiş HAD simülasyonu gerçekleştirilmiştir. AVL-FIRE yazılımı kullanılarak silindir içi basınç, sıcaklık, ısı salınım oranı, yanma süreci ve emisyon oluşumları farklı püskürtme açıklarında gösterilmiştir. Yanma modeli olarak gelişmiş ECFM-3Z model kullanılmış olup, NO ve İs oluşumları için sırasıyla gelişmiş Zeldovich ve Kinetik modeller kullanılmıştır. Sayısal simülasyonlar, silindir içi basınç ve ısı salınım oranına bağlı deneysel verilerle doğrulandıktan sonra, püskürtme açısının etkisinin incelenmesi için geliştirilmiştir. Sayısal çalışmalarla silindir içi basınç ve ısı salınım oranının 120º ve 160º püskürtme açılarında kısmen artığı gözlenmiştir. Kütlesel NO oranı 150º püskürtme açısında en düşük olarak elde edilirken, kütlesel İs oranı 120º ve 160º püskürtme açılarında en düşük sonucu vermiştir. Tüm simülasyon konfigürasyonları yanma stroku boyunca silindir içi etkileri anlamak için gerçekleştirilmiştir. Elde edilen sonuçlar yanma sürecini etkileyecek ve yeni nesil emisyonları tamamen değiştirecek kadar önemlidir.
Anahtar Kelimeler: Çoklu püskürtme, Dizel yanması, Kirletici Emisyonlar, HAD simülasyonu

INTRODUCTION

In diesel engines, the formation of droplets, droplet breakup, spray propagation and vaporization are important processes that determine the start of combustion and the combustion process. The distribution and concentration of fuel droplets and fuel vapor in the combustion chamber directly affect the performance, combustion efficiency and emissions of the combustion system. If the spray dynamics and vaporization of the fuel spray were known in detail, the design of fuel injection systems, particularly the injectors and combustion chambers, could be optimized efficiently without the need for experimental trial and error. The in-cylinder flow field and spray dynamics have a significant effect on engine performance, combustion and engine emission levels (Jaichandar and Annamalai, 2013, Varol et.al., 2010). Mobasheri et al. (2012) studied the effects of injection strategies on engine performance and pollutant emissions in a heavy duty DI-diesel engine. This numerical study was performed using AVL-FIRE commercial code. They found that using pilot injection has a significant and beneficial effect on the combustion process and NOx emissions. However, with more stringent emission regulations, diesel engine developers are continuously forced to optimize combustion processes to improve emissions, particularly the NOx production and soot emission (Su et.al., 2014, Yu et. al. 2014, Soid and Zainal, 2011). Studies reported that a combustion chamber with a special piston cavity can lead the in-cylinder flow to realize a useful fuel/air equivalence ratio distribution. Yadollahi and Boroomand (2013) shows that the effects of cylinder head shape, combustion chamber geometry, injector type, injection parameters, and spray dynamics on mixing air and fuel in the combustion chamber. In the last decade, significant advances have been made in the study of spray dynamics and combustion process simulation which can provide foreseeable guidance on understanding the air/fuel mixture and combustion process. The computational fluid dynamics software such as AVL-FIRE, KIVA, etc., can predict mixture formation, spray propagation, fuel combustion, flame processes for different injection systems and other engine specifications. Several modifications of the injection system design, including changes in the number of nozzle holes, nozzle diameter and the spray cone angle are commonly used to increase the rate of combustion and reduce pollutant emissions in direct injection diesel engines (Kim and Lee, 2007, Firat, 2013). The numerical simulation of the effects of the spray angle in a direct injection diesel engine was performed by Wei et al.(2014) They concluded that the spray nozzle angle has an effect on the fuel/air equivalence ratio and the in-cylinder temperature distribution in the combustion chamber. They also changed spray characteristics, the rate of combustion, the full combustion process and emissions. Ganippa et al. (2003) studied the nozzle-hole inlet hydrogrinding effects on cavitation, penetration, spray momentum, dispersion, internal turbulence, combustion and emissions formation. They showed that the fuel jet angles, ignition delay, penetration and flame volumes have very different initial turbulence and cavitation levels. Further, the in-cylinder gas velocity affects the combustion rate when it is disturbed to generate swirl and turbulence during the intake stroke, so the combustion rate will increase at given engine speed (Li et.al., 2010, Xin et. al., 1998). Three-dimensional CFD (Computational Fluid Dynamics) methods were used by Parasad et al. (2011) to study and understand clearly the effect of changes made to the engine on in-cylinder flow and combustion characteristics and to arrive at an optimal engine configuration. The results show that the emission, in-cylinder swirl and turbulence decreased with the used piston bowl. The NOx and soot emissions seriously reduced with injection timings. Desantes et al. (2009) investigated the injection parameters of biodiesel blends on DI diesel-injection using a standard injection system. The analysis was performed on the spray force, injection rate shape, cone angle and spray tip penetration in non-evaporative conditions. They results that fuel density influenced the injection rate, but spray momentum did not show any effect. Also, the pure rape methyl ester fuel has slightly longer penetration and narrower cone angle. Injection angle which is one of the injection parameters determines turbulence characteristics in combustion chamber. Depending on injection angle, good atomization, better air-fuel mixing and the optimal vaporization process are obtained. Spray dynamics and air-fuel mixing characteristics play an important role in improving the combustion process in a DI diesel engine. In the present study, five new alternative injection angle configurations are designed. Employing three dimensional advanced CFD simulations, these five alternatives are compared to the base configuration of the test engine injection angle. The results highlight the advantages of the new injection angle configurations in terms of combustion characteristics, combustion pressure, in-cylinder temperature distribution, heat release rate and significant emissions for a direct injection diesel engine.

METHODOLOGY

An advanced three-dimensional CFD (Computational Fluid Dynamics) model was developed using the AVL-FIRE commercial software. The simulation was conducted at an engine speed of 2,000 rpm (maximum torque speed), while also considering other important engine speeds. Unstructured grids formed the computational domain. The generated mesh was reproduced by means of a re-zone procedure within each time step. The time step was set to the crank angle. During each step of crank angle revolution, a dynamic algorithm moved the generated mesh to a new situation. This dynamic mesh model was provided by the AVL-FIRE ESE Diesel Meshing Tool. The computational step proceeds from both intake and exhaust valve closures at TDC to closure of both valves after BDC. All analyzes were performed during 285 CA. Intake and exhaust ports are not included in the numerical mesh. This calculation is focused on the compression and combustion stroke. Figure 1 depicts the combustion chamber in its base configuration, which was meshed along with the combustion chamber at TDC. The used model in the study was chosen as one-sixth at sector model. To investigate the mesh independency, five different cases were considered, with each containing a different number of cells. Though the resulting in-cylinder pressures and heat release rates were identical for all cases, the case which contained approximately 100,000 cells had the most accurate result compared to experimental results (Firat, 2014). The five spray cone angles which are 120,130, 140, 150 and 160 were simulated with this mesh number. The sectional view of the combustion chamber is shown in Fig. 2.

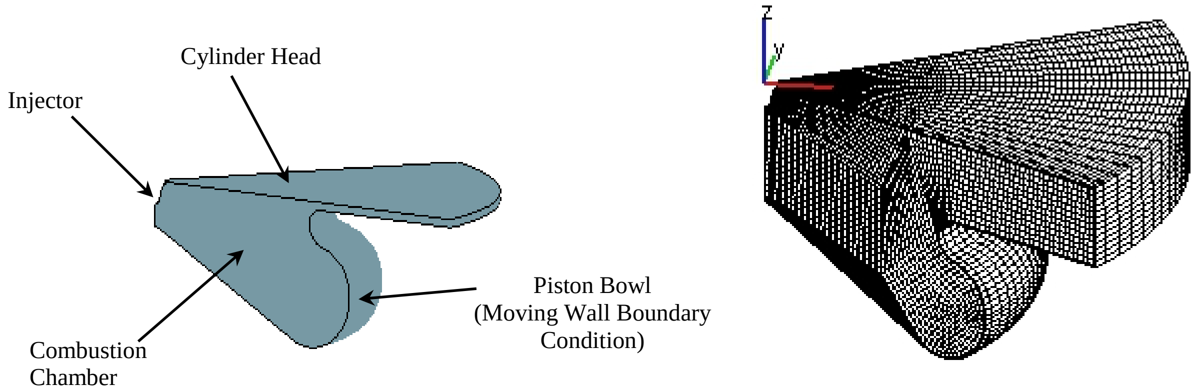


Fig. 1. Model and mesh for numerical study

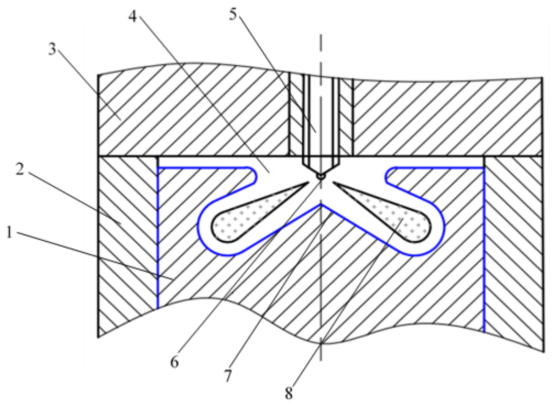


Fig.2. Sectional view of the combustion chamber, 1) Piston, 2)Cylinder wall, 3) Cylinder head, 4) Combustion chamber, 5) Injector, 6) Spray nozzles, 7) Piston bowl, 8) Spray droplets

The Spray and Turbulence Model

The primary and secondary atomizations were modeled by the standard Wave model, which applied to the resulting droplets. It is recommended that the initial droplet diameter should remain within the range of the nozzle hole diameter (= blob injection). In this model, the growth of an initial perturbation on a liquid surface is linked to its wavelength and to other physical and dynamic parameters of the injected fuel and the domain fluid (Liu and Reitz, 1993). As in Reitz and Diwakar (1986), a rate of change equation is employed to estimate the reduction of the droplet's radius (Eq. (1)).

$$\frac{dr}{dt} = -\frac{r - r_{stable}}{\tau_a} \tag{1}$$

where τ is the break-up time of the model, which can be calculated as:

$$\tau = \frac{3.726 C_2 r}{\Lambda \Omega} \tag{2}$$

The constant C_2 corrects the characteristic break-up time and varies from one injector to another. Gonzalez et.al (1992) used the value of C_2=10 in engine spray modeling studies. r_{stable} is the droplet radius of the product droplet, which is proportional to the wavelength Λ of the fastest growing wave on the liquid surface.

$$r_{stable} = C_1 \Lambda \tag{3}$$

The recommended default value of C_1 taken from the original paper by Liu et. al.(1993) is 0.6.

In this study, the heat-mass transfer and vaporization processes are described by a model originally derived by Dukowicz (1979). The model is based on spherical symmetry, uniform droplet temperature along the drop diameter, a quasi-steady gas-film around the droplet, thermal equilibrium on the droplet surface as the assumptions and uniform physical properties of the surrounding fluid and liquid – vapor.

The Walljet model was used for spray wall interaction in the calculations. This model is based on the spray/wall impingement model of Naber and Reitz (1988). Under engine conditions, a vapor cushion is formed under the droplets and the droplets rebound or slide along the walls. The O'Rourke model was applied to collisions of the droplets, which is described in O'Rourke (1989).

The k–zeta-f model turbulence equations have been implemented for estimating turbulence in terms of Turbulence Kinetic Energy (TKE). This is the model often preferred in the literature for internal combustion engines turbulence analysis (Petranović et. al., 2018, Petranović et. al., 2017). AVL-FIRE software is more likely to prefer this model for solving problems . These additional turbulence effects on the spray particles cannot be resolved by the flow field in detail so a turbulent dispersion model is used. Two dispersion models are implemented in FIRE and can be activated via Enable model and O'Rourke model. In this study, the Enable model was used to solve this interaction (Gosman and Ioannides, 1981).

The Combustion and Pollutants Model

In this paper, the combustion model was originally based on the Coherent Flame Model (CFM)(Combustion Module, 2013). The Extended Coherent Flame Model (ECFM), based on CFM, has been primarily developed

to describe combustion in DI-SI engines .The existing ECFM model is devoted to gasoline combustion. The ECFM-3Z model was developed by the GSM consortium (Groupement Scientifique Moteurs) specifically for Diesel combustion (Combustion Module, 2013). The ECFM-3Z combustion model is used to simulate the combustion process in this study.
In this study, the extended Zeldovich mechanism was used to calculate NO emissions (Emission Module, 2013). In engines, the cylinder pressure rises during the combustion process, so earlier burnt gases are compressed to a temperature level higher than their temperature immediately after their combustion. Therefore, the thermal NO formation in the burnt gases always dominates in comparison to the NO formed in the flame front and represents the main source of the nitric oxide in engines whose reaction paths are effective at high temperatures. The reaction mechanism can be expressed in terms of the so-called extended Zeldovich mechanism.

The formation of soot is another important problem in diesel engine emissions. The Kinetic model was applied for soot formation. The complete detailed kinetic scheme of the soot formation process incorporates 186 species, 1,850 gas phase reactions and 100 heterogeneous reactions with participation of four ensembles of micro-heterogeneous particles of different types (Emission Module, 2013). The current model contains a reduced number of species and reactions and has been developed to provide a computationally efficient Kinetic overall soot model.

Model Validation

The experimental study was based on a four-stroke, four-cylinder, multiple-injection DI diesel engine with a high pressure common rail injection system without any modifications. The in-cylinder combustion pressure was measured by a pressure sensor which was adapted to the cylinder head. Crank angle was measured through a crank shaft encoder. The heat release rate and the combustion pressure are the most important parameters used to verify the combustion characteristics of diesel engines, and they affect the combustion, emissions and engine performance. In this paper, the experimental heat release rate is computed by the experimental cylinder pressure measurements and based on the first law of thermodynamics as shown in Eq. (4).

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma + 1} V \frac{dP}{d\theta} \qquad (4)$$

Where, $\frac{dQ}{d\theta}$ is heat release rate, γ is the ratio of specific heats (c_p/c_v), θ is crank angle, P is cylinder gas pressure, and V is cylinder volume.

Experiments were carried out at Firat University, Faculty of Technology, Department of Automotive Engineering, Engine Test Laboratory. The engine tests were conducted on a Cussons brand engine test bed, which consists of a hydraulic brake, test engine, measurement instruments, and a control and monitoring panel. In the experiments, a 4-cylinder, 4- stroke, direct-injection, water-cooled diesel engine was used. Table 1 lists the main engine specifications. The tests were carried out with a constant engine speed of 2000 rpm. The schematic diagram of the engine test bed is shown in Fig. 3.

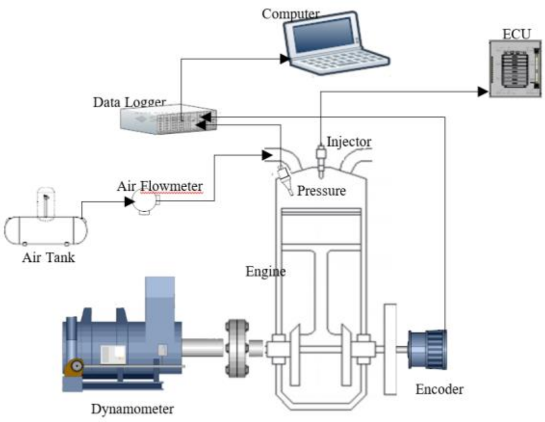


Fig. 3. Schematic diagram of the engine test system

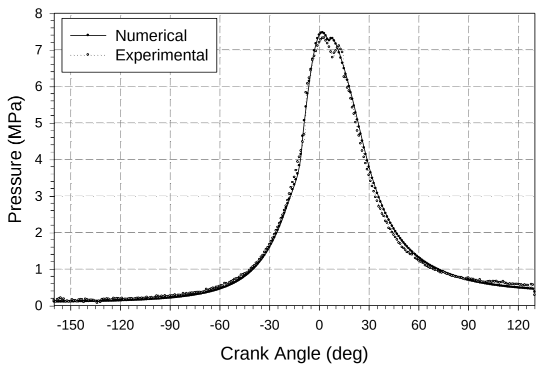
FEBRIS combustion analysis system was used for combustion analysis. In addition, a crank angle encoder (Kuebler, 5000 pulses per revolution) and pressure sensor (Optrand, pressure range:0-3000psi) were connected to the system. The in-cylinder pressure and heat release rate values versus crank angle were collected by using this software. In-cylinder pressures and other engine parameters were recorded for each CA and mean values of 400 cycles are used.

The numerical calculations were performed using the AVL-FIRE commercial code. The numerical model of the engine was validated by experimental data. Test engine operating conditions at engine speed = 2,000 rpm and reference spray angle = 140° were chosen to conduct the present study. This angle is the original spray angle of the test engine. Therefore, the spray angle was selected as reference angle for this study.

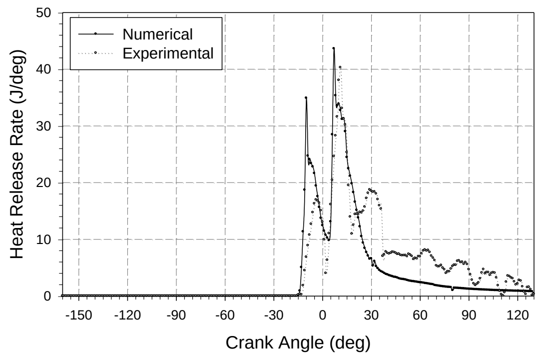
Table 1. Test Engine Specifications

Maximum power	75 kW @ 4000 rpm
Maximum torque	280 Nm @ 2000 rpm
Cylinder arrangement	four cylinders, in-line
Bore (mm)	82
Stroke (mm)	90.4
Compression ratio	18:1)
Displacement (l)	1.9
Fuel injection	common rail, with pilot
Number of nozzle	6
Spray angle	140°
Nozzle hole diameter	0.145mm

This study was performed on the effect of spray angle parameters on the combustion and emissions of diesel engine. In this study the impact of spray angle on thermodynamics, combustion and emissions characteristics of a diesel engine was studied by CFD method, and the detailed changing fuel course and distribution of combustion and emissions parameters at different spray angles were presented. Fig. 4 shows the computed and measured heat release rate traces and in-cylinder pressure depends on the crank angle during combustion. As seen, the agreement of the pressure and heat release rate traces are good. Maximum in-cylinder pressure and HRR were obtained from simulations. These pressure results diverged less than 4% from the experimental results. Although heat release rate results were calculated with equation 4, some differences were observed and generally correct trends were obtained.



a)



b)

Fig. 4. Comparison of computed and measured in-cylinder pressure (a) and heat release rate (b)

Table 2 provides the boundary conditions and the computational model for this computational study. All these parameters were kept constant and injection angles were changed. Using multiple injectors results in two peak values. This case is observed clearly in the heat release rate and the in-cylinder combustion pressure results.

Table 2. Parameters of the simulated engine operating conditions

Engine speed	2000 rpm
Intake air temperature	293.15 K
Fuel injection temperature	320.15 K
Cylinder head temperature	550.15 K
Piston top temperature	550.15 K
Cylinder wall temperature	470.15 K
1. Start and end of injection	-20/-10 CA
2. Start and end of injection	5 / 15 CA
Fuel Consumption	5.8mg/cycle

RESULTS AND DISCUSSION

Influence of Spray Cone Angles on Combustion Characteristics

Fig. 5 shows simulation results of the cylinder pressures and heat release rates for different spray cone angles relative to the basis spray angle (140^o). It can be concluded that 120^o and 160^o spray cone angles increase the cylinder peak pressure and heat release rate particularly during the second injection pulse where, for both cases, there is a higher peak cylinder pressure and heat release rate. This is primarily due to the availability of a higher amount of premixed fuel and air mixtures that depend on the fuel injection area in the piston bowl and moving air. 130^o and 150^o spray cone angles are observed to produce similar results relative to the basis spray angle because these spray cone angles are approximately the same into the combustion chamber. Therefore, the air-fuel mixture and combustion is carried out in a similar process. According to the pressures and heat release curves, 120^o and 160^o spray cone angles yield better results.

Influence of Spray cone angles on Temperature

The variations of in-cylinder temperature relative to crank angle at 2,000 rpm for different spray cone angles are presented in Fig. 6. This figure shows that the temperature changes depend on the spray cone angles. Further, the influence of different spray cone angles on temperature is less pronounced compared with the temperature curves. This figure shows high temperatures obtained at 160^o and 120° spray cone angles. In addition, 140^o and 150^o spray cone angles produced similar results and lower temperatures. During the first injection, the temperature is observed to exhibit similar results in all spray cone angles, and the important temperature increase is observed during the second injection. It can be determined that injecting adequate fuel in second injection leads to the increase of temperature in late stage of combustion process.

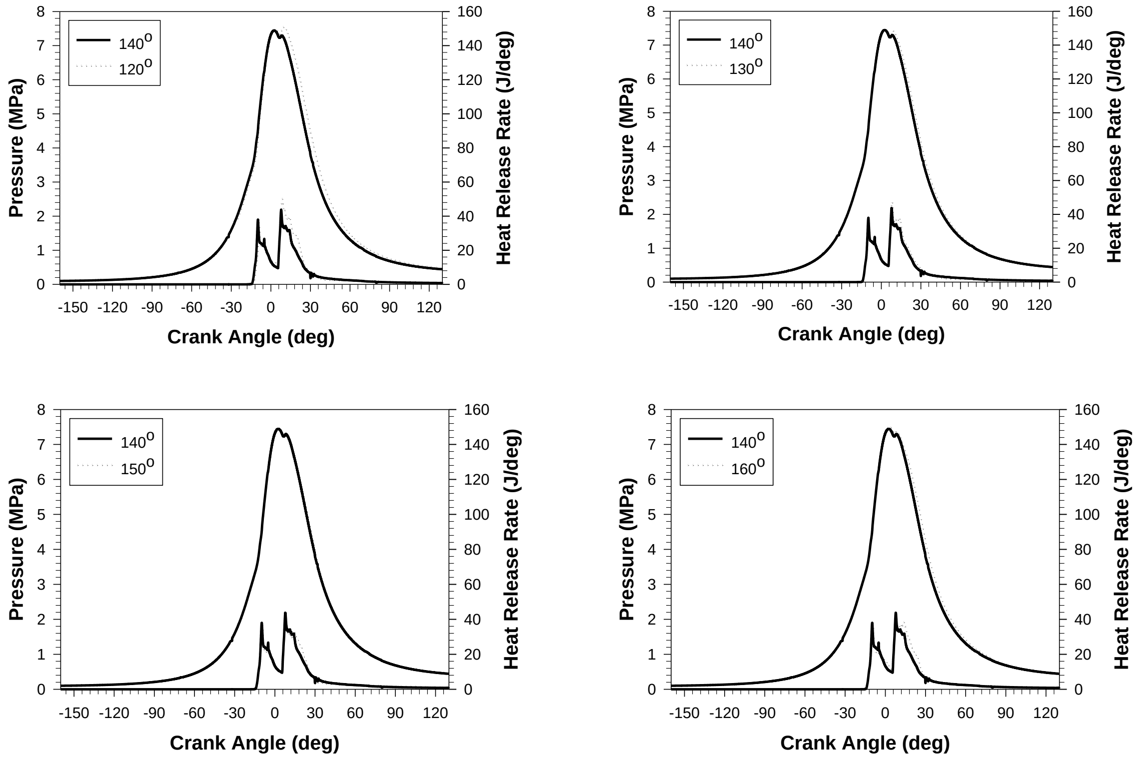


Fig. 5. Comparison of in-cylinder pressure and heat release rate at different spray cone angles

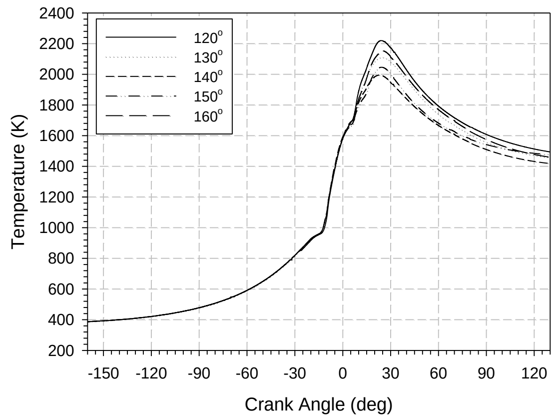
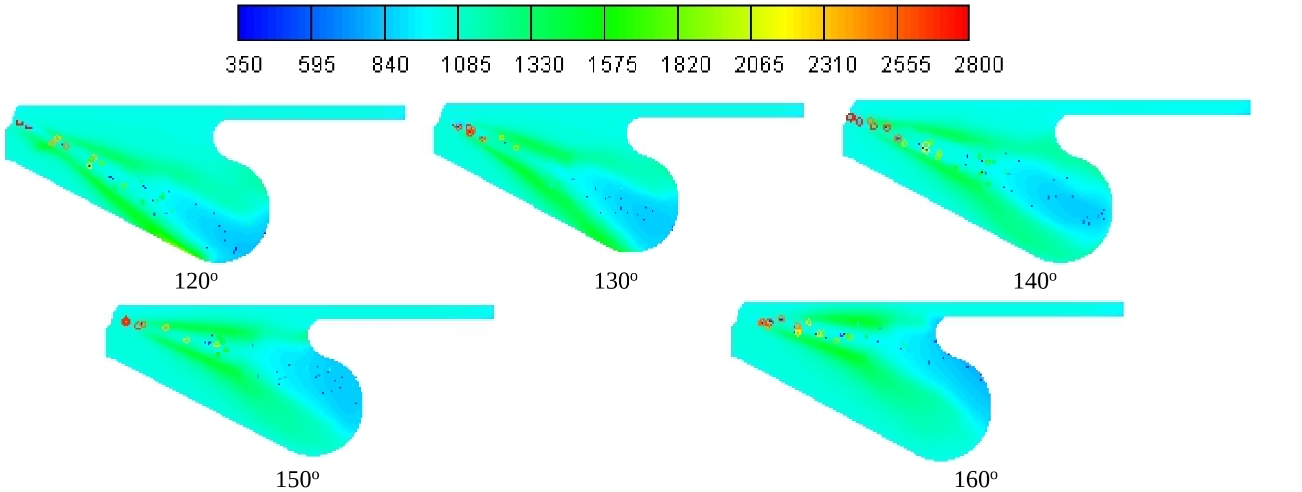
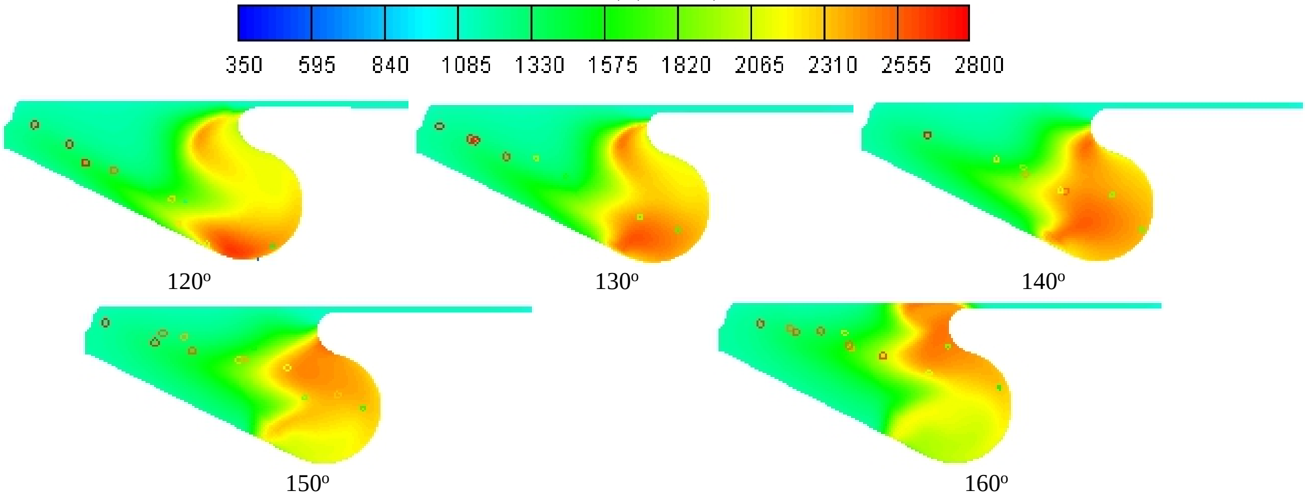


Fig. 6. Comparison of combustion temperatures at different spray cone angles

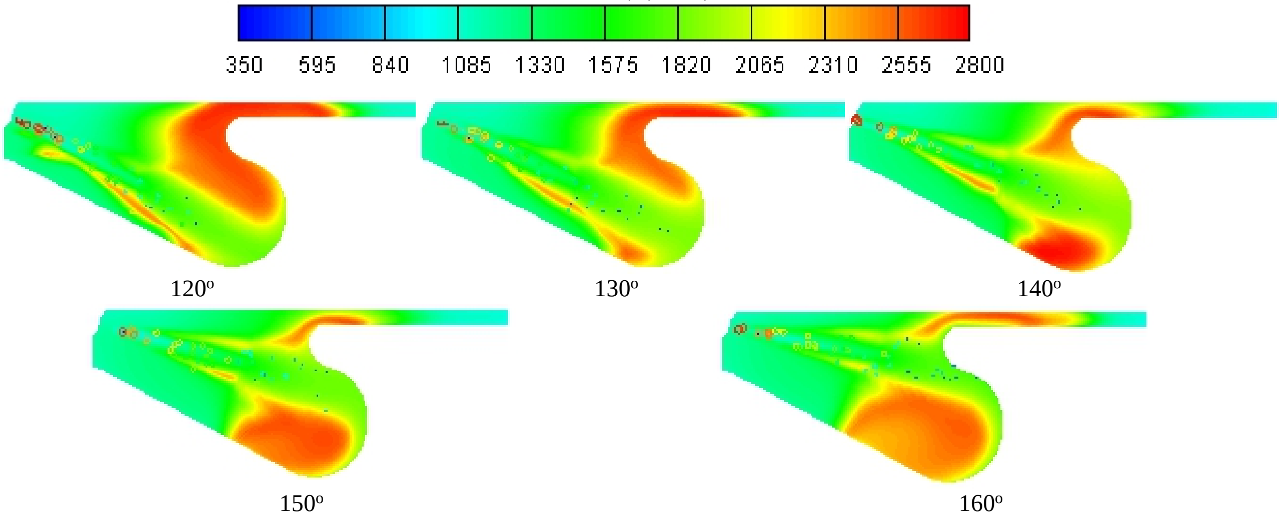
The next figure investigated local temperature changes as to provide evidence for different crank angles. Fig. 7 shows the stated advantages of three-dimensional and chemical numerical models for in-cylinder temperatures for the engine condition of 2,000 rpm. Furthermore, in-cylinder temperature contours are also presented for the four crank angles (CA) of -10°, 0°, 10° and 20°, based on TDC. These results were obtained with multiple injections for a diesel engine. Fig. 7a presents temperature and spray propagation for the start of the first injection at -10° CA. In this case, the first fuel injection and fuel evaporation is started. It is shown that the trends of evaporation are significantly influenced by the spray cone angles. After the first injection and evaporation, the combustion process is started in the cylinder at 0° CA where the piston is at TDC (Fig. 7b). Fig. 7c indicates the start of the second injection at 10° CA and that the combustion process continues to gather speed. Furthermore, as mentioned earlier, the spray angle effects the combustion process during the combustion stroke. The spray angle has a significant effect on the fuel to determine the road map in the combustion chamber. In this way, the formation and progression of the flame in the combustion chamber is obtained. In the combustion process, the distribution of the flame in the cylinder and the emission formation due to the flame extinction in the cylinder walls are directly related to the spray angle.



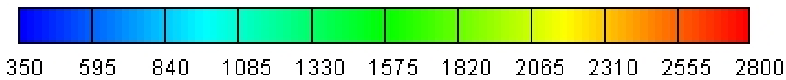
a) (-10ºCA)

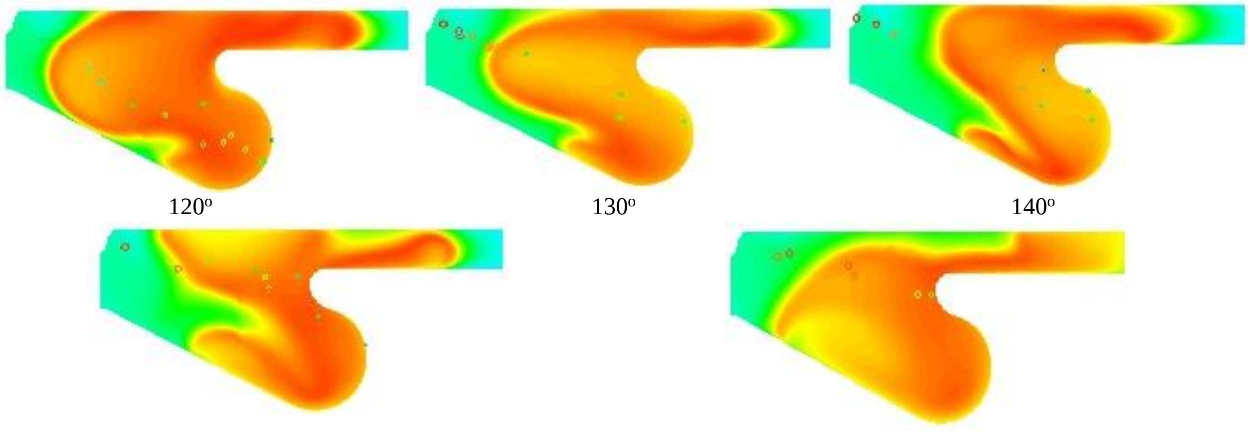


b) (0ºCA)



c) (10ºCA)





d) (20°CA)

Fig. 7. Spray formation and temperature contour (K) for different spray cone angles

Influence of Spray cone angles on Emissions

The main objective of the changes in engine design and injection parameters is to improve engine performance and minimize the formation of particular pollutant emissions. In this context, the effects of different spray cone angles should be examined over emission formation. The variations of CO and CO_2 emissions with respect to crank angle at 2,000 rpm for different spray cone angles are shown in Fig. 8. CO emissions are formed in regions where combustion is incomplete. This result shows the overall combustion quality.

High CO formation is composed at a 120° spray angle. Other spray angle curves are observed to compose similar CO formations. When CO_2 emissions are analyzed based on spray angle, results show a lower formation of CO_2 for the 140° and 150° spray cone angles, while other angles appear to be relatively similar in formation of CO_2.

Other important emission products for diesel engines are NO and soot emissions. Fig. 9 shows the variation of NO and soot emissions for different spray cone angles depending on crank angle at an engine speed of 2,000 rpm. NO is formed in the combustion chamber by high temperatures. Considering the temperature distribution for the formation of NO, high NO formation is a correct result for 120° and 130° spray cone angles. Lower NO emissions are obtained as an important result at higher spray cone angles. If soot emissions contain unburned carbon, the formation of these emissions is also affected by the combustion efficiency. Spray angle affects the formation of soot, fuel distribution and orientation. The NO mass fraction as a result of a 120° spray angle is the highest throughout the combustion process, while the soot mass fraction is the lowest. The NO mass fraction of a 150° spray angle is the lowest. The kinetic energy of the 140° and 150° spray cone angles is relatively lower, and the spray cannot entrain enough air because of its proximity to the combustion chamber wall. The spray forms over the rich zone and leads to higher soot emissions. The soot mass fraction of a 140° spray angle is higher than the other spray cone angles at the early stage of combustion, and the soot mass fraction of a 120° spray angle is the lowest.

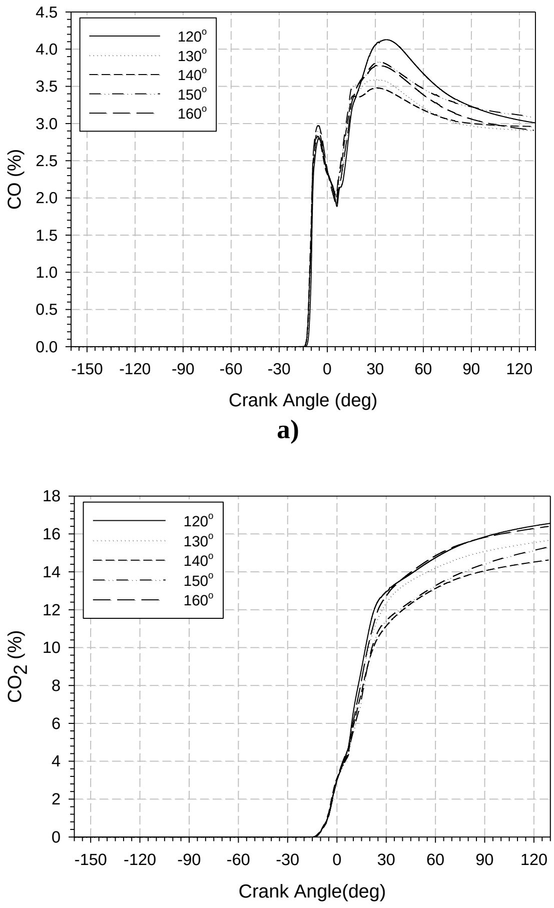


Fig. 8. Comparison of CO (a) and CO_2 (b) emissions at different spray cone angles

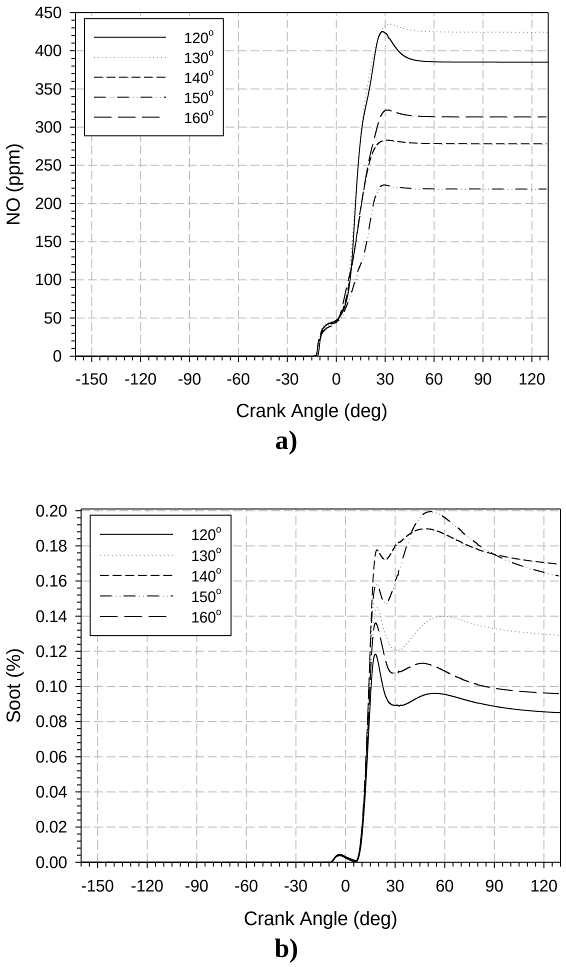
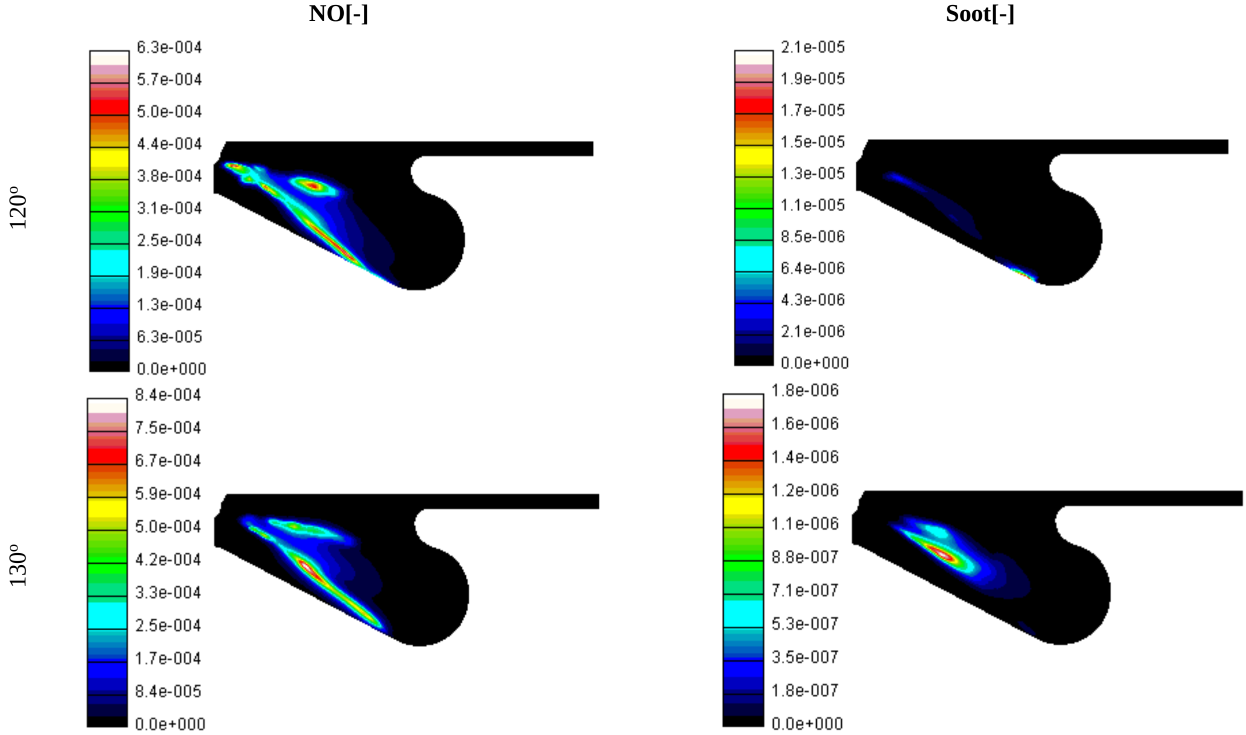
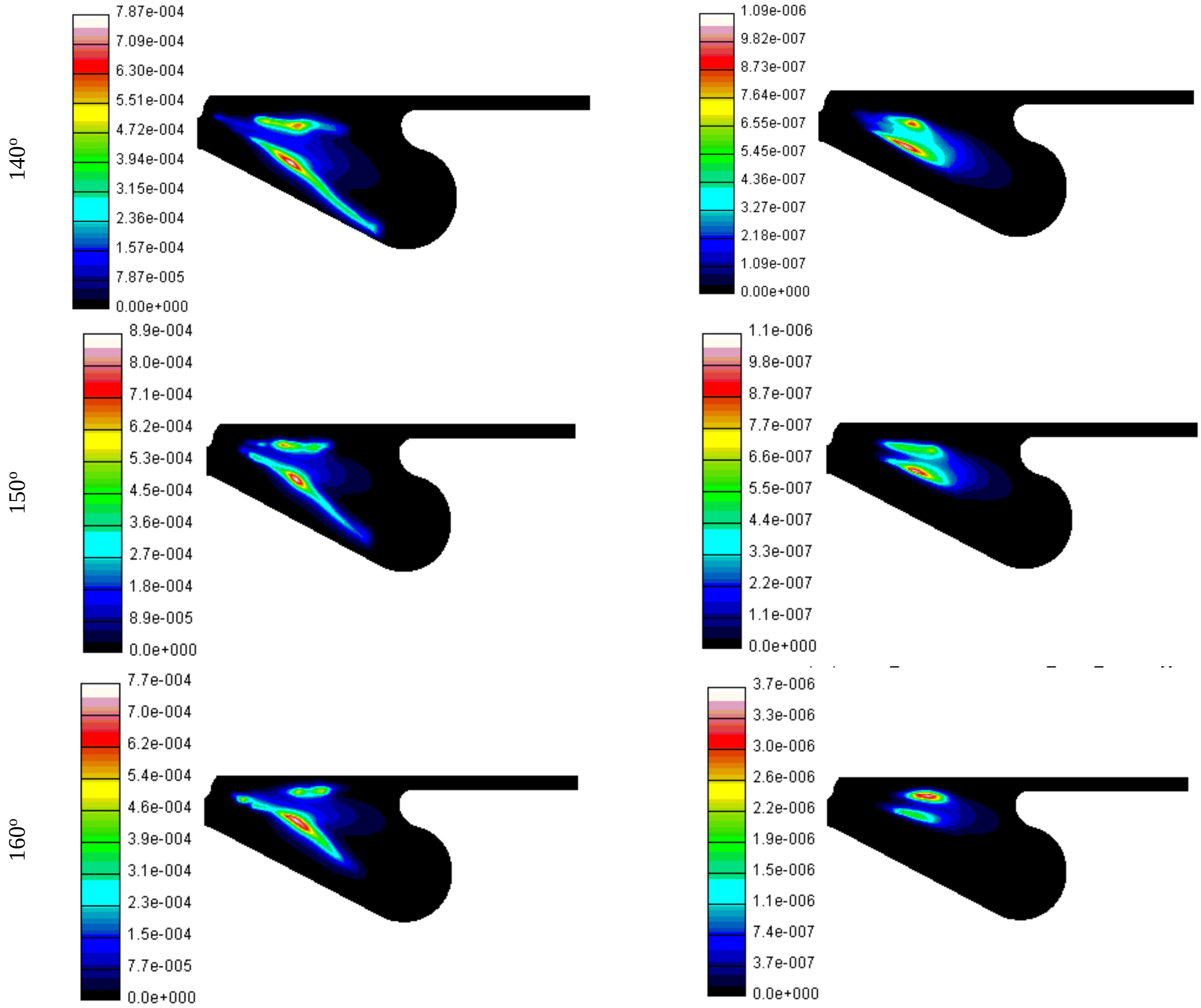


Fig. 9. Comparison of NO (a) and Soot (b) emissions at different spray cone angles

As seen in Figure 10, the local Soot and NO mass fractions are evident in these contour plots, as the NO formation and Soot formation occur on opposite sides of the high temperature region. It is known that NO formation have three requirements: high gas temperature, oxygen rich mixtures, and high temperature with long time. From the comparison of NOx mass fraction distribution in the cylinder for different spray angle, it can be seen that the NOx formation zone of both closely follow the combustion high temperature region. Soot formation is therefore significantly reduced because the injected fuel is rapidly consumed by combustion before a rich soot region can accumulate. As is well known, soot is mostly carbon and is produced during the high temperature pyrolysis of hydrocarbons. The emission of soot is determined by the competition between the soot formation and oxidation, which are highly influenced by temperature and equivalence ratio. In the multiple injection case, the soot formed in the later combustion process is difficult to oxidize for two reasons. First, it is close to the end of the combustion period, and second, the temperature decreases rapidly in the expansion stroke.




140º
7.87e-004
7.09e-004
6.30e-004
5.51e-004
4.72e-004
3.94e-004
3.15e-004
2.36e-004
1.57e-004
7.87e-005
0.00e+000
1.09e-006
9.82e-007
8.73e-007
7.64e-007
6.55e-007
5.45e-007
4.36e-007
3.27e-007
2.18e-007
1.09e-007
0.00e+000
150º
8.9e-004
8.0e-004
7.1e-004
6.2e-004
5.3e-004
4.5e-004
3.6e-004
2.7e-004
1.8e-004
8.9e-005
0.0e+000
1.1e-006
9.8e-007
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160º
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7.0e-004
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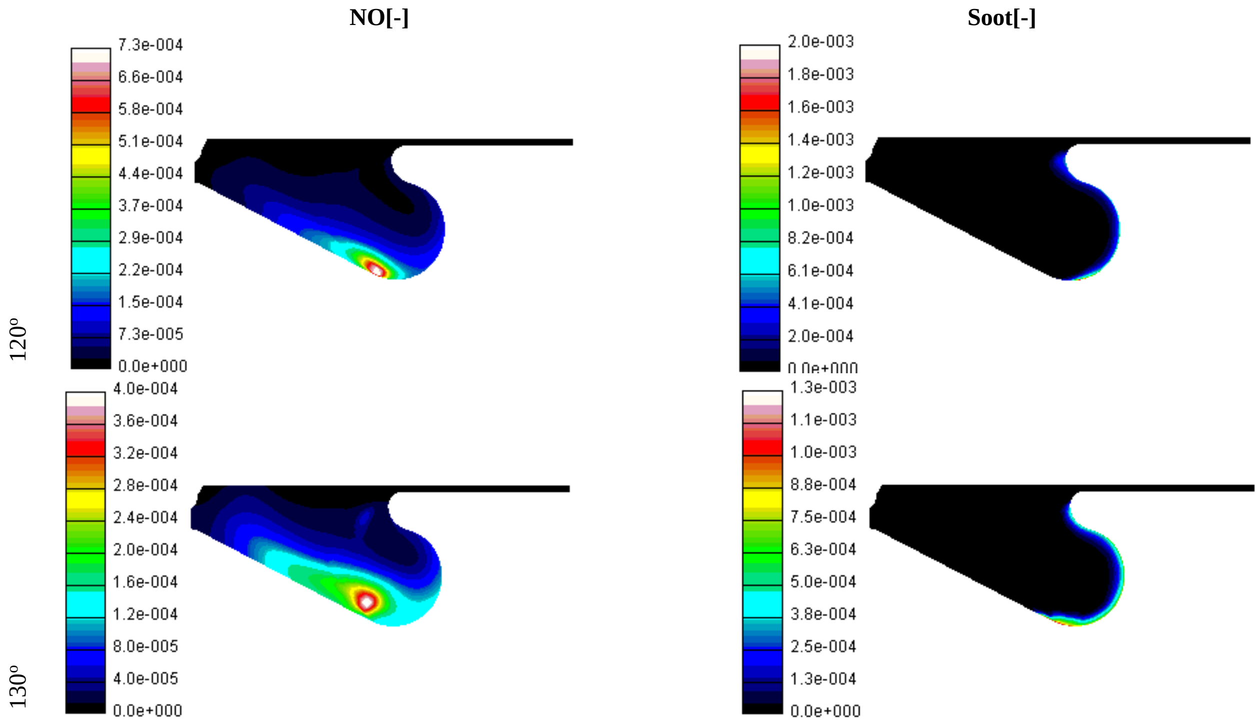
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130º
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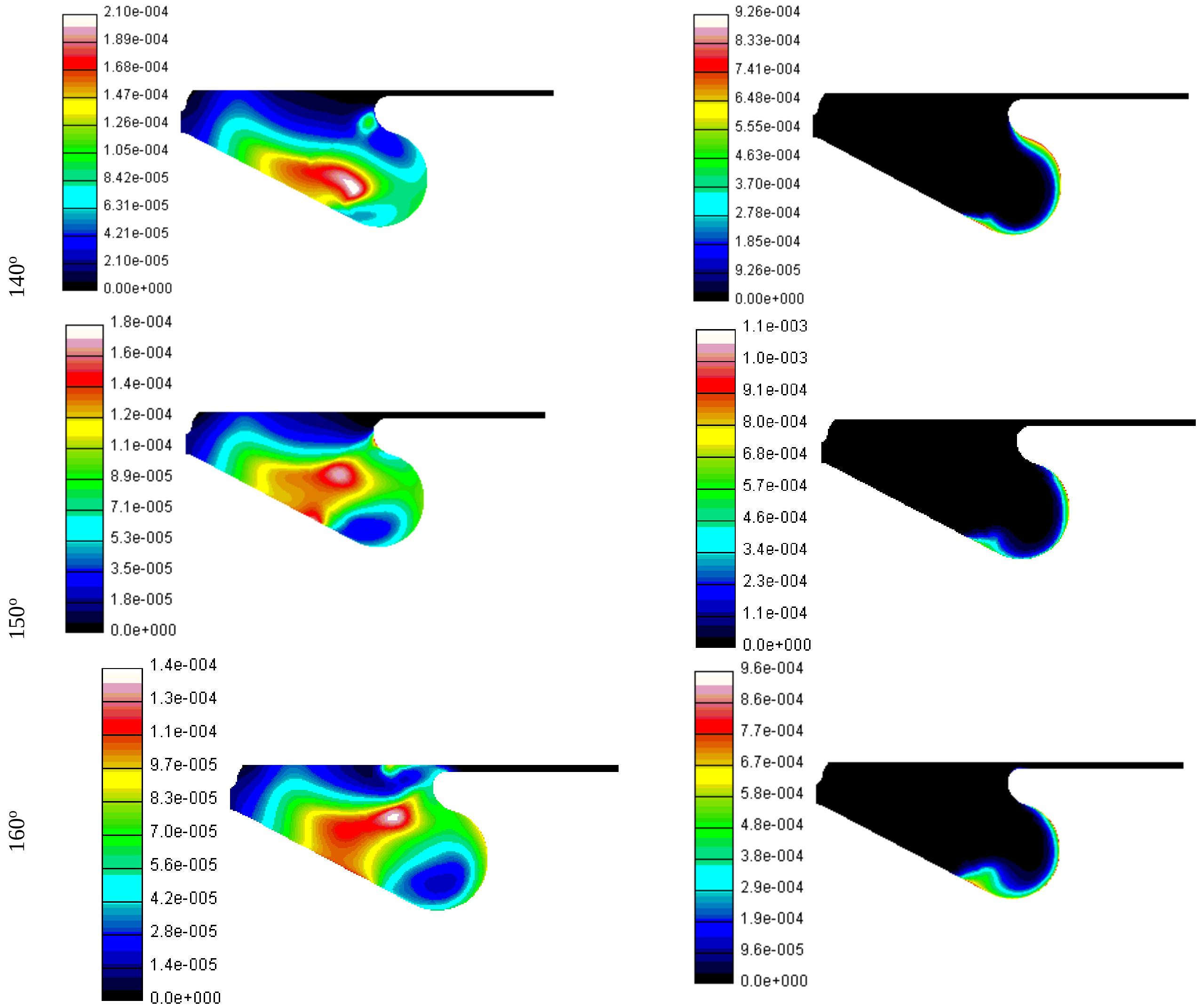
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2.10e-005
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8.33e-004
7.41e-004
6.48e-004
5.55e-004
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3.70e-004
2.78e-004
1.85e-004
9.26e-005
0.00e+000
150º
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1.6e-004
1.4e-004
1.2e-004
1.1e-004
8.9e-005
7.1e-005
5.3e-005
3.5e-005
1.8e-005
0.0e+000
1.1e-003
1.0e-003
9.1e-004
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6.8e-004
5.7e-004
4.6e-004
3.4e-004
2.3e-004
1.1e-004
0.0e+000
160º
1.4e-004
1.3e-004
1.1e-004
9.7e-005
8.3e-005
7.0e-005
5.6e-005
4.2e-005
2.8e-005
1.4e-005
0.0e+000
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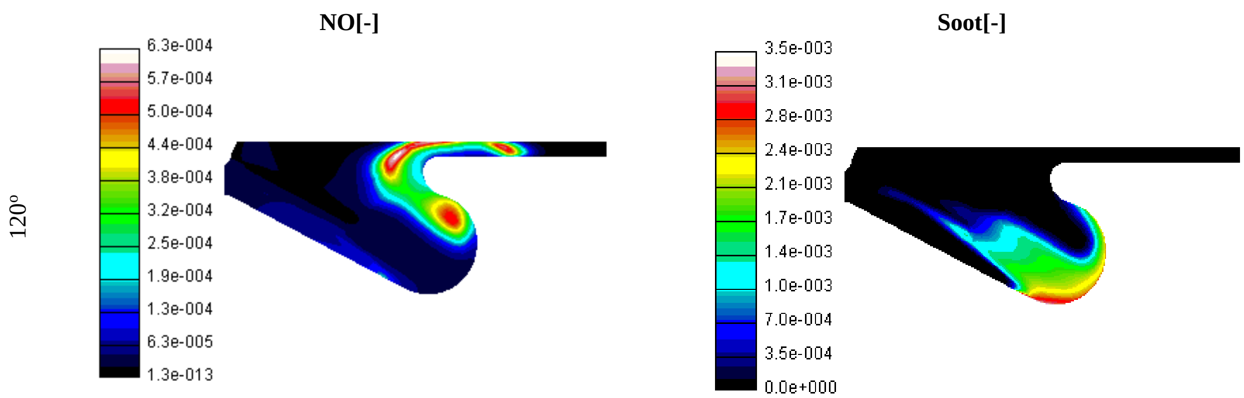
b) 0º CA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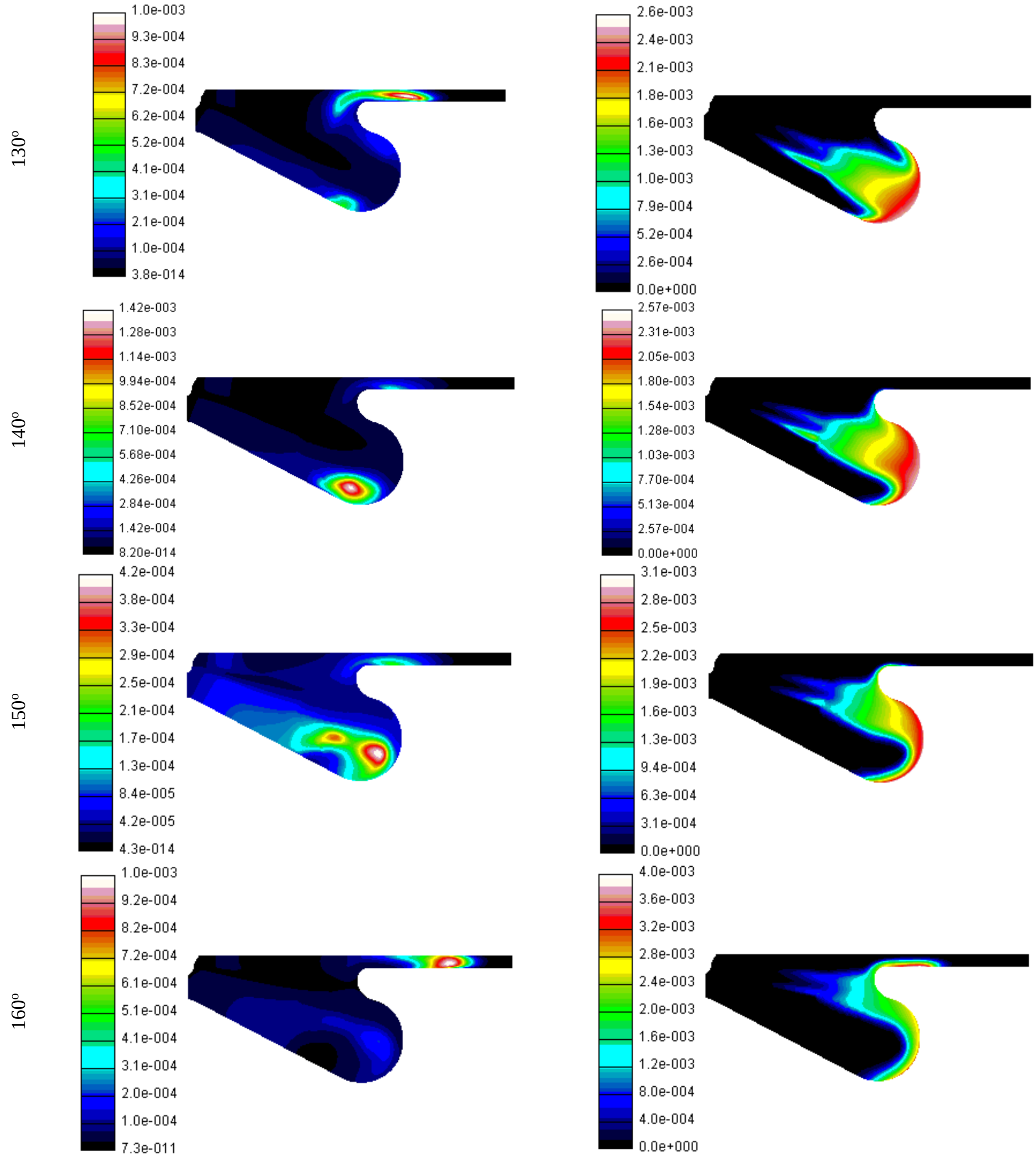
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1.8e-003
1.6e-003
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1.0e-003
7.9e-004
5.2e-004
2.6e-004
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140º
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150º
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160º
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9.2e-004
8.2e-004
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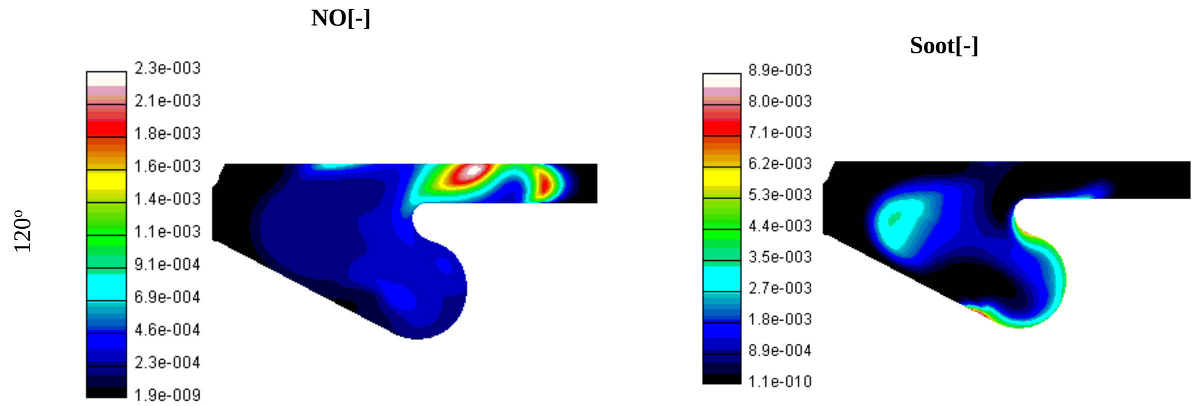
c) 10º CA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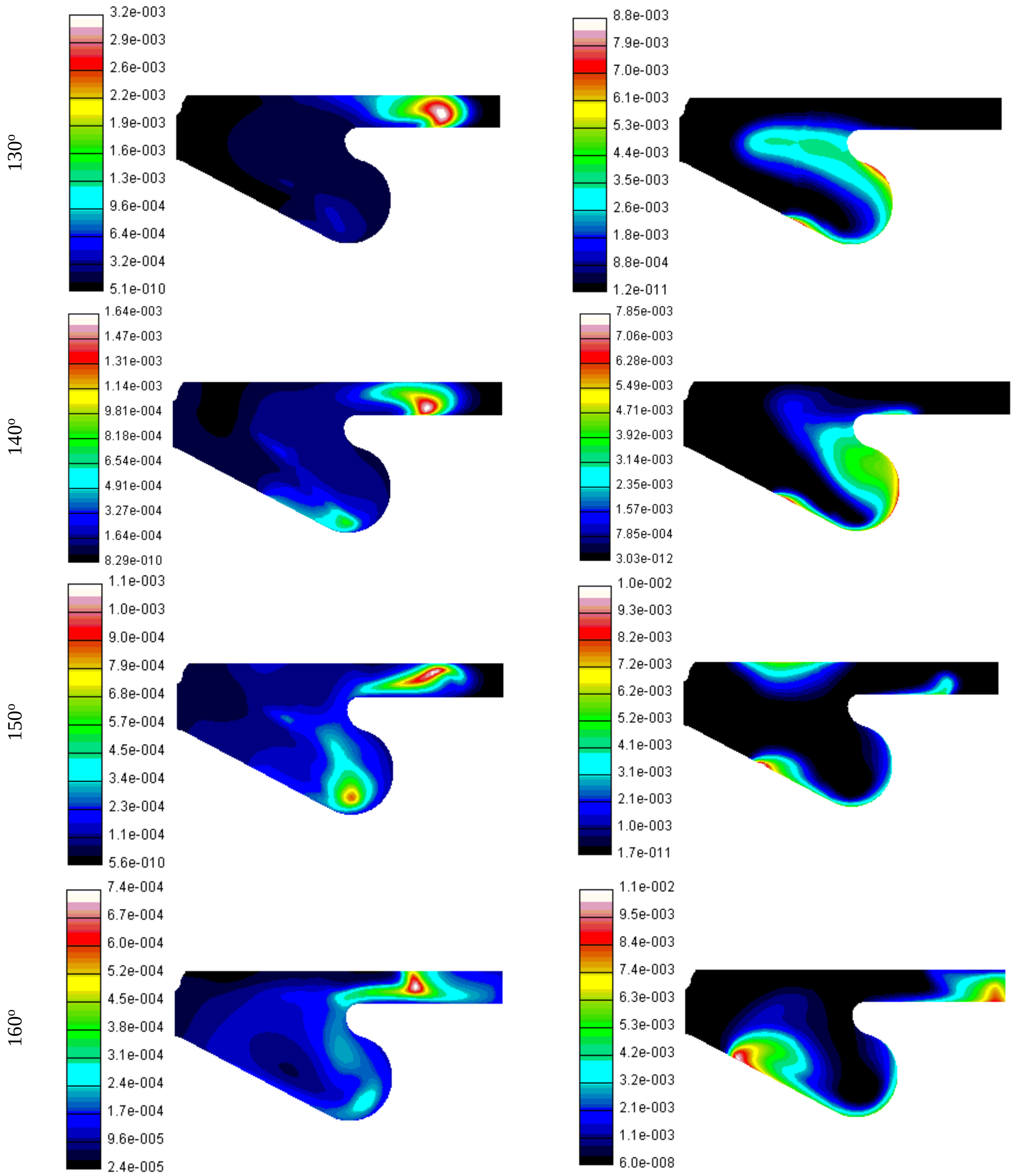

d) 20º CA

Fig. 10. NO and Soot local mass fraction contours at different spray cone angles

CONCLUSIONS

The effects of different spray cone angles for multiple injection strategies on the improvement of fuel atomization, liquid and vapor penetrations, combustion characteristics, temperatures and the formation of emission characteristics were analyzed on a DI diesel engine. This study has been conducted numerically with different spray cone angles by using the AVL-FIRE program. These results were compared with those obtained experimentally from a basis spray angle at identical operating conditions. The conclusions are summarized as follows:

- ✓ The study confirms the benefit of spray cone angles and multiple injections to control both Soot and NO emissions simultaneously.
- ✓ The spray angle has a significant influence on the in-cylinder temperature distribution. Spray cone angles also change the combustion process and emissions accordingly.
- ✓ The tested spray cone angles were very effective for reducing Soot and NO emissions.
- ✓ The overall mixture distribution of the 120° and 160° spray cone angles are quite uniform, and their soot

mass fractions are the lowest, while the NO emission mass fraction of the 150° spray angle is the lowest.

- ✓ This work demonstrates that multidimensional modeling can now be used to gain insight into the combustion process and to provide direction for exploring new injection systems concepts.

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