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A Simulation Study on a Premixed-charge Compression Ignition Mode-based Engine Using a Blend of Biodiesel/Diesel Fuel under a Split Injection Strategy

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***Abstract*—Environmental pollution from transportation means and natural resource degradation are the top concern globally. According to statistics, NOx and PM emissions from vehicles account for 70% of total emissions in urban areas. Therefore, finding solutions to reduce NOx and PM emissions is necessary. Changing the engine's internal combustion method is considered promising and influential among the known solutions. One of the research directions is a combustion engine using the Premixed Charge Compression Ignition (PCCI) method combined with biofuels to improve the mixture formation and combustion process, reducing NOx and PM emissions. Therefore, this study presents the mechanism of the formation of PM and NOx emissions in the traditional combustion and the low-temperature combustion process of internal combustion engines. Besides, the theoretical basis of flame spread during combustion is also introduced. The key feature of this research is that it has modeled the combustion process in diesel engines under the PCCI modes. This was accomplished using blends of waste cooking oil (WCO)-based biodiesel and diesel fuel, as well as the ANSYS Fluent software. The results showed that PCCI combustion using B20 fuel can significantly reduce NOx and PM emissions, although HC and CO emissions tend to increase, and thermal efficiency tends to decrease. In further studies, different modes of the PCCI combustion process should be thoroughly examined so that this process can be implemented in practice to reduce pollutant emissions.**

***Keywords*— Pollutant emissions; low-temperature combustion; premixed charge compression ignition; thermal efficiency; NOx and PM emissions; soot formation.**

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I. INTRODUCTION

The growth of human civilization as a whole, modernization, and industry have all been assisted by the creation and use of internal combustion engines [1], [2]. The fact is that internal combustion engines in every nation worldwide make a substantial contribution to its economic prosperity by producing energy and power [3]–[5]. Diesel engines are widely employed in several vital sectors, such as farming, surface transport, and construction, owing to their excellent thermal efficiency and higher compression ratio compared to gasoline engines [6]–[10]. However, emissions from vehicles using diesel engines contribute significantly to pollution emissions globally, causing many adverse effects on economic as well as social development; they have detrimental effects on human health [11]–[14]. Owing to these reasons, various studies were conducted to investigate internal combustion engines over the past decades to find ways such as using alternative fuels, developing the combustion, changes in engine structure, applying post-treatment exhaust gas aiming to reduce NOx and PM emissions, pollutants, as well as diversify the providing fuel sources [15]–[24].

NOx includes compounds including nitrogen dioxide (NO_2) and nitrogen oxides (NO), which are products of fuel combustion in vehicles, power plants, industrial plants, and other combustion activities [25], [26]. NOx is considered one of the environmental severe pollutants, contributing to climate change, harming human health, and injuring plants and animals [27]–[30]. Meanwhile, particulate matter (PM) is particulate matter, solid or liquid particles smaller than 10 micrometers (μm) emitted by combustion activities, production processes, transportation, and other industrial activities [31], [32]. PM is categorized into two types based on size. PM10 comprises particles in the range of 10 µm while PM2.5 comprises particles having 2.5 µm in diameter [33]. PM2.5 is a smaller particle and can penetrate deep into the lungs, causing health problems such as pneumonia, reduced lung function, lung cancer, and other respiratory problems [34]–[36]. Both NOx and PM are considered essential air pollutants, affecting air quality and the health of humans and the natural environment [37], [38]. Thus, reducing NOx and PM emissions is one of the main goals of concern worldwide.

There has been a significant number of research undertaken on the topic of reducing pollutant emissions by using alternative fuels/biofuels and increasing fuel injection systems to improve engine efficiency and emissions [39]–[44]. For example, some engines operating according to high-pressure fuel injection system diagrams, exhaust gas recirculation, and intake turbochargers have been researched to reduce emissions as well as improve engine performance [45]–[47]. Diesel engines use exhaust gas approaches integrated into exhaust lines, filters for diesel PM, selective emission control systems, catalysts for diesel oxidation, or other waste heat recovery techniques to meet emission standards [48]–[52]. However, exhaust gas treatment methods cannot mitigate all exhaust gas components to the desired level, always have side effects, and can increase back pressure leading to reduced thermal efficiency [53], [54]. Furthermore, the application of exhaust gas treatment technologies can be better at reducing soot and NOx emissions, but this method consumes more fuel [54]–[56]. Consequently, it is of the utmost significance to enhance the combustion process to enhance the engine's performance and maintain a particular degree of engine emissions management. It has been shown that a combination of homogenous fuel and air may lessen the amount. A smaller equivalent ratio, on the other hand, results in reduced NOx emissions [57], [58]. The vast majority of researchers have concluded that the primary parameters that influence engine emission characteristics, thermal efficiency, and emissions of PM and NOx are the fuel oxidation temperature and the fuel-air equivalency ratio. The high combustion temperature results in lower PM emissions and vice versa [59]–[61]. Hence, engine efficiency use can be improved by restricting the emissions framework. The mechanism of NOx formation in engines is that nitrogen gas in the air reacts with the air entering the engine to be oxidized into NOx [62], [63]. High pressure and temperature in the engine can also increase the rate of NOx formation. PM emissions in diesel engines are also a severe problem, PM is created during the combustion process and by chemical reactions of organic substances. The size and composition of PM depend on the fuel used and the engine's operating conditions.

Among various components of nitrogen oxide (NOx) emission, the NO is the main oxide produced in the combustion chamber. Nitrogen gets oxidized in the combustion chamber of diesel engines owing to higher temperatures. This is also termed as thermal NOx. When greater temperatures are present during combustion, the chemical bonds that hold nitrogen molecules together break down, producing an atomic state of nitrogen. This nitrogen's atomic state participates in a series of interactions with oxygen, which ultimately results in the synthesis of nitrogen oxides (NOx) according to the Zeldovich thermal mechanisms and the Fenimore mechanism [64], [65]. The morphology of NOx is mainly based on oxygen fusion, cylinder temperature, higher air residual coefficient, and time. The Fenimore mechanism defines that NO formation occurs from the intermediate state of HC elements during the process. During fuel combustion, these intermediate radicals of HC react with N_2 to form intermediate species containing N. Then, NO is formed through a reaction process using oxygen [66]. The Fenimore mechanism, on the other hand, is only often seen under fuel-rich circumstances, which are characterized by the presence of a sufficient quantity of HC components that can react with nitrogen in the engine cylinder [67]. Therefore, it is assumed that the Zeldovich mechanism is the primary contributor to the generation of NOx in the majority of combustion circumstances [68]. Under the situation, typically, the air residue coefficient is roughly 1; the primary processes that take place in the Zeldovich mechanism are concerned with the formation and decomposition of NO [69]. During the process of combustion, PM emissions from diesel engines are formed when mixtures of certain organic elements are accrued [70], [71], and PM evolves via the gas-to-particulate transition. Among the small particles that make up PM, there are also liquid droplets that include carbon black, ash, hydrocarbons, and water-soluble organic components, and PM is a considerably complex substance [72]–[74]. Typically, different sizes, shapes, quantities, surface areas, solubilities, chemical compositions, and origins are characterized in the PM. These are available in three distinct types, namely fine, coarse, and ultra-fine based on size [75]. The mechanism of PM formation is depicted in Fig. 1 [76].

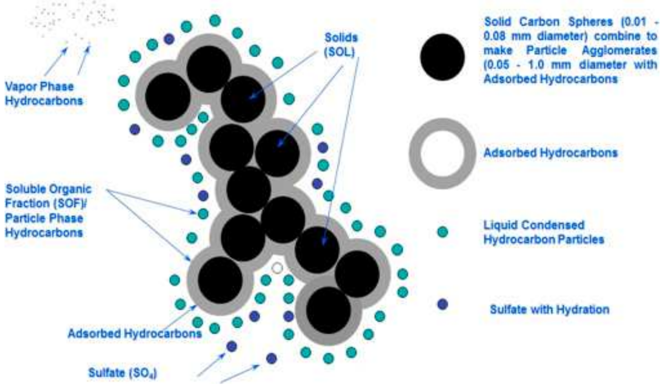


Fig. 1 PM formation process and components of PM [76]

It can be seen that the PM size found in the first state is minimal from 1 nm to 2 nm [64]. Smoke opacity can indicate the soot content of the exhaust gas, hence the parameter can depict the correlation with the PM generation propensity of the fuel used in the combustion process [77]. EGR has been shown to decrease NOx emissions, one of the many strategies suggested to reduce emissions of nitrogen oxides and particulate matter. However, using EGR results in a rise in particulate matter emissions, in addition to deposits caused by soot on the mechanical components of the engine [78], [79]. Implementing a few exhaust gas treatment technologies is one approach to reducing emissions. Even though it is thought that exhaust gas treatment processes may decrease NOx and PM emissions in more significant quantities, installing these technologies will be expensive due to the investment and maintenance costs [53], [80]. Some methods could be used to improve fuel-air mixing and diffuse combustion diesel engines to minimize the formation of NOx and PM such as increasing fuel injection pressure to control fuel pressure at the fuel injector to achieve optimal performance and reduce fuel consumption [81], using gaseous fuels [82], using fuel additives [83], [84].

In recent years, to reduce PM as well as NOx emissions and to achieve the needed engine performance, controlling engine combustion at low temperatures is considered an effective method [85]–[87]. Low-temperature combustion (LTC) is a potential control method to reduce NOx and PM emissions, in which in-cylinder combustion temperatures are significantly reduced through combustion phase management. The LTC mode of the engine requires lower combustion temperatures than conventional diesel engines [88]–[92]. Among the LTC methods, the Premixed Charge Compression Ignition (PCCI) mode of combustion is deemed as a variation of LTC technology that has improved control over the combustion process [93], [94]. To ensure that there is adequate time for air mixing, PCCI combustion is managed using a sophisticated fuel injection system that is midway between Homogeneous Charge Compression Ignition (HCCI) and a traditional diesel engine at the beginning of the combustion process with fuel [95], [96]. In the PCCI mode of combustion, the uniformity of the air-fuel mixture is comparatively poor compared to the HCCI approach [97]. PCCI combustion, on the other hand, is comparable to HCCI combustion in the sense that the central portion of the fuel is used during the premixed combustion phase, which results in the absence of the diffusion process during the combustion phase [98], [99]. This technique dramatically decreases PM and NOx emissions; nevertheless, PCCI mode produces higher CO and HC emissions than traditional diesel engines [100]. However, CO as well as HC emissions are lesser than those from HCCI mode [101]. In broad terms, PCCI mode provides a transitional technique between the HCCI model and traditional diesel, reducing NOx and PM emissions while maintaining superior control throughout the process combustion phase.

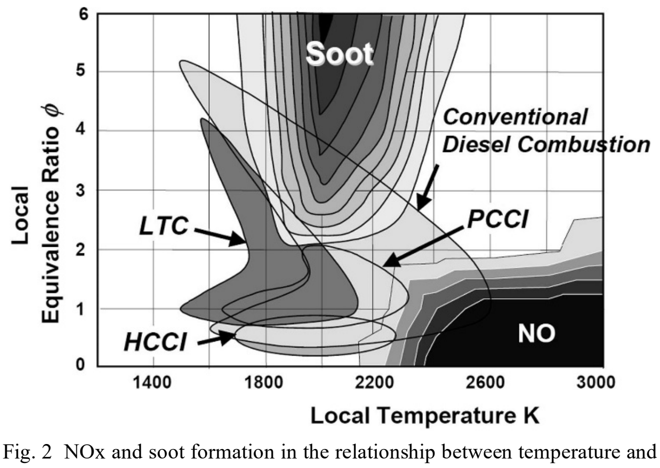


Fig. 2 NOx and soot formation in the relationship between temperature and equivalence ratio for diesel engine, PCCI, and HCCI mode [102]

Several approaches are used to manage the combustion process in PCCI mode, including multi-stage fuel injection paired with either late or early injection, employing restricted injection angles, and using a variety of fuel types. or EGR [103]–[106]. However, improving the injection timing will reduce engine performance, slowing down the injection timing reduces the combustion time because of the late fuel injection, and therefore it lowers the maximum pressure in the cylinder, as well as increasing the phenomenon of incomplete combustion [107], [108]. Therefore, the combination of high-pressure fuel injection with diesel engine combustion control in PCCI mode is expected to be effective in reducing NOx and PM emissions. Pertersen et al. [109] studied UHC emissions and CO emissions from PCCI combustion. At the same time, the research results also evaluated the fuel properties and engine load that affect the number of emissions released. Amin and colleagues [110] experimented with and simulated the LTC combustion process on a CI engine. Two high and low air and fuel mixture stratification cases were experimentally conducted using early (SOI - 80ATDC) and late (SOI - 40ATDC) injection timing. The optimal stratified mixture can provide the required activation energy equal to the engine's heat load. Therefore, it can usefully control the moment of second-stage ignition and the speed of the combustion process, supplementing the combustion phase of the PCCI engine and the subsequent emission formation. Fan Zhang and colleagues [111] blended a mixture of gasoline and diesel fuel to promote partial combustion of the pre-mixed mixture, thereby comparing and evaluating the combustion process of conventional diesel fuel. The results show that the smoke and NOx emissions can be reduced by more than 95% with diesel fuel's PCCI combustion process. Compared to traditional diesel fuel, the particle counts in the form of accumulation significantly reduce the total concentration of PM by 95%. A study by Drews et al. [98] also demonstrated that PCCI is a modern clean combustion method with great potential in reducing pollutants such as soot and NOx. Cheng [112] investigated the effects of n-butanol/diesel mixture on the PCCI combustion process. With an increase in the mixing ratio, soot emissions can be reduced by a maximum of 70%, while NOx increases slightly at low loading speeds. Thus, improving combustion efficiency and minimizing exhaust pollution on diesel engines by enhancing the combustion process using the PCCI method and alternative fuels is exceptionally urgent. Therefore, this work has simulated the PCCI combustion process through a two-stage injection process using biodiesel from WCO.

II. Materials and Methods

A. Flame model in PCCI Combustion Process in ANSYS Fluent Software

Premixed combustion involves the molecular mixing of fuel and oxidizer before combustion. Combustion happens whenever a flame front spreads into the unburned reactants [113]. Mixed combustion is far more complex to simulate than unmixed combustion. The explanation is that premixed combustion is often characterized by a thinly spreading flame that is stretched and deformed by turbulent conditions. One of the most critical aspects of the premixed combustion model is its ability to accurately represent the turbulent flame velocity, which is affected by both the laminar flame speed and the turbulence. Before approaching the combustion chamber, both the oxidizer and the fuel are combined in a flame that is known as a premixed flame [114]. It is possible to simulate the premixed flame by employing the finite-speed vortex dispersion concept that is available in ANSYS Fluent [115].

1) Flame spread:

The flame front propagation can be simulated by using the solution of the transport equation in case of mean reaction, shown as [116], [117]:

$$\frac{\partial}{\partial t}(\rho c) + \nabla \cdot (\rho \vec{v} c) = \nabla \cdot \left(\frac{\mu t}{Rc_t} \nabla c\right) + \rho R_c \tag{1}$$

wherein, c denotes the variable for the mean reaction progress, Rc_t represents the Chaotic Schmidt number and the R_c denotes the reaction progress in the case of the source term.

The progress variable can be specified as the sum of the normalized component types:

$$c = \frac{\sum_{i=1}^{n} z_i}{\sum_{i=1}^{n} z_{i,\text{eq}}} \tag{2}$$

wherein, n is used for the number of components, Z_i denotes the product's volume fraction for types i, and $Z_{i,\text{eq}}$ represents the balanced mass fraction in the case of product types i.

At every flow input, 'c' value is established as BC being applied. It is often denoted as either 0 (there is no burning) or 1 (there is burning). The mean rate of reaction in Eq. (1) can be simulated through [118]:

$$\rho S_c = \rho_u U_t |\nabla c| \tag{3}$$

wherein ρ_u denotes the unburnt mixture's density and U_t represents the speed of turbulent flame.

2) Turbulent flame speed:

The speed of the turbulent flame is perpendicular to the mean surface of the flame. The speed of the turbulent flame is affected by the speed of the laminar-type flame. Therefore, the speed of the turbulent flame is estimated by temperature, fuel concentration, and properties of molecular diffusion in front of the turbulent flame [119], [120]. While implementing the simulation in ANSYS Fluent software, the Zimont vortex flame velocity is calculated employing the model for turbulent flame fronts [118] :

$$U_t \& = A(u')^{3/4} U_l^{1/2} \alpha^{-1/4} \ell_t^{1/4} \tag{4}$$

$$U_t = Au' \left(\frac{\tau_t}{\tau_c}\right)^{1/4} \tag{5}$$

herein, A denotes the model constants, u' represents the root mean velocity in (m/s), and U_t denotes speed of laminar flame (m/s).

$\alpha = k/\rho c_p$: Molecular heat transfer coefficient of mixed non-combustible substances (thermal diffusivity) (m^2/s)

Wherein, the ℓ_t denotes the turbulence length (m),

$\tau_t = \ell_t / u'$: Turbulent duration (s)

$\tau_c = \alpha / U_l^2$: Chemical duration

Turbulence length, ℓ_t, could be calculated as:

$$\ell_t = C_D \frac{(u')^3}{\epsilon} \tag{6}$$

where: ϵ denotes the rate of dissipation in the case of turbulence.

The model assumes small-scale turbulence balance within a laminar flame, leading to an expression of the fully turbulent flame speed for large-scale turbulence parameters [118]. The default setting of 00.37 C_D should also work for most pre-mixed flames. This model is completely applicable whenever the tiniest turbulent eddies in the stream (Kolmogorov scale) are less than the flame thickness and enter the flame area. This is known as the narrow reaction zone combustion zone as well as may be calculated using the Karlovitz number (Ka). Ka has been defined as:

$$\text{Ka} = \frac{t_l}{t_\eta} = \frac{v_\eta^2}{U_l^2} \tag{7}$$

where t_l is characteristic flame time, t_η is minimum disturbance time (Kolmogorov), $v_\eta = (\nu\epsilon)^{1/4}$ is Kolmogorov speed, and ν : Kinematic viscosity.

3) Modeling NOx and soot formation in ANSYS Fluent:

ANSYS FLUENT commercial software has been employed to solve the mass transport equation in the case of the NO species. It takes into consideration the diffusion, convection, production, as well as consumption of the NO as well as connected species [121]. Through the use of convection components in the governing equations that are constructed employing the Euler reference frame, the influence of residence duration on the NOx mechanism, which is also referred to in terms of the Lagrangian reference frame idea, is shown. When taking into account the thermal as well as transient NOx process, the only solution that is needed is the NO species transportation formulation [122], [123]:

$$\frac{\partial}{\partial_t}(\rho Y_{NO}) + \nabla.(\rho \vec{v} Y_{NO}) = \nabla.(DY_{NO}) + S_{NO} \tag{8}$$

It is important to monitor nitrogen-containing intermediates. ANSYS FLUENT finds the solution of the transport equation for NH_3, HCN, or N_2O species, and also NO species [121], [122], [124]:

$$\frac{\partial}{\partial_t}(\rho Y_{NH_3}) + \nabla.(\rho \vec{v} Y_{NH_3}) = \nabla.(DY_{NH_3}) + S_{NH_3} \tag{9}$$

$$\frac{\partial}{\partial_t}(\rho Y_{HCN}) + \nabla.(\rho \vec{v} Y_{HCN}) = \nabla.(DY_{HCN}) + S_{HCN} \tag{10}$$

$$\frac{\partial}{\partial_t}(\rho Y_{N_2O}) + \nabla.(\rho \vec{v} Y_{N_2O}) = \nabla.(DY_{N_2O}) + S_{N_2O} \tag{11}$$

$$\frac{\partial}{\partial_t}(\rho Y_{soot}) + \nabla.(\rho \vec{v} Y_{soot_2}) = \nabla.(DY_{soot}) + S_{soot} \tag{12}$$

wherein, the Y_{HCN}, Y_{N2O}, and Y_{NH3} denote the mass fraction in the case of HCN, NO, and NH_3 are the effective coefficient diffusion.

B. Test engine for simulation

The Kirloskar TV1 engine, as shown in Fig. 3, is a low-power diesel engine manufactured by Kirloskar Oil Engines Limited in India. This engine is highly durable and used in many different applications such as generators, agricultural machines, water pumps, air compressors, and other industrial equipment. The Kirloskar TV1 engine has a cylinder capacity of 661cc and a maximum power of about 3.5 kW at 1500 rpm engine rotation. It uses a water-cooling system and a direct oil injection system. This engine also has a high-pressure oil lubrication system to increase its life and durability.

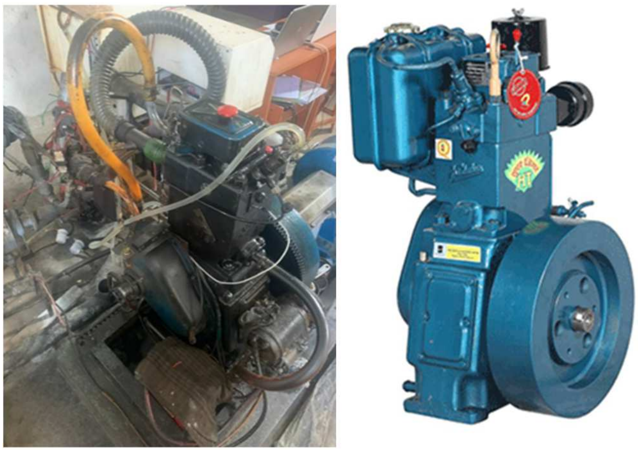


Fig. 3 Kirloskar TV1 engine for simulation

C. Test Fuel

Some essential properties of WCO compared to fossil diesel fuel are listed in Table I. The WCO availability globally is huge. However, large WCO is dumped into wastelands and rivers, causing ecological threats. An efficient way to process WCO is transesterified to biodiesel and used as fuel in diesel engines [125].

TABLE I
PROPERTIES OF WASTE COOKING OIL-DERIVED BIODIESEL (WCO) AND DIESEL FUEL [126]

Properties	Diesel fuel	WCO
Density (kg/m^3)	840	880
Viscosity (cSt) @ 30^{o}C	4,59	45
Lower heating value (kJ/kg)	42,490	39.600
Flashpoint (^{o}C)	52-96	273
Self-ignition temperature (^{o}C)	260	300
Cetane number	45	37

D. Simulation Model of the PCCI Engine Using Diesel Fuel/WCO Blends

A cylindrical combustion chamber used to burn a mixture of diesel and WCO under different torque conditions is studied using a dissipation model in ANSYS Fluent. On the other hand, the fuel stream is injected in pulse form (split injection) as shown in Fig. 4.

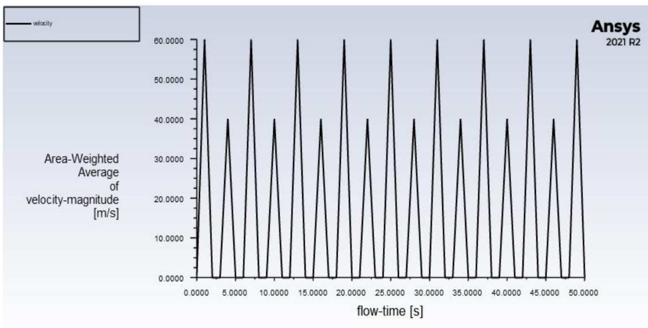


Fig. 4 Fuel injected in pulse form

The combustion reaction is determined according to the enthalpy of formation, and stoichiometric coefficients, as well as the parameters controlling the rate of reaction. The rate of reaction is estimated with the assumption that turbulent-type mixing is a rate-restricting process, with chemical-turbulence interactions modeled employing a model of eddy dissipation. The eddy dissipation model calculates reaction rates with the consideration that the chemical kinetics are quicker in comparison with the pace at which the mixing of reactants takes place caused by turbulent oscillations. ANSYS Fluent can model species transport and reactions using a partially premixed combustion method model.

At the end of the injection process, two-dimensional results of pressure, temperature, velocity, and mass fraction of diesel, oxygen, carbon dioxide, soot, and water vapor can be obtained. Split injection in computational fluid dynamics refers to fuel injection in two stages or injection locations during the combustion process in a diesel engine. The split injection process includes stage 1 injection corresponding to 50^{o}BTDC, and stage 2 injection corresponding to 20^{o}BTDC top dead center, and the injection pressure is 500 bar. The objectives of the simulation are as follows: Activating physical models and defining boundary conditions for turbulent flows with mixing and reactions of fuel types B10, B20, B30, and B40; Solving combustion simulations using a pressure-based solver; Checking reaction flow results graphically; and Predicting temperature and NOx and soot emissions. Fig. 5 and Fig. 6 depict the temperature and mass fraction of diesel fuel burnt in cylinders.

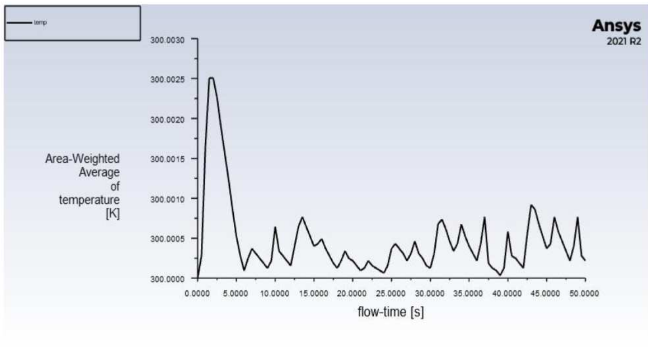


Fig. 5 Temperature in cylinder

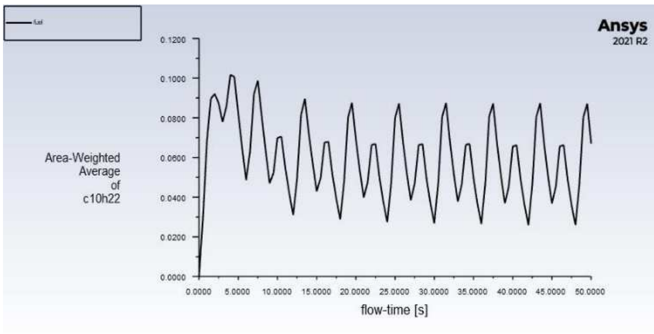


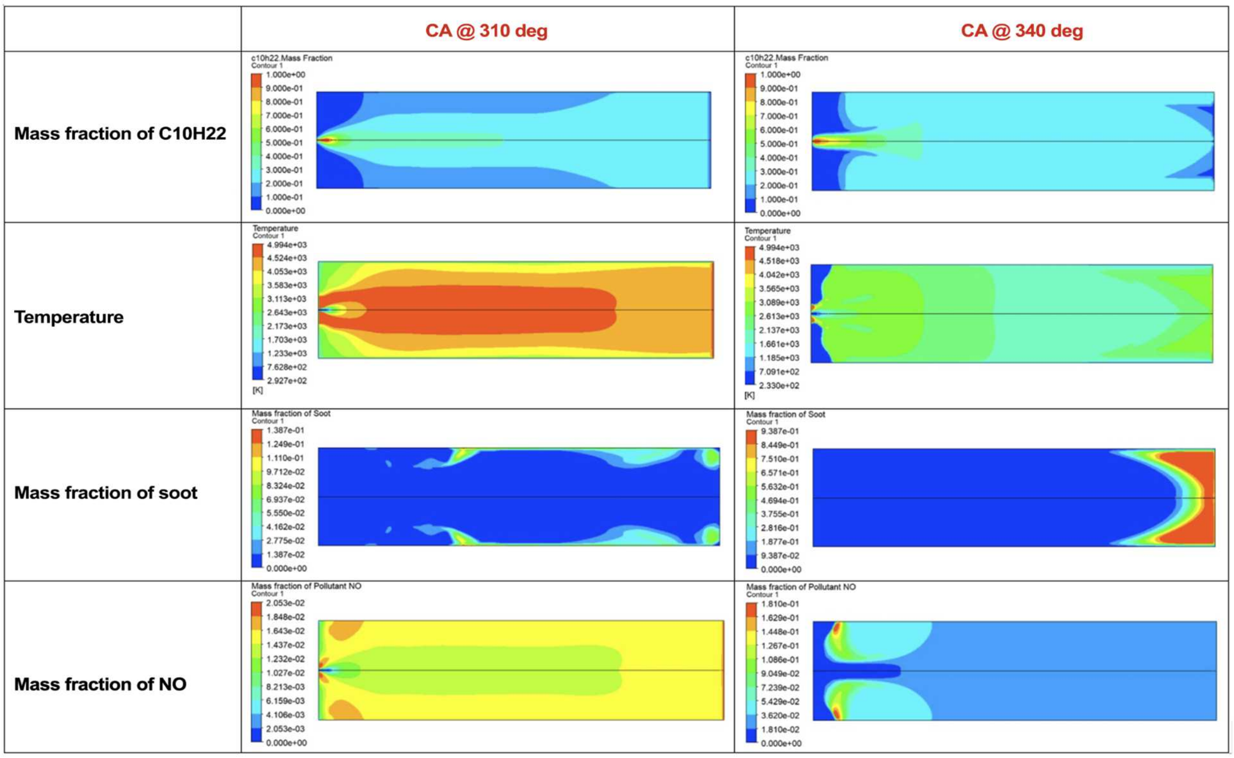
Fig. 6 Mass fraction of diesel fuel burnt in cylinder

PCCI mode corresponds to the first spray volume of 60% and the second spray volume of 40% at a constant time interval of CA 310^o and 340^o, it is meaning that constant timing CA 310^o and 340^o (PCCI 50^o - 20^o), first fuel injection at 50^o BTDC and second fuel injection of 20^o BTDC were used for split injection in PCCI node. Combustion of diesel mixture with waste cooking oil at torque modes of 0 Nm, 4.875 Nm, 9.75 Nm, 14.625 Nm, and 19.5 Nm was investigated employing eddy dissipation framework in ANSYS Fluent.

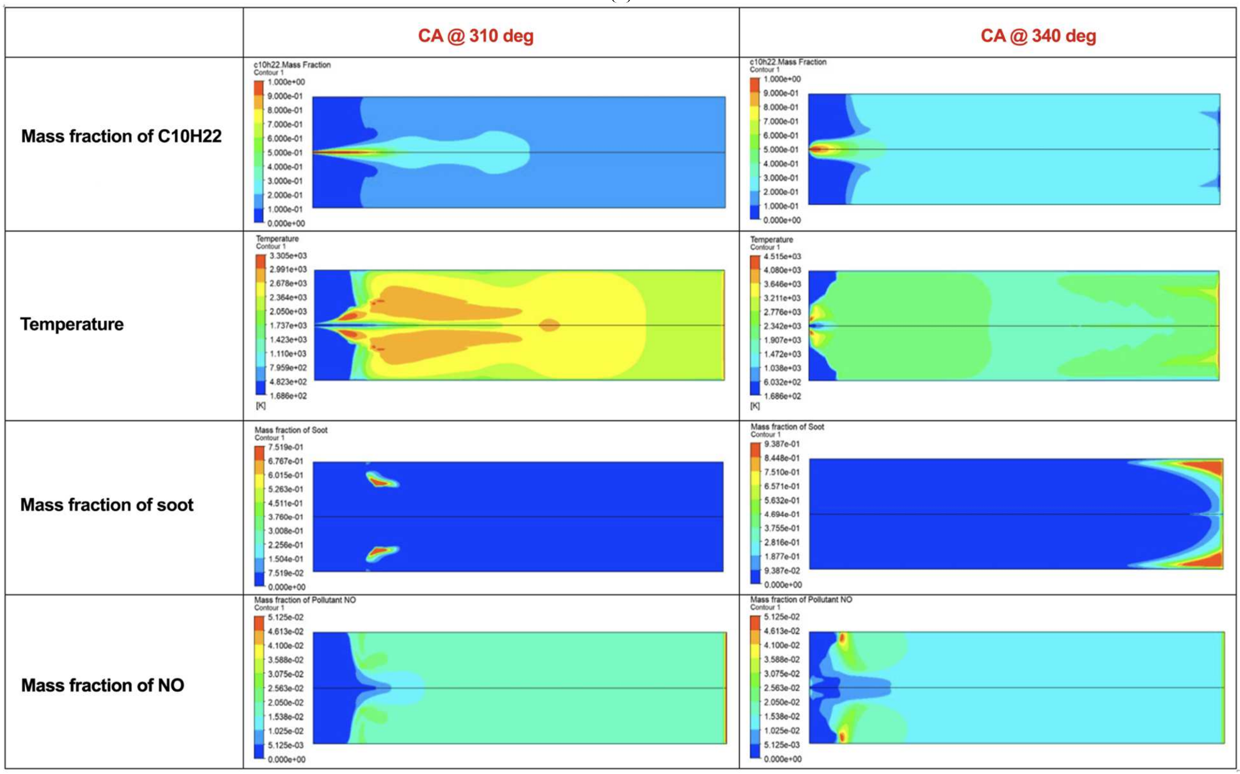
III. Results and Discussion

A. PPCI Mode with 60% and 40% of Split Injection for Diesel Fuel

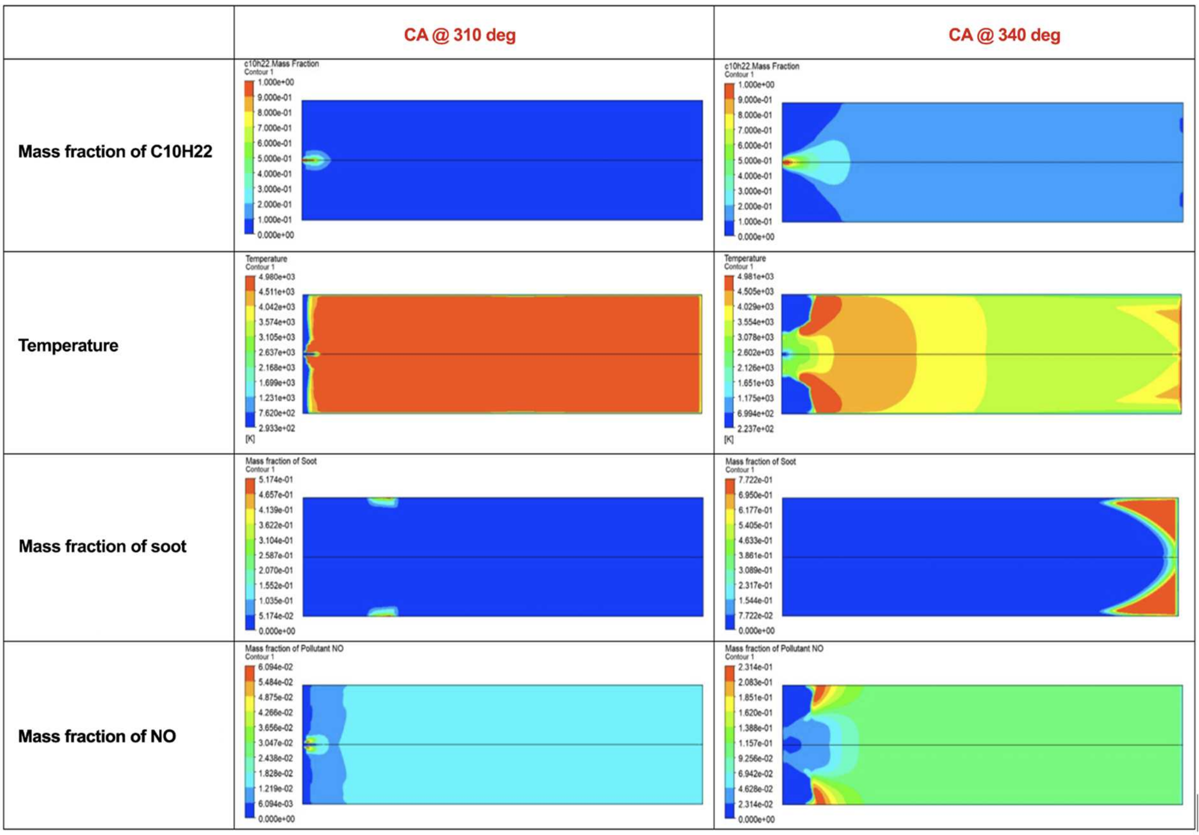
The simulation results provide a detailed depiction of the combustion process, including fuel injection, mixing, ignition, flame propagation, and heat release. By visualizing key parameters such as fuel distribution, temperature profiles, pressure contours, and species concentrations the effectiveness of the split injection strategy in promoting efficient combustion and minimizing emissions can be assessed. The simulation utilized a pressure-based solver with unsteady Reynolds-Averaged Navier-Stokes (RANS) equations and a multi-species transport model to track the behavior of fuel components and air during the combustion process. The effects of injection rate in split injection for diesel fuel applied to PCCI mode can be shown in Fig. 7.



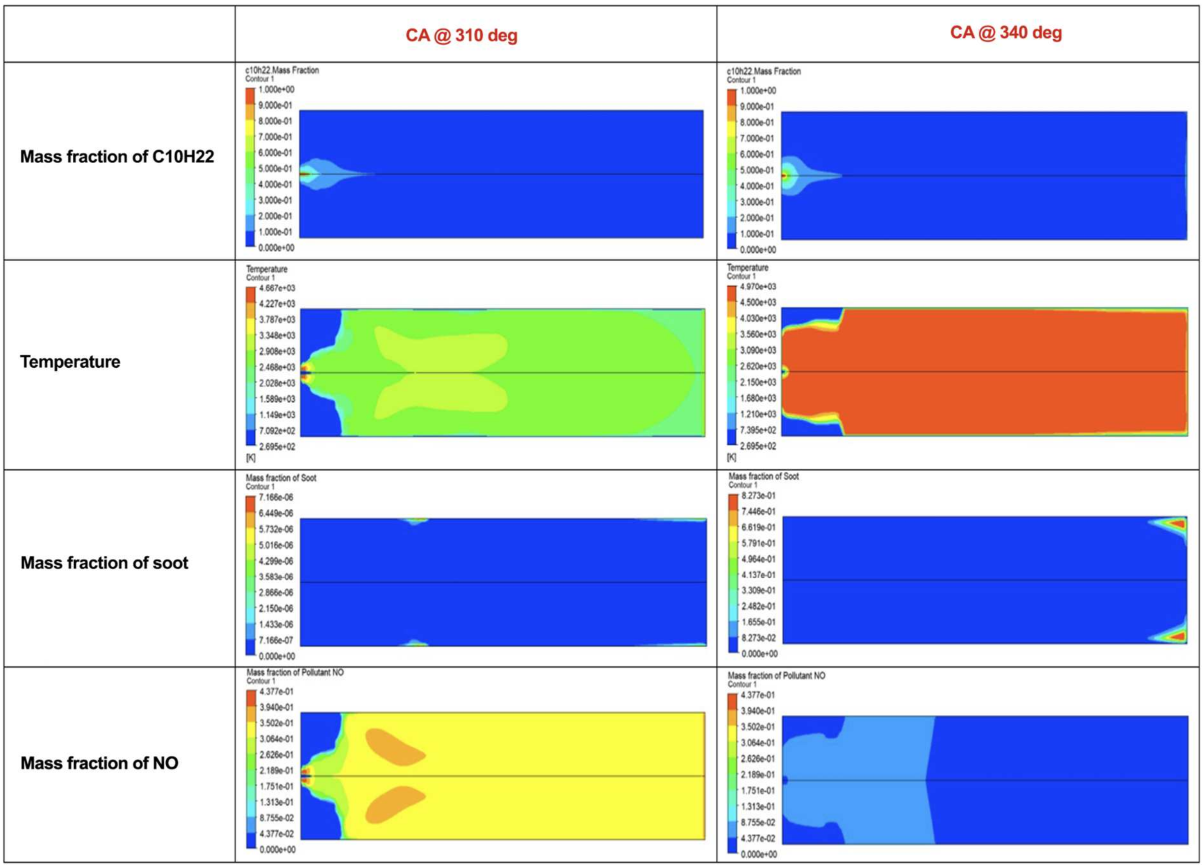
(a)



(b)



(c)



(d)

Fig. 7 Simulation results of PCCI mode using diesel fuel at various torque values, (a) 19.5 Nm, (b) 14.625 Nm, (c) 9.75 Nm, (d) 4.875 Nm

Temperature distributions within the cylinder provided information on combustion patterns and potential hotspots. Species concentration data allowed for tracking fuel components and pollutant formation (like NOx and PM). Pressure variations were analyzed to evaluate engine performance parameters such as peak pressure and indicated power. Emission levels were estimated based on the species concentration data. The temperature contour plot provides insights into the thermal environment within the diesel engine during combustion. High temperatures are indicative of intense heat release and combustion activity, while low temperatures may signify regions of incomplete combustion or quenching effects [127]. The temperature distribution influences various combustion parameters, including ignition delay, flame propagation, and pollutant formation kinetics [128], [129]. Analyzing temperature gradients across different regions of the combustion chamber and exhaust system facilitates the optimization of engine design and operating conditions for improved performance and reduced emissions.

The NOx contour plot generated from the ANSYS CFD simulations illustrates the spatial distribution of nitrogen oxides within the combustion chamber and exhaust system of the diesel engine. High NOx concentrations typically occur in regions where combustion temperatures exceed the threshold for nitrogen and oxygen to react, such as near the flame front and in regions of high turbulence intensity. The NOx contour plot enables the identification of hot spots and areas of localized NOx formation, which are critical for understanding emission formation mechanisms and developing strategies for NOx reduction. Interpreting NOx, soot, and temperature contour plots from ANSYS CFD simulations involves considering several factors, including turbulence modeling, combustion chemistry, and boundary conditions.

When using D100 fuel, the temperature inside the cylinder increases higher than when using B10, B20, B30, or B40. In addition, the temperature inside the cylinder depends on the operating conditions of the engine. The greater the torque, the greater the temperature inside the cylinder, and vice versa [130]. NOx emissions are formed when nitrogen and oxygen molecules in the air react at high temperatures. The higher the temperature, the easier these reactions occur, and the more NOx is produced. When using D100 fuel, NOx emissions increase higher than when using B10, B20, B30, B40. Similar to temperature, engine design and operating conditions (load, speed) influence combustion characteristics and NOx formation. The increase in NOx emissions became more significant as the engine faced heavier workloads [131]–[133]. The amount of soot emitted is influenced by the oxygen content and other properties of the WCO. D100 fuel has a lower oxygen content than B10, B20, B30, and B40, causing incomplete combustion, leading to increased soot emissions

B. B. PPCI Mode with 60% and 40% Split Injection for B10, B20, B30, B40

1) Effect of WCO blend on temperature:

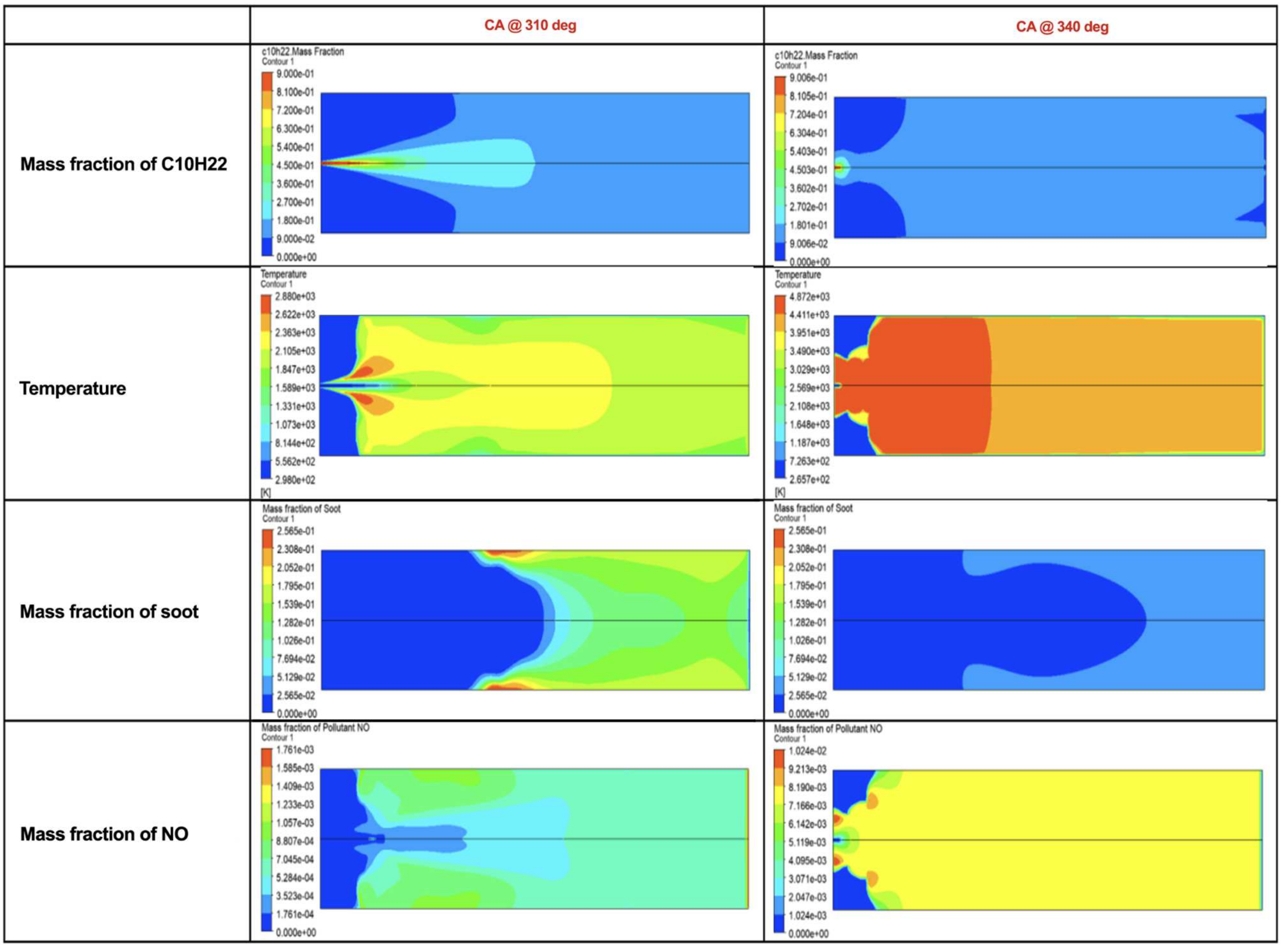
Waste cooking oil (WCO)/diesel fuel blends often have different combustion characteristics compared to pure diesel fuel. Due to differences in viscosity, cetane number, and chemical composition, the ignition delay, flame stability, and heat release rate may vary. These properties can affect the atomization and vaporization of fuel droplets, thereby influencing the combustion process and, consequently, combustion temperature. These variations affected the temperature distribution within the combustion chamber during combustion.

When using blends of diesel fuel and WCO (B10, B20, B30, B40), the temperature inside the cylinder decreases slightly compared to when using D100. WCO biodiesel typically has a lower heating value compared to diesel. This means it releases less energy during combustion, potentially leading to a slight decrease in exhaust gas temperature. Lower blends (e.g., B10, B20) might have a lesser impact on temperature compared to higher blends (e.g., B40). The observed pattern could be attributed to elevated cylinder temperatures within the engine resulting from increased fuel combustion. Furthermore, as engine load rises, there is a corresponding escalation in heat loss through exhaust gases. Some studies suggest WCO biodiesel might have a higher boiling point than diesel. This could delay complete fuel vaporization, leading to a temporary rise in peak in-cylinder temperature during the early stages of combustion.

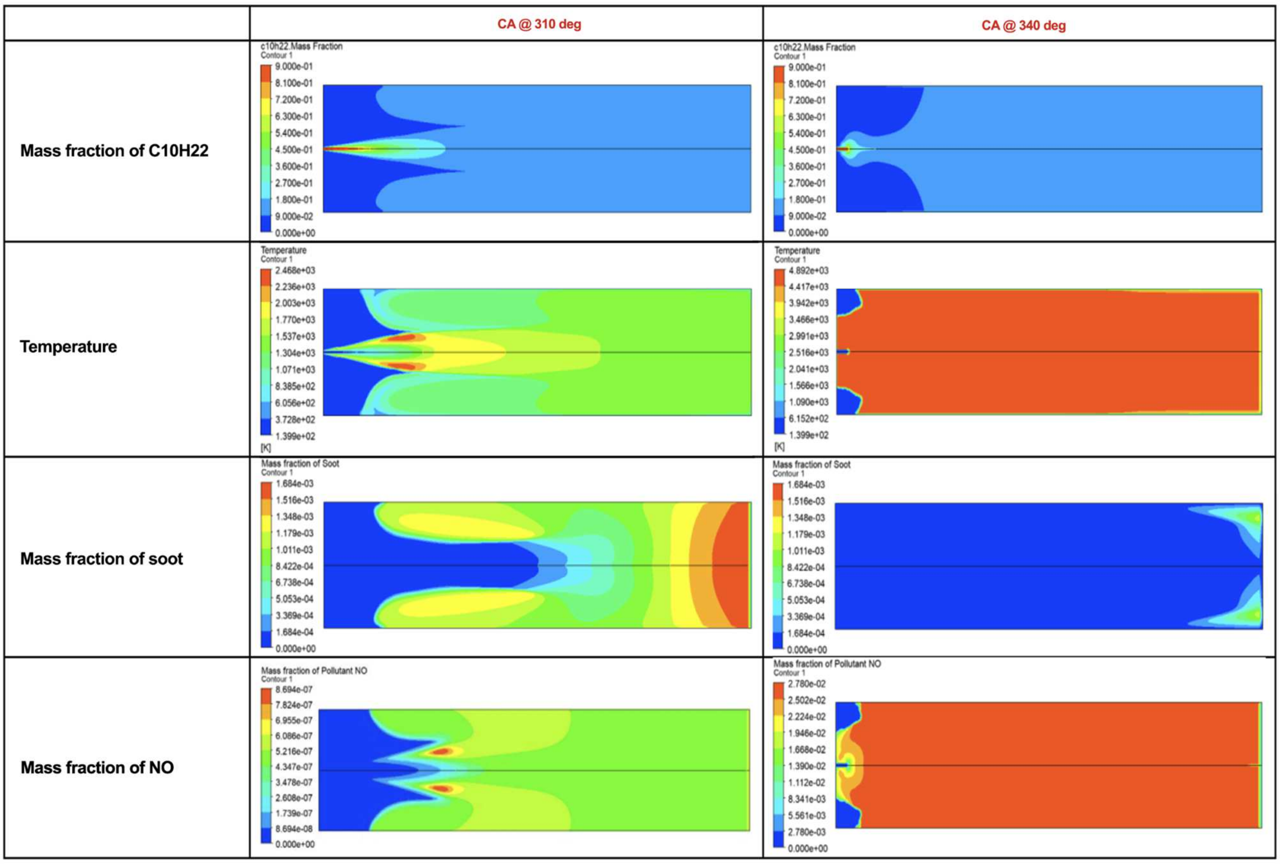
2) Effect of WCO blend on NOx:

WCO biodiesel boasts a higher oxygen content compared to diesel. This extra oxygen within the cylinder aids in a more complete combustion process, potentially reducing NOx formation. By promoting complete combustion, less unburnt fuel and nitrogen are available to react, potentially lowering NOx emissions. While complete combustion is desirable, WCO biodiesel might cause a temporary rise in peak in-cylinder temperature. These higher temperatures favor the formation of thermal NOx, negating the benefit of increased oxygen. Due to the reduced temperature when using B10, B20, B30, and B40 compared to D100, there is a slight reduction in NOx. Indeed, B10, B20, B30, and B40 fuels have a higher oxygen content than D100 fuel, making the combustion process improved, leading to a slight decrease in soot emissions. Two-stage injection allows for better control of the combustion process by precisely timing the injections. Primer injection creates a more favorable air and fuel mixture before the main injection, which can result in a gradual and controlled release of heat during combustion. This helps avoid localized hot spots and reduces peak combustion temperatures, which is beneficial for reducing the formation of NOx and soot emissions. The effects of injection rate in split injection for B10, B20, B30, and B40 applied to PCCI mode could be shown in Fig. 8 to Fig. 11.

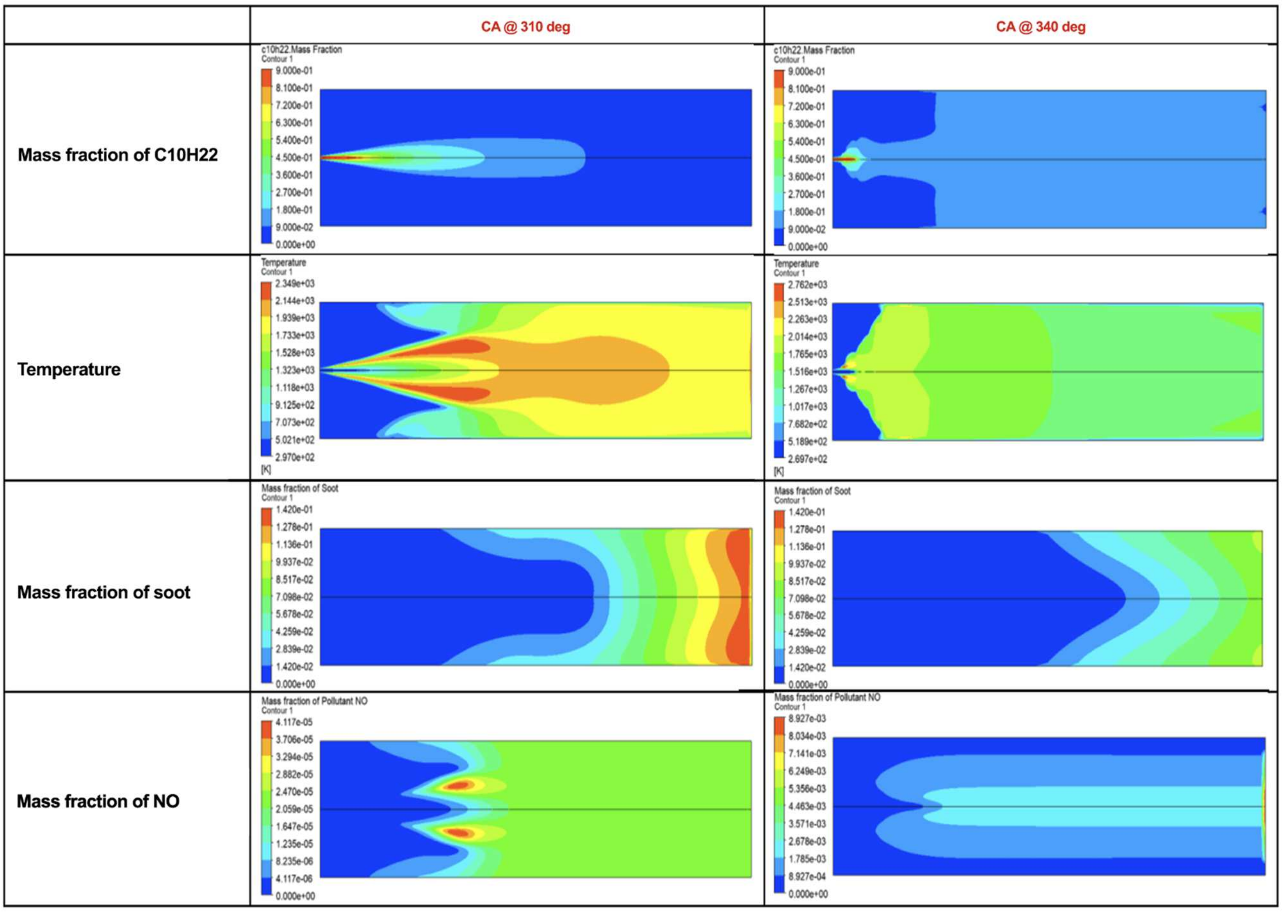
WCO biodiesel makes engines release more NOx pollutants. This happens because biodiesel has more oxygen and burns hotter inside the engine compared to regular diesel fuel. The B20 blend produced the most NOx, while pure diesel fuel (D100) resulted in the least. Beyond the temperature increase, several factors contribute to the rise in NOx emissions. These include the unique chemical makeup of biodiesel, how it sprays within the engine, and the time it takes for the fuel to ignite. These factors influence how quickly and completely the fuel burns, impacting the formation of NOx [134], [135]. WCO blends often contain higher levels of oxygenates and unsaturated fatty acids compared to pure diesel fuel [136]. These compounds may contribute to increased NOx formation by promoting more complete combustion and higher flame temperatures [137].


CA @ 310 deg
CA @ 340 deg
Mass fraction of C10H22
Temperature
Mass fraction of soot
Mass fraction of NO

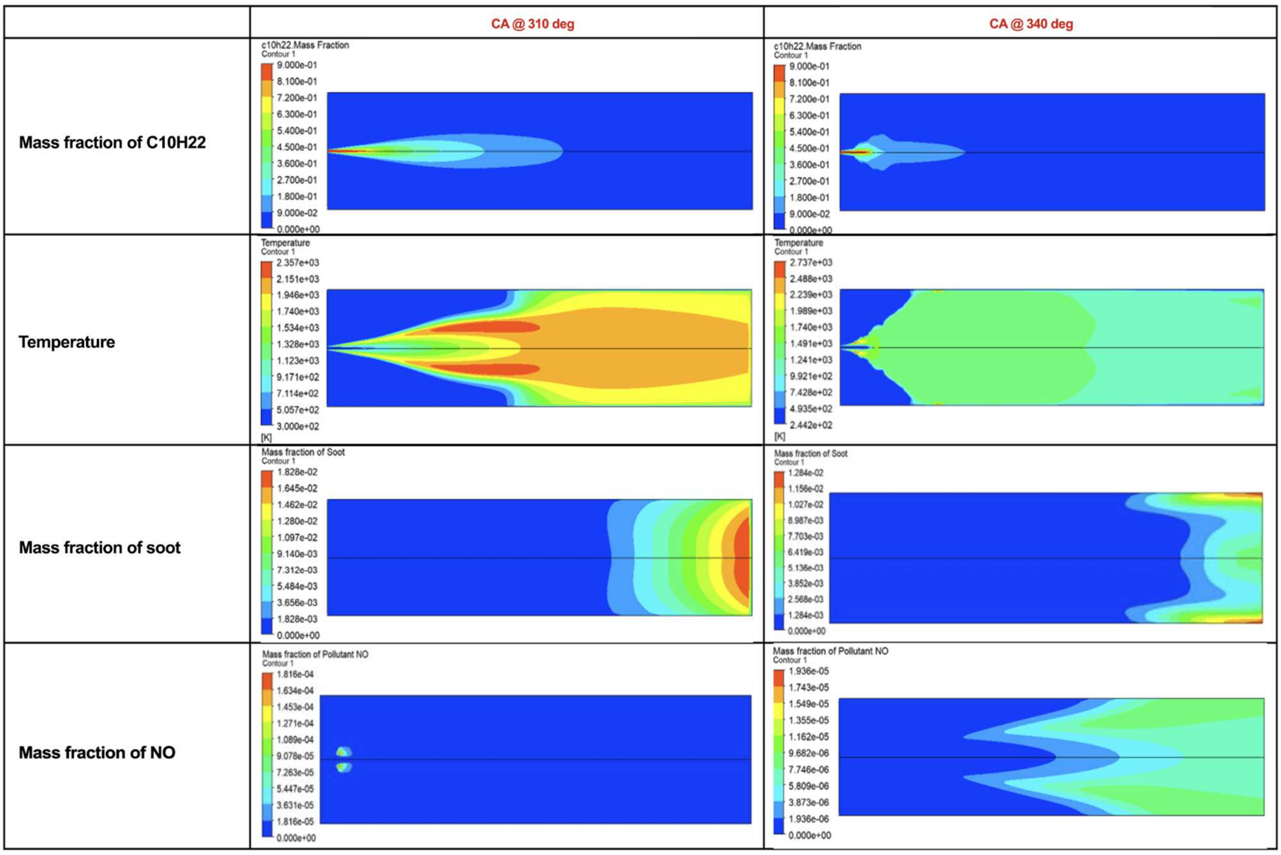
(a)


CA @ 310 deg
CA @ 340 deg
Mass fraction of C10H22
Temperature
Mass fraction of soot
Mass fraction of NO

(b)

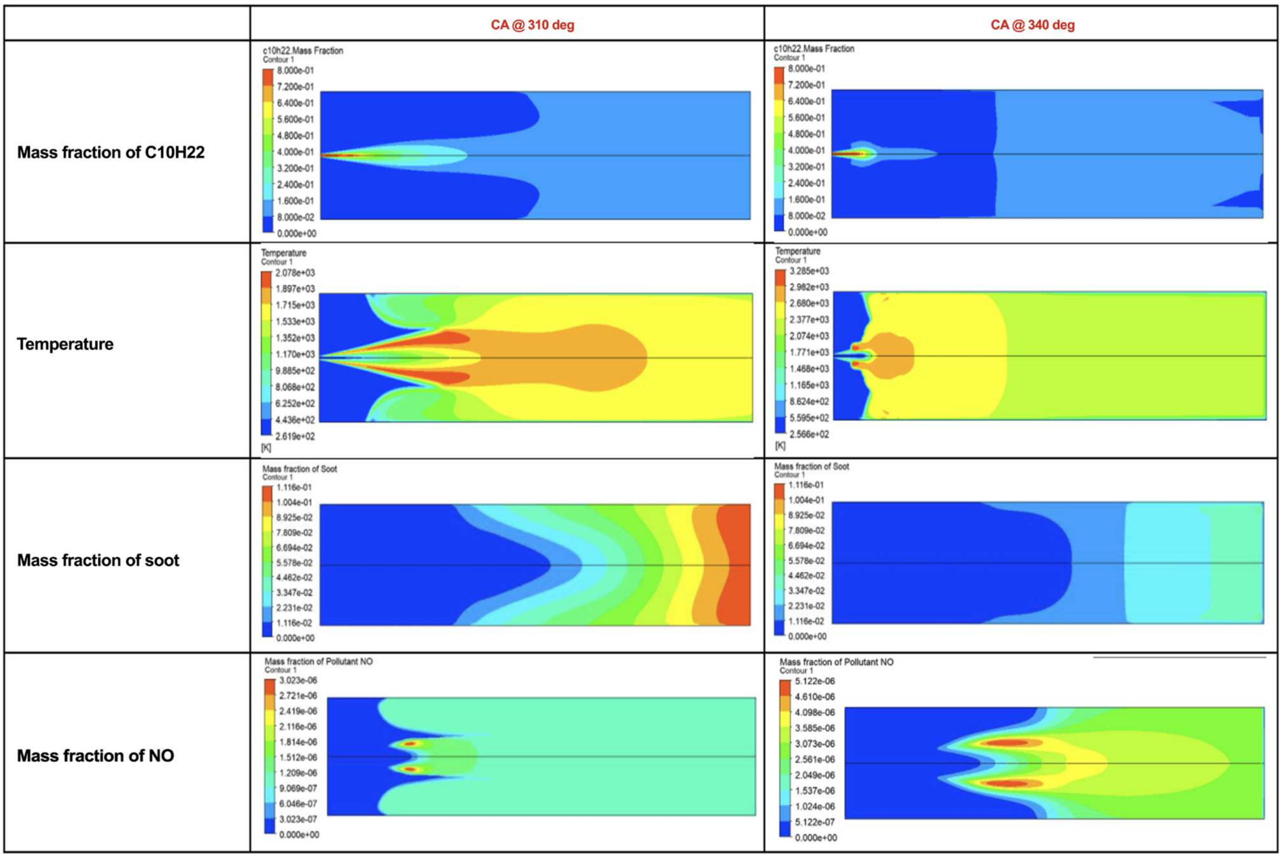


(c)

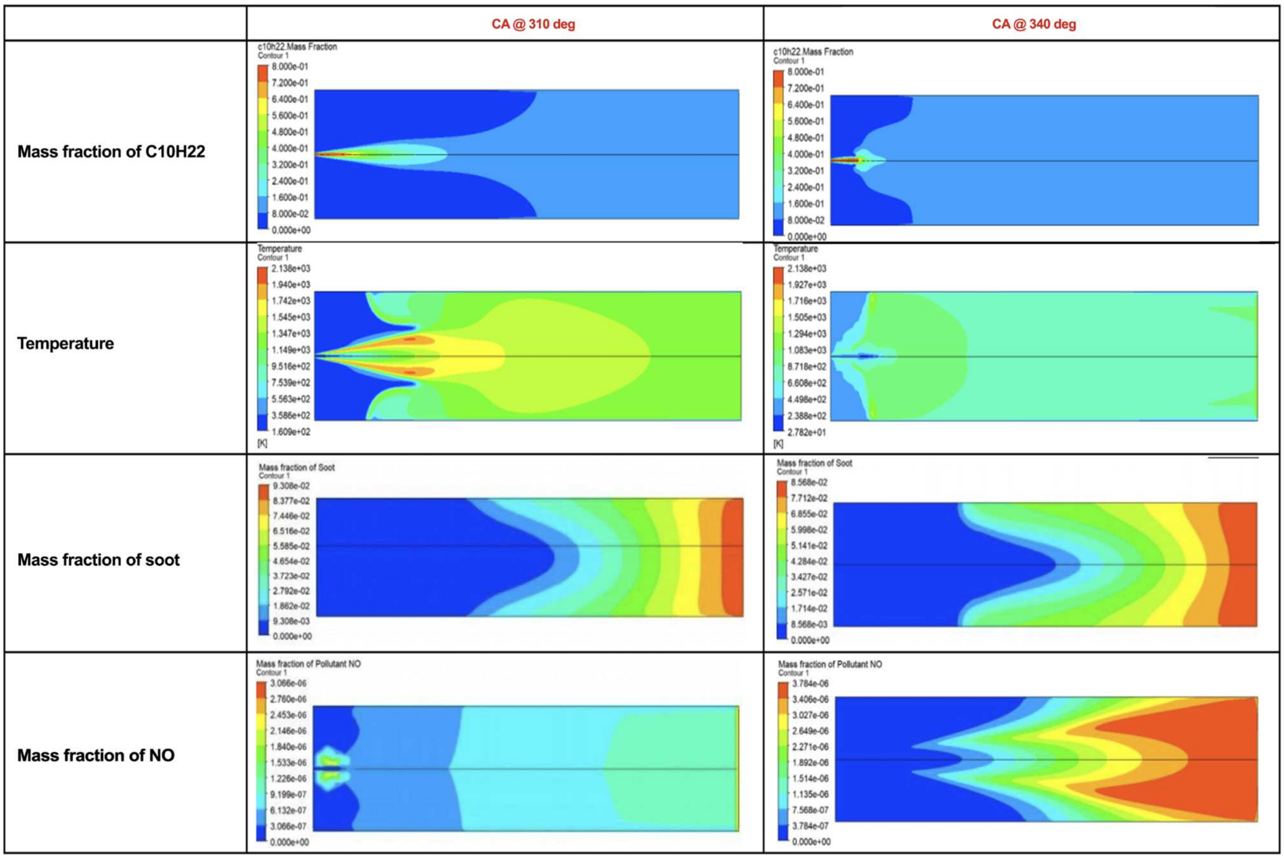


(d)

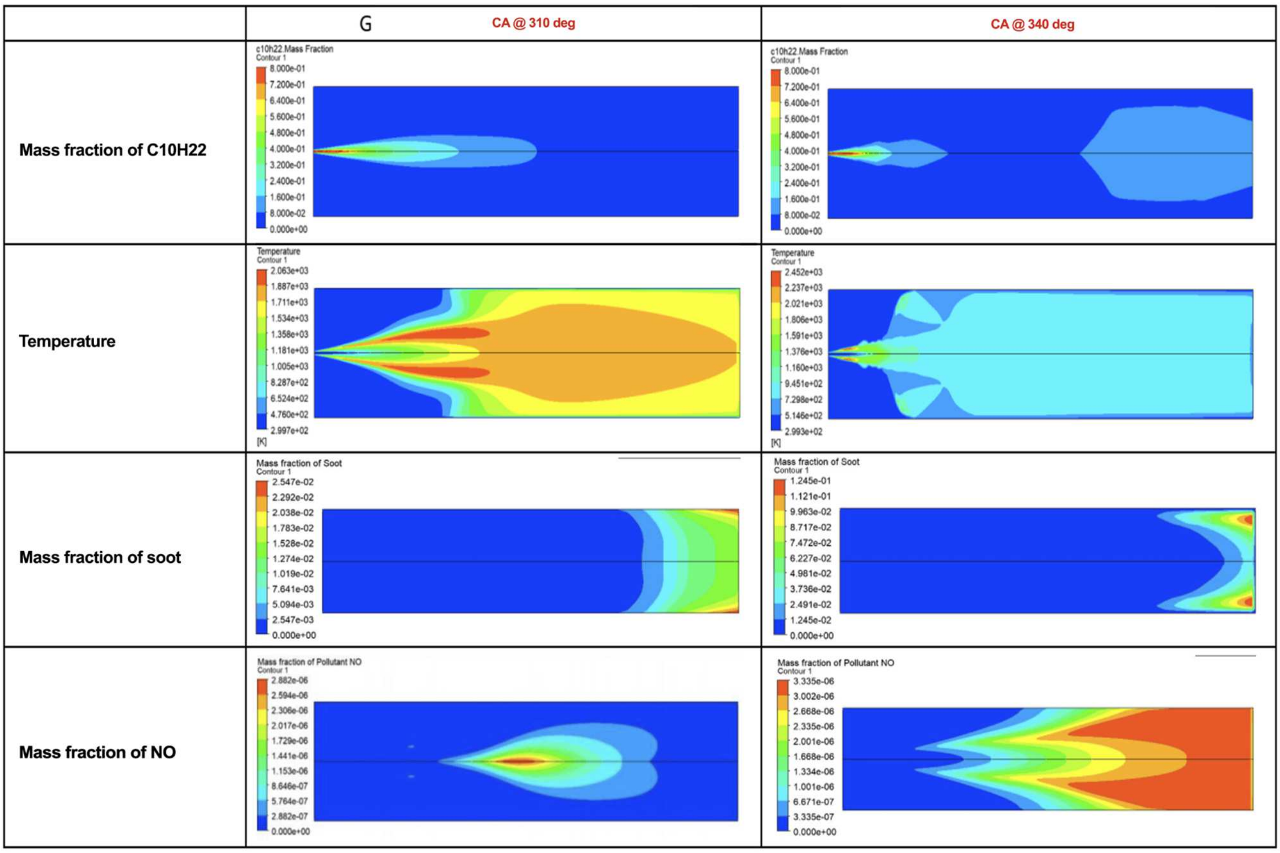
Fig. 8 Simulation results of PCCI mode using B10 at various torque values, (a) 19.5 Nm, (b) 14.625 Nm, (c) 9.75 Nm, (d) 4.875 Nm


CA @ 310 deg
CA @ 340 deg
Mass fraction of C10H22
Temperature
Mass fraction of soot
Mass fraction of NO

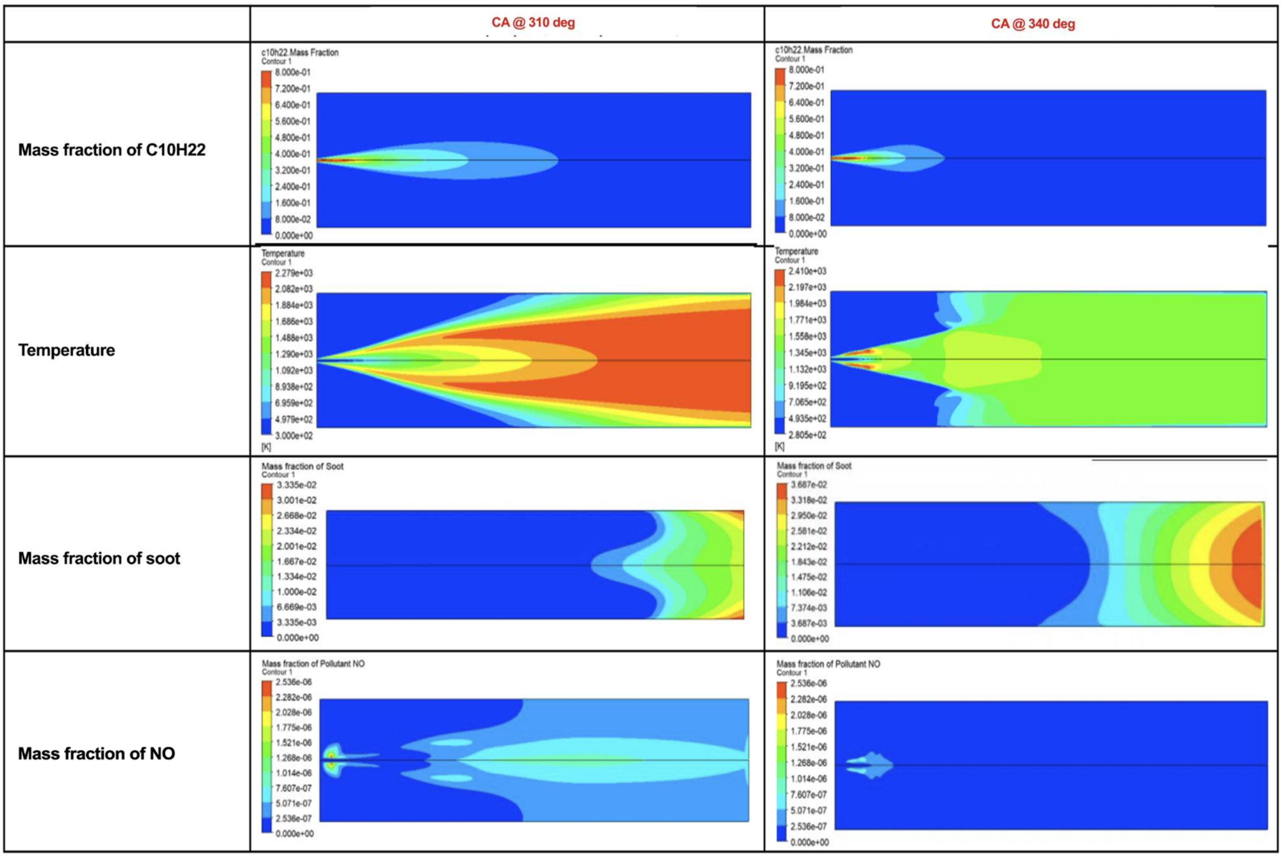
(a)


CA @ 310 deg
CA @ 340 deg
Mass fraction of C10H22
Temperature
Mass fraction of soot
Mass fraction of NO

(b)

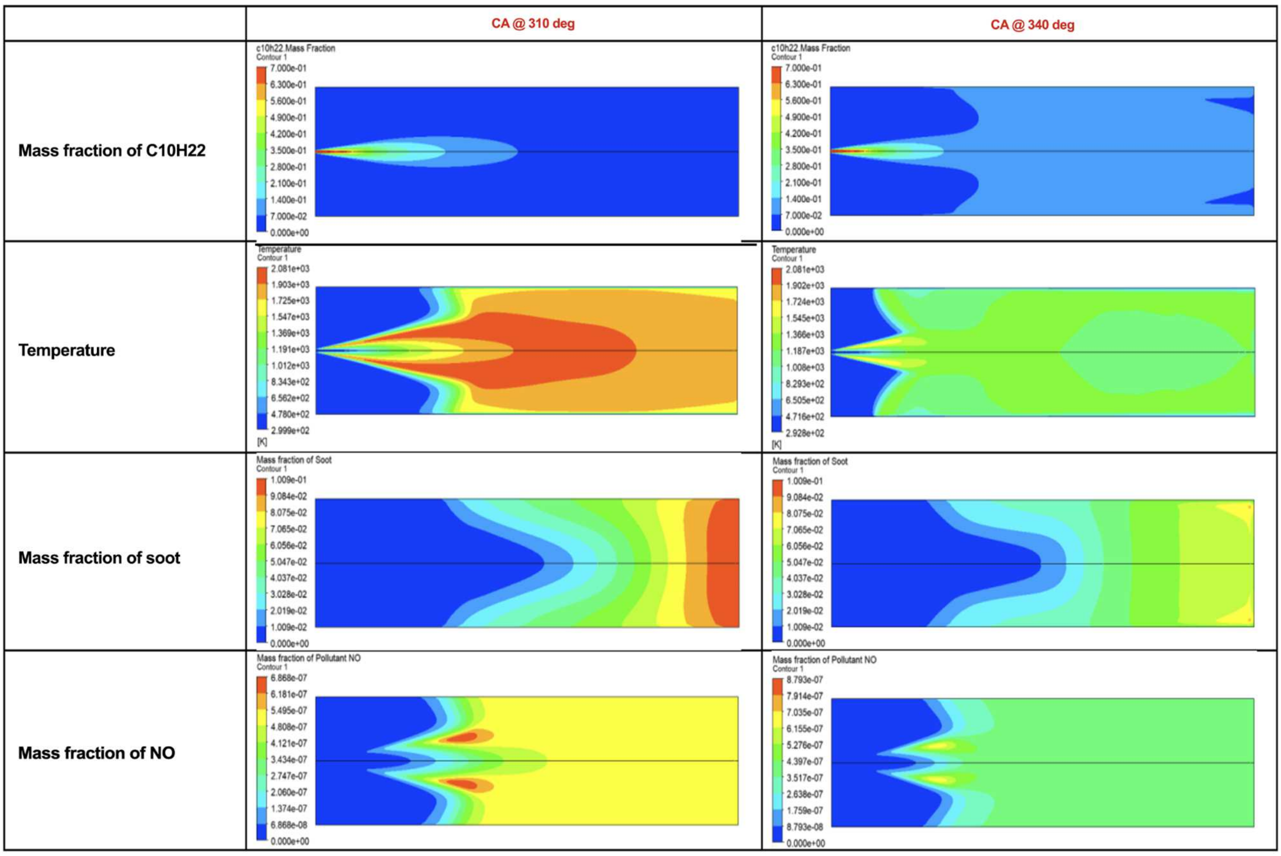


(c)

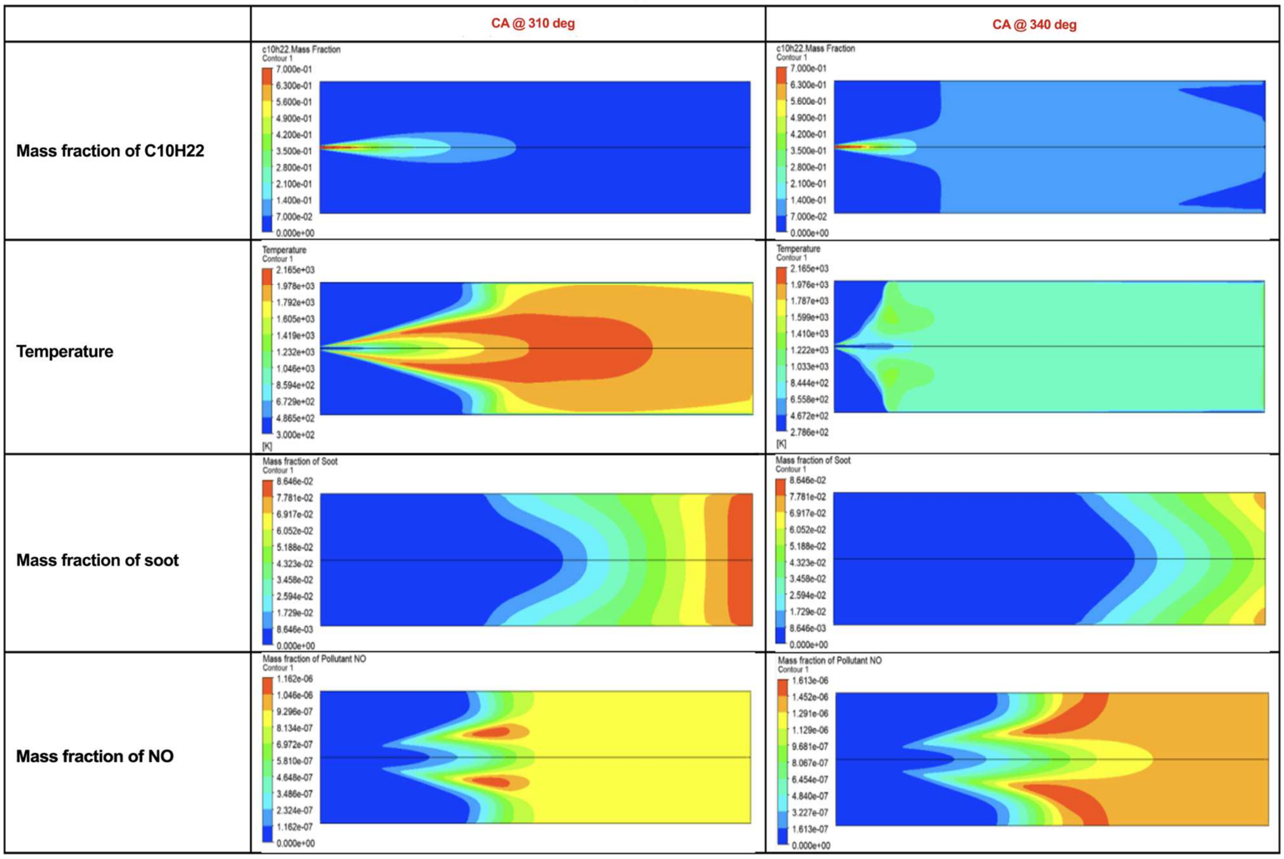


(d)

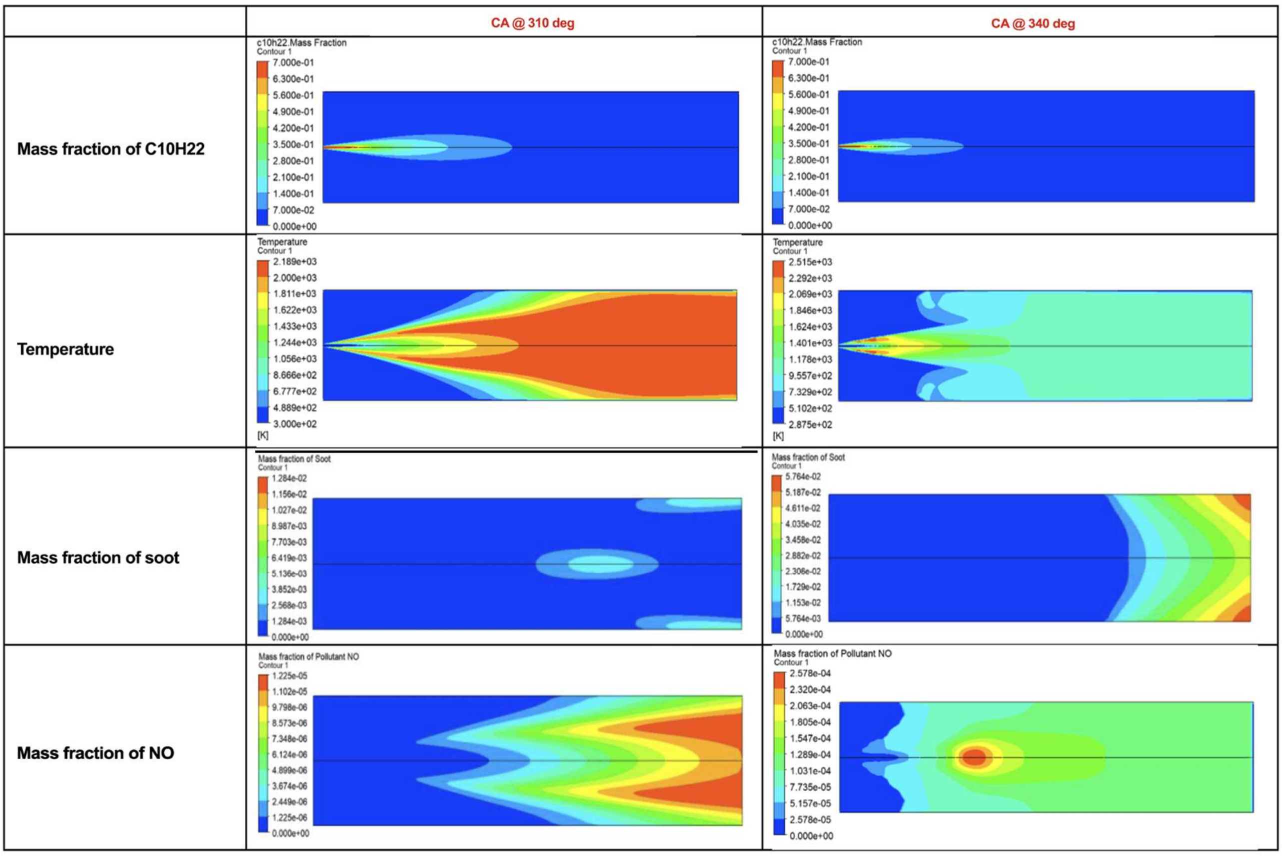
Fig. 9 Simulation results of PCCI mode using B20 at various torque values (a) 19.5 Nm; (b) 14.625 Nm; (c) 9.75 Nm; (d) 4.875 Nm


CA @ 310 deg
CA @ 340 deg
Mass fraction of C10H22
Temperature
Mass fraction of soot
Mass fraction of NO

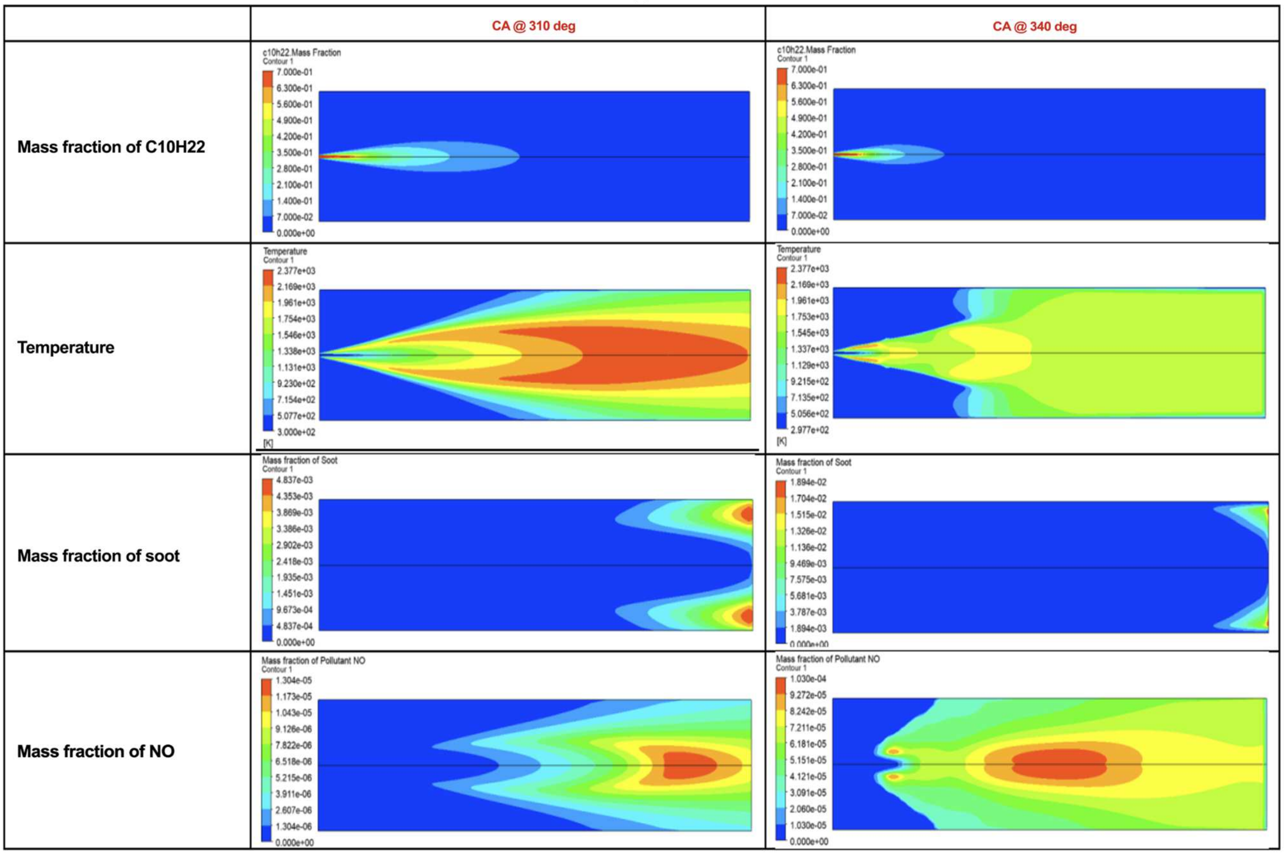
(a)


CA @ 310 deg
CA @ 340 deg
Mass fraction of C10H22
Temperature
Mass fraction of soot
Mass fraction of NO

(b)

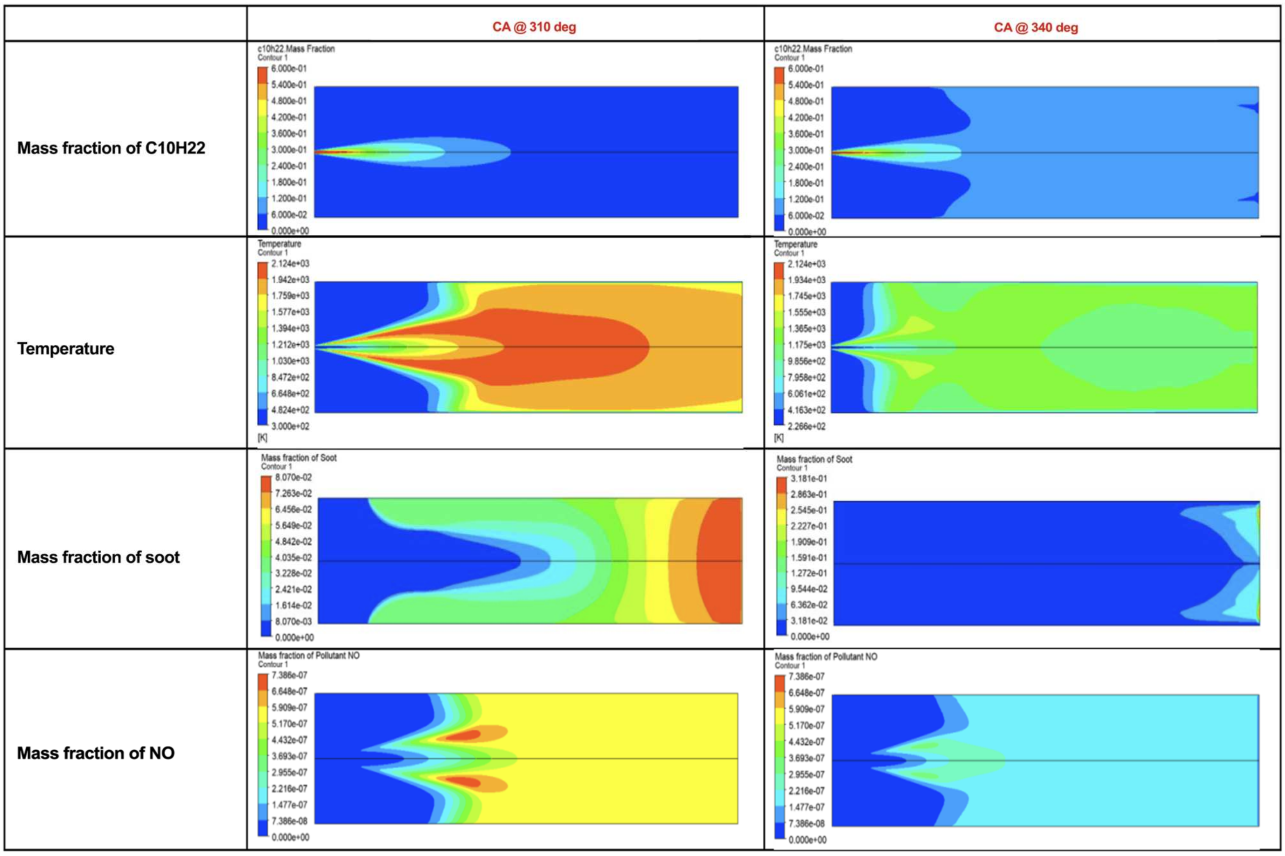


(c)

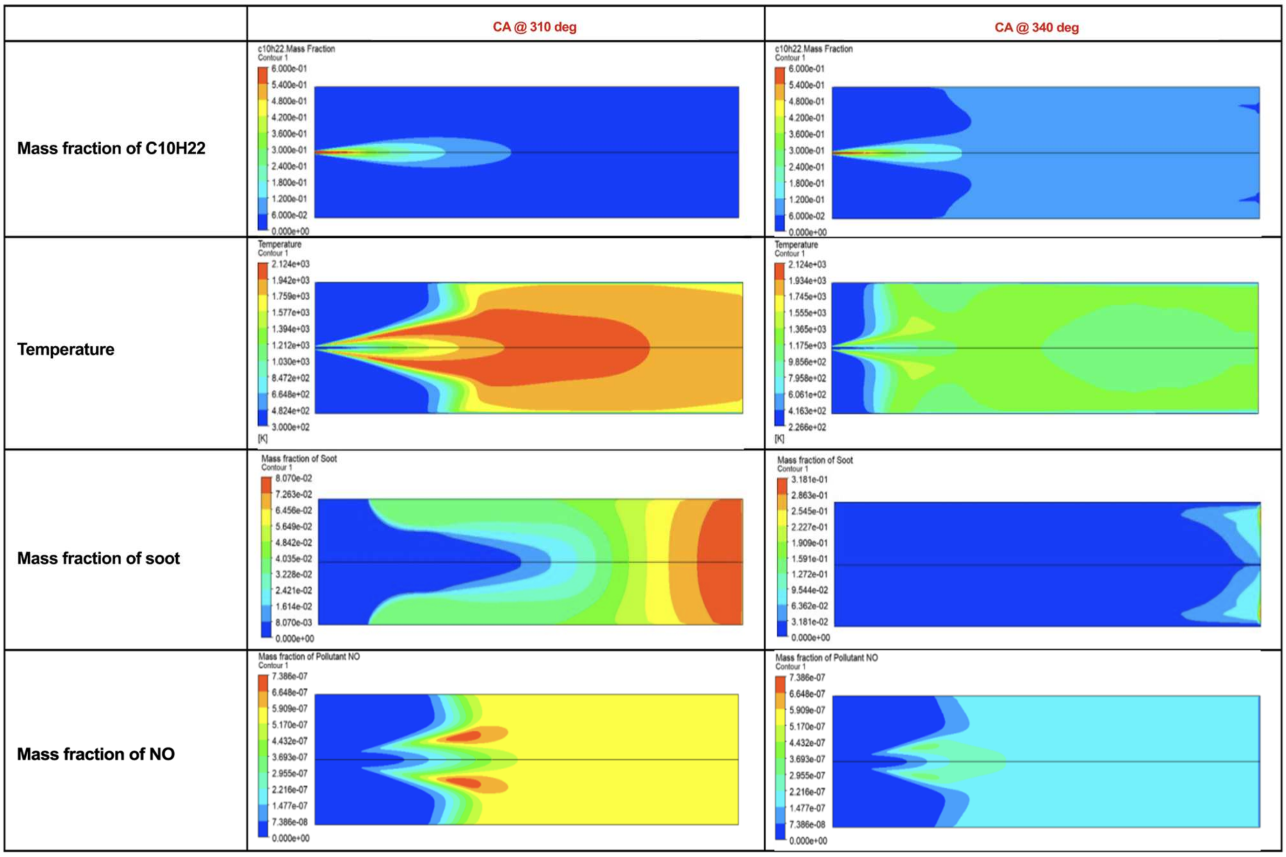


(d)

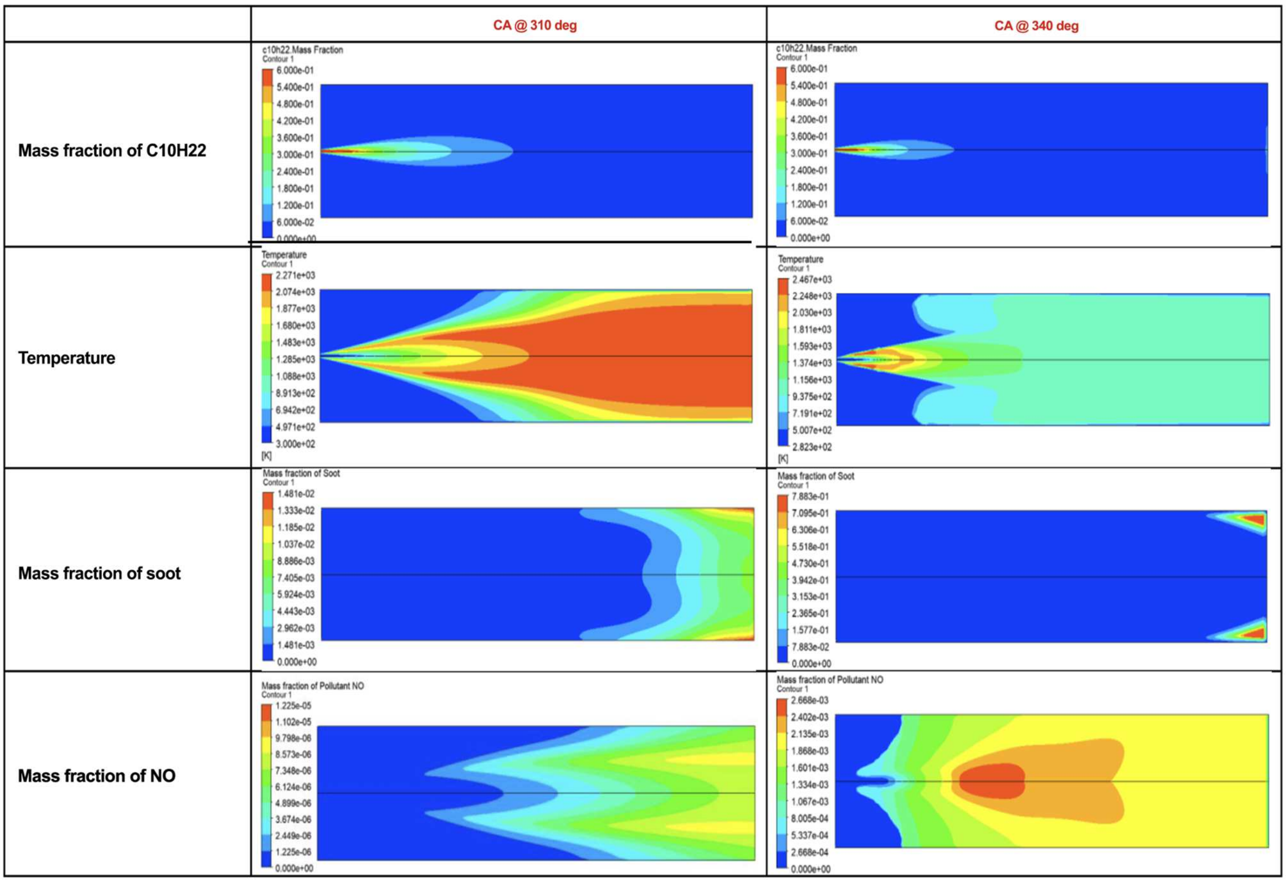
Fig. 10 Simulation results of PCCI mode using B30 at various torque values (a) 19.5 Nm; (b) 14.625 Nm; (c) 9.75 Nm; (d) 4.875 Nm


CA @ 310 deg
CA @ 340 deg
Mass fraction of C10H22
Temperature
Mass fraction of soot
Mass fraction of NO

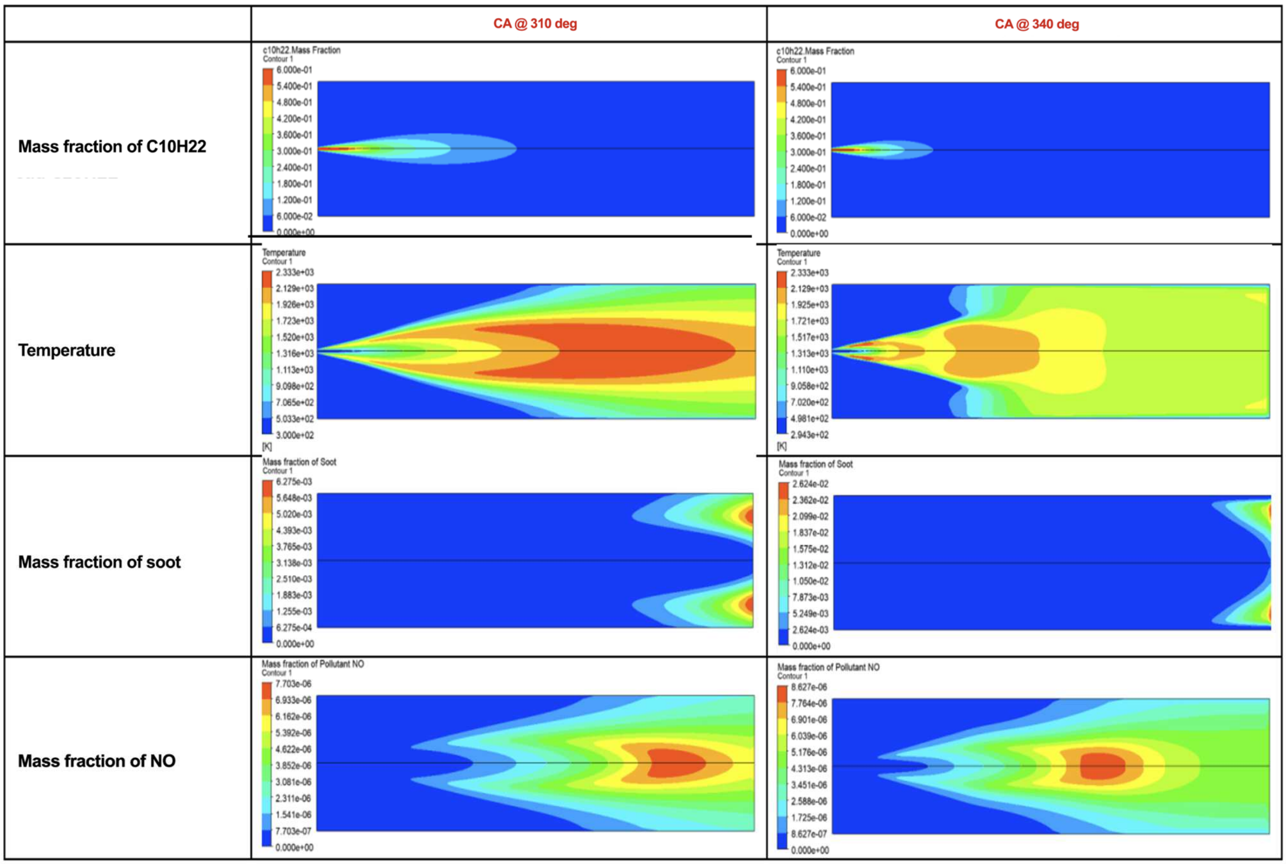
(a)


CA @ 310 deg
CA @ 340 deg
Mass fraction of C10H22
Temperature
Mass fraction of soot
Mass fraction of NO

(b)



(c)



(d)

Fig. 11 Simulation results of PCCI mode using B40 at various torque values (a) 19.5 Nm; (b) 14.625 Nm; (c) 9.75 Nm; (d) 4.875 Nm

Additionally, differences in fuel atomization, vaporization, and mixing may affect the distribution of fuel-air mixture and subsequently impact NOx emissions. Some studies reported a reduction in NOx with lower WCO biodiesel blends (e.g., B10, B20). The increased oxygen content has a dominant effect, promoting complete combustion and potentially lowering NOx. Other studies observed higher NOx emissions with higher WCO biodiesel blends (e.g., B40). The combined effect of higher in-cylinder temperatures and trace nitrogen content from WCO might outweigh the oxygen advantage.

When blending diesel fuel with WCO, NOx emissions may be affected depending on the blend ratio and characteristics of the WCO used. However, the actual impact on NOx emissions will depend on several factors, including engine type, operating conditions, and the specific chemical composition of the WCO. For B10, B20, B30, and B40, NOx emissions compared to pure diesel fuel are reduced by 5 - 20% Overall, two-stage injection allows for better control of the combustion process by precisely timing the injections [138], [139]. The initial injection creates a more favorable air and fuel mixture before the main injection, which can result in a gradual and controlled release of heat during combustion [140], [141]. This controlled heat release can help manage peak temperatures inside the cylinder and reduce the possibility of knocking or engine damage from excessive heat. A shorter ignition delay results in more efficient and controlled combustion, helping to maintain lower peak cylinder temperatures [142], [143]. By dividing the fuel supply, the temperature rise during combustion is more evenly distributed. This helps avoid localized hot spots and reduces peak combustion temperatures, which is beneficial for reducing NOx formation. Lower peak temperatures also contribute to more efficient and stable combustion [144]. The PCCI combustion method promotes temperature uniformity in the cylinder. By injecting fuel in two stages, the temperature distribution throughout the combustion chamber becomes more uniform [145], which results in better thermal efficiency and reduced emissions [146].

3) Effect of WCO blend on soot

In the fact, WCO/diesel fuel oil blends exhibited different combustion characteristics, including ignition delay, flame stability, and temperature profiles, compared to pure diesel fuel [147], [148]. These variations can impact the distribution of temperature and residence time within the combustion chamber, influencing the formation and oxidation of soot particles. Basically, inefficient combustion due to poor fuel-air mixing or incomplete combustion leads to increased soot emissions [149], [150]. The soot of WCO blended with diesel contains more light hydrocarbons, 10% more than diesel soot. This is because WCO itself is less volatile, leading to the formation of smaller particles when the exhaust cools down [151], [152]. This effect is especially strong at low engine loads, where exhaust temperatures are low and unburnt fuel condenses onto the particles. Additionally, the smaller size of WCO diesel particles provides more surface area for these hydrocarbons to stick to, further increasing the volatile fraction in the soot. Studies report a reduction in soot emissions with lower WCO biodiesel blends (e.g., B10, B20) due to the dominant effect of increased oxygen content and potentially favorable biodiesel properties promoting complete combustion.

IV. CONCLUSION

This study presents the impacts and control of NOx and PM emissions by PCCI low-temperature combustion. This study has built a model to simulate the combustion process of a diesel engine with the support of ANSYS Fluent software to assess diesel engine working and emission characteristics when using the PCCI combustion method using the PCCI combustion method using WCO-derived biodiesel /diesel fuel blends. Research results based on the RNG k- ε turbulence model were carried out to evaluate the impact of two-stage injection on the combustion processes of WCO (B10, B20, B30, B40) and diesel fuel (D100). The effects of temperature, mass fraction of NOx, soot, and mass fraction of $C_{10}H_{22}$ are also presented. When using B20 for the combustion mode of a traditional diesel engine, NOx and soot emissions decrease slightly, but HC and CO emissions increase. However, when using B20 fuel for PCCI combustion mode, soot and NOx emissions are significantly reduced. The simulation findings suggest that employing the PCCI combustion process with WCO fuel in diesel engines has several economic, technical, and environmental advantages. Furthermore, employing a WCO fuel combination minimizes dependency on conventional fuels and emissions that result in adverse effects on the environment.

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