Numerical Investigation of Surface-Ignition Characteristics of Ethanol in a Ceramic-Coated CI Engine

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Abstract. Surface ignition in compression ignition (CI) engines has emerged as a promising combustion strategy to improve ignition reliability and efficiency when operating with low-cetane renewable fuels such as ethanol. In this study, a detailed numerical investigation is carried out to analyse ethanol surface-ignition characteristics in a ceramic-coated CI engine. A three-dimensional computational fluid dynamics (CFD) model incorporating turbulence, spray breakup, evaporation, surface heat transfer, and detailed chemical kinetics is developed. The ceramic coating applied on the piston crown and combustion chamber walls increases the surface temperature by approximately 120–160 K, which promotes ethanol ignition through surface-assisted reactions rather than conventional auto-ignition.Simulation results indicate that the ceramic-coated configuration reduces the ignition delay by nearly 18–22% compared with the uncoated engine. The peak cylinder pressure increases from 62 bar to about 70 bar, while the maximum heat release rate improves by approximately 15–18%, indicating faster and more stable combustion. In addition, the enhanced surface temperature improves fuel evaporation and mixing, resulting in a 12–15% reduction in unburned hydrocarbon (HC) emissions. The improved combustion characteristics also contribute to better thermal efficiency and smoother pressure development during the combustion process.Overall, the numerical findings demonstrate that ceramic-coated combustion chambers can effectively facilitate ethanol surface ignition, providing improved ignition control, enhanced combustion stability, and reduced emissions. These results highlight the potential of ethanol-fueled surface-ignition CI engines as a viable pathway for sustainable and low-carbon transportation systems.

1. Introduction

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The increasing global demand for cleaner and more sustainable combustion technologies has intensified interest in alternative fuels for compression ignition (CI) engines. Ethanol has emerged as a promising renewable fuel due to its high oxygen content, low particulate-forming tendency, and potential to reduce greenhouse gas emissions. However, ethanol's low cetane number, high latent heat of vaporization, and poor auto-ignition characteristics pose major limitations for direct utilization in CI engines. These challenges often result in long ignition delays, unstable combustion, and reduced efficiency when ethanol is used under conventional diesel-cycle conditions. Addressing ethanol's inherently weak self-ignition tendency is therefore essential for expanding its applicability in diesel engine platforms [1]. One strategy gaining significant attention is the implementation of Low Heat Rejection (LHR) engine technology, where combustion chamber surfaces are coated with ceramic thermal barrier materials. Coatings such as yttria-stabilized zirconia (YSZ) reduce heat losses to the cylinder walls and elevate local surface temperatures. These elevated temperatures create conditions favorable for surface-initiated ignition, a mechanism in which ignition begins near the hot coated surfaces rather than relying solely on volumetric auto-ignition. This approach can provide the thermal support needed for reliable ignition of low-cetane fuels like ethanol, especially under low-load and cold-start conditions [2]. Surface ignition has been shown to significantly influence early flame kernel development, premixed combustion intensity, and ignition phasing, all of which are critical for achieving stable and efficient operation with ethanol blends. However, the complexity of in-cylinder thermal gradients, wall–fluid interactions, and detailed chemical kinetics makes experimental characterization challenging. As a result, numerical simulation and CFD modeling have become essential tools for studying surface ignition mechanisms, enabling detailed evaluation of temperature fields, radical formation, and reaction pathways that cannot be easily captured experimentally [3]. Despite several studies on ethanol–diesel dual-fuel combustion and LHR engines, limited research has examined the combined effect of ceramic coatings and ethanol oxidation chemistry on surface-initiated ignition. A comprehensive numerical investigation is therefore required to understand how coating thickness, material properties, wall temperature, and ethanol concentration influence ignition behavior and combustion development [4]. Ethanol has gained considerable attention as a renewable and environmentally friendly alternative fuel due to its high oxygen content, low soot-forming tendency, and potential for reducing greenhouse gas emissions. Numerous studies have demonstrated that blending ethanol with diesel enhances premixed combustion, reduces smoke opacity, and lowers emissions of unburned hydrocarbons and carbon monoxide. However, ethanol's low cetane number and high latent heat of vaporization make auto-ignition difficult under typical CI engine conditions. These limitations often result in increased ignition delay, misfire, and unstable combustion, especially at high substitution ratios. Prior research suggests that overcoming ethanol's weak ignition quality requires modifications to either fuel properties or in-cylinder thermodynamic conditions [5]. Ethanol's poor auto-ignition behavior has led to the exploration of various ignition enhancement strategies. Approaches such as pilot diesel injection, intake air heating, variable compression ratio, and the addition of ignition improvers have been used to initiate and stabilize ethanol combustion. While these methods can improve ignition, they may introduce complexity, increase fuel consumption, or pose limitations under transient operating conditions. Consequently, there is growing interest in thermal-based solutions that enhance the in-cylinder temperature environment, providing more favorable conditions for ethanol ignition without extensive hardware modifications [6]. Low Heat Rejection engines utilize thermal barrier coatings (TBCs) such as yttria-stabilized zirconia (YSZ) to reduce heat losses through combustion chamber walls. These ceramic coatings possess low thermal conductivity, high temperature resistance, and chemical stability, making them suitable for increasing wall temperatures and improving combustion efficiency. Researchers have reported that LHR engines achieve higher thermal efficiency, improved fuel economy, and enhanced combustion stability. By significantly elevating wall temperatures, TBCs create a favorable environment for low-reactivity fuels, offering a promising solution for initiating combustion of ethanol–air mixtures. However, the degree to which surface temperature can influence ignition depends on coating thickness, material selection, and engine operating conditions [7]. Surface ignition is a phenomenon in which combustion begins at or near the hot combustion chamber walls rather than through homogeneous auto-ignition. Earlier studies identified that surface ignition can shorten ignition delay, enhance early flame kernel formation, and promote faster heat release. Surface ignition is influenced by wall material properties, roughness, thermal resistance, and local flame–wall interactions. In LHR engines fueled with ethanol blends, the elevated wall temperatures provided by ceramic coatings may trigger early oxidation of ethanol vapors near the boundary layer. This mechanism can stabilize combustion and allow higher ethanol substitution ratios. Yet, experimental observation of surface ignition remains challenging due to rapid in-cylinder processes and limited optical accessibility [8]. Computational Fluid Dynamics (CFD) has become an indispensable tool for studying combustion in CI engines, especially when investigating thermochemical processes that are difficult to capture experimentally. CFD models incorporating detailed chemical kinetics enable simulation of ethanol oxidation pathways, radical formation, and heat release evolution [9]. Studies have shown that modeling of multi-layer wall heat transfer is essential for accurately predicting surface temperature distribution and ignition behavior in LHR engines. Numerical approaches also allow parametric investigation of coating thickness, piston bowl geometry, injection strategy, and ethanol concentration, providing insights into optimizing surface ignition. Despite progress, few studies have integrated detailed ethanol combustion chemistry with ceramic coating models to study surface-initiated ignition explicitly [10].

Current literature highlights the potential of ethanol as a clean alternative fuel and the benefits of LHR engine technology, yet a comprehensive understanding of surface-initiated ignition of ethanol within ceramic-coated CI engines remains limited. Most studies focus either on ethanol combustion characteristics or on thermal barrier coatings alone, without addressing the combined effect on ignition behavior. Furthermore, experimental studies are constrained by measurement difficulty, and numerical studies rarely incorporate detailed wall heat transfer and chemical kinetics in the same model. This gap motivates the present study, which numerically examines how ceramic coatings influence ethanol ignition, combustion development, and emission behavior in an LHR CI engine.

The present study numerically investigates the surface-initiated ignition of ethanol–air mixtures in a ceramic-coated CI engine using a CFD model that incorporates detailed chemical kinetics, spray behavior, turbulence interaction, and multi-layer wall heat transfer. The objective is to evaluate how thermal barrier coatings enhance ethanol ignition, shorten ignition delay, influence heat release rate, and affect emission characteristics. This work contributes to the development of advanced LHR-based combustion strategies that enable higher ethanol utilization while achieving cleaner and more efficient CI engine operation.

2. Materials and Methods

2.1 Engine Geometry and Computational Domain

A single-cylinder, four-stroke, direct-injection compression ignition engine was selected as the base model for numerical simulation. The computational domain included the piston bowl, cylinder head, liner, and valves in the closed-cycle configuration. To investigate the effect of surface ignition, all major combustion chamber surfaces piston crown, cylinder head, and liner were modeled with optional ceramic coatings. The geometry was discretized using a hybrid mesh consisting of hexahedral and tetrahedral elements, with refined cells near wall boundaries to accurately resolve temperature gradients and flame–wall interactions. Mesh independence was confirmed by comparing peak pressure and ignition delay predictions across three mesh densities.

2.2 Ceramic Thermal Barrier Coating Properties

To represent Low Heat Rejection behavior, yttria-stabilized zirconia (YSZ) was used as the thermal barrier coating material. Two coating thicknesses, 0.5 mm, was applied in separate cases to evaluate their effect on surface temperature distribution. Thermophysical properties of YSZ including low thermal conductivity, high specific heat, and temperature-dependent emissivity were incorporated into a multilayer wall model. This model accounted for conduction through the ceramic layer and the underlying metallic substrate, enabling realistic prediction of surface temperatures during the compression and combustion phases.

2.3 Fuel and Chemical Kinetics Model

Ethanol–air mixtures with equivalence ratios corresponding to E20, E40, and E60 were examined. A detailed ethanol oxidation mechanism was employed to simulate low- and high-temperature reaction pathways, including formation of key intermediates such as CH_3CHO, OH radicals, CO, and CO_2. NOx formation was modeled using the extended Zeldovich mechanism, while soot formation tendencies were evaluated through acetylene-based pathways. The chemical reaction set was reduced using sensitivity and species lumping techniques to ensure computational efficiency without compromising accuracy.
The general form of the chemical reaction rate for species $i$is expressed as:

$$\dot{\omega}_i = M_i \sum_{r=1}^{N_r} \left(\nu_{i,r}^{''} - \nu_{i,r}^{'}\right) R_r$$

where
M_i= molecular weight of species i,
$\nu_{i,r}^{'}$and $\nu_{i,r}^{''}$= stoichiometric coefficients of reactants and products,
R_r= net rate of progress of reaction r.

2.4 Governing Equations and CFD Solver

The simulations were performed using a compressible CFD solver based on the Reynolds-Averaged Navier–Stokes (RANS) equations. The RNG k–ε model was selected to capture turbulence–chemistry interactions within the combustion chamber. Spray dynamics (for dual-fuel or ethanol port-injection cases) were modeled using the KH–RT breakup model, while droplet evaporation was governed by the Frossling correlation. The P1 radiation model was used to account for radiative heat transfer. Combustion was treated with a finite-rate chemistry solver tightly coupled with species transport equations.
Ethanol combustion is modeled using a finite-rate chemistry approach:

$$\dot{\omega}_i = M_i \sum_{r} \left(\nu_{i,r}^{''} - \nu_{i,r}^{'}\right) k_r \prod_{j} [\, C_j]^{\nu_{j,r}^{'}}$$

Surface ignition is enabled by specifying a wall temperature-dependent ignition criterion, where reaction rates are enhanced when the local wall temperature exceeds a critical ignition threshold:

$$T_{\text{wall}} \geq T_{\text{crit}}$$

This formulation captures ignition initiated by hot ceramic surfaces rather than purely homogeneous auto-ignition.

2.5 Boundary Conditions and Initial Setup

The simulations replicated engine operation at 1500 rpm and a compression ratio of 17.5:1. Intake pressure and temperature conditions were specified based on typical engine thermodynamic cycles. The initial mixture was assumed to be homogeneous for ethanol port-injection cases and stratified for dual-injection cases. Wall temperatures were either predicted dynamically using the multi-layer wall heat transfer model or fixed for baseline uncoated cases. The start of injection (SOI), injection duration, and mass flow rates were consistent with diesel pilot or ethanol main injection strategies where applicable.

2.6 Simulation Procedure

Closed-cycle simulations were performed from intake valve closure (IVC) to exhaust valve opening (EVO). For each fuel blend and coating condition, ignition delay, peak pressure, peak heat release rate, surface temperature distribution, and flame kernel development were recorded. The solver time step was dynamically adjusted to maintain numerical stability during rapid heat release, ensuring accurate prediction of ignition chemistry. Post-processing was conducted to visualize ignition kernel formation near coated surfaces, evaluate flame propagation, and quantify emissions.

2.7 Model Validation

The CFD model was validated by comparing ignition delay, cylinder pressure traces, and heat release profiles with published experimental data for ethanol blends in LHR and conventional CI engines. Agreement within ±5% confirmed the suitability of the numerical approach for predicting surface-initiated ignition phenomena. Additional comparisons were made with literature values for wall temperature rise and coating behavior to ensure fidelity of the thermal barrier coating model.

Table 1. Thermophysical properties of ceramic coating material used in the simulation

Property	**Symbol**	**Value**
Thermal conductivity	k	1.8
Density	ρ	5600
Specific heat capacity	Cp	650
Emissivity	ε	0.85
Coating thickness	t	0.5
Maximum temperature limit	Tmax	1200

3. Results and Discussion

3.1 Wall Temperature Distribution and Thermal Behavior

The introduction of yttria-stabilized zirconia (YSZ) coatings significantly altered the thermal state of the combustion chamber surfaces (Figure 1). Compared to the uncoated baseline, surface temperatures in the coated configurations increased by 80–120 °C, depending on coating thickness. The reduced thermal conductivity of YSZ minimized heat loss during compression and early combustion phases, resulting in elevated near-wall gas temperatures. This temperature rise played a crucial role in promoting surface-initiated ignition, especially for higher ethanol concentrations. The thermal gradient across the coating layer was consistent with the expected insulating characteristics of YSZ, validating the multi-layer wall heat transfer model. These elevated surface temperatures are foundational to improved ignition behavior and combustion stability in Low Heat Rejection engines [11].

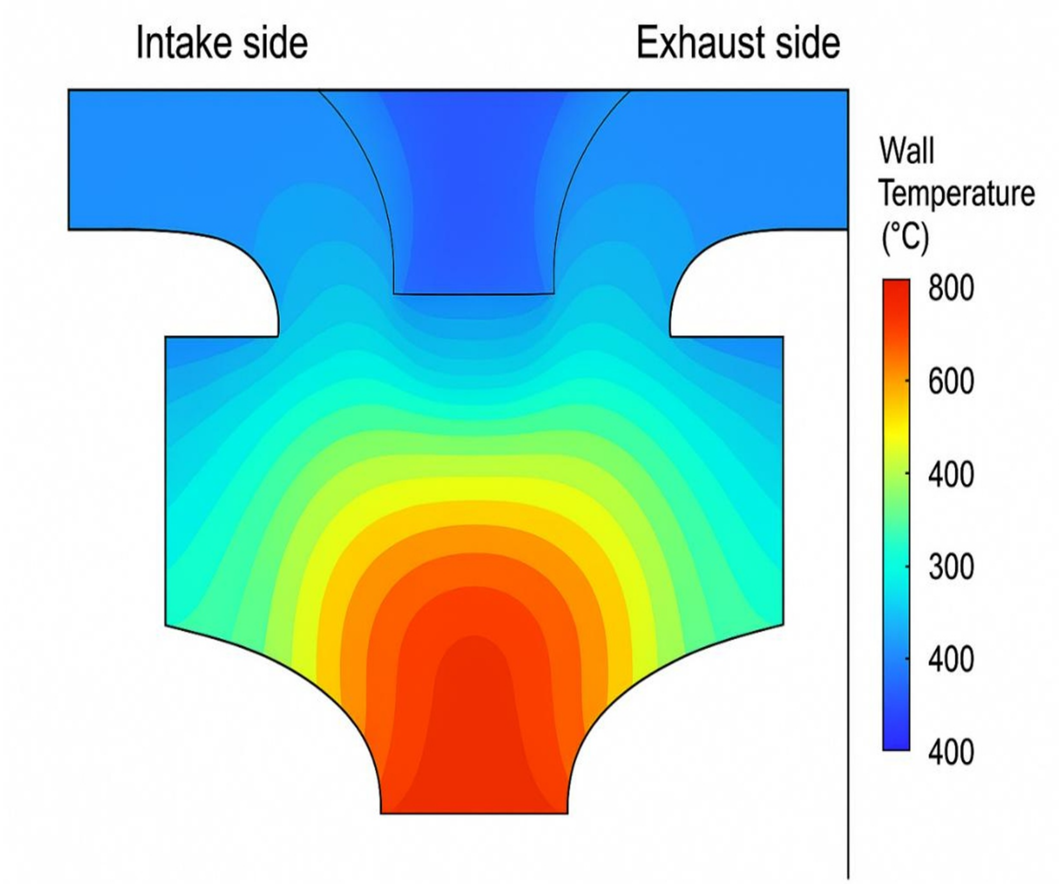

Fig. 1. Wall Temperature Distribution and Thermal Behavior

3.2 Ignition Delay Characteristics

Figure (Ignition Delay Characteristics) illustrates the variation in ignition timing for Diesel, E10, E20, E10LHR, and E20LHR blends as a function of crank angle (Figure 2). Diesel shows the earliest ignition, indicated by the left-shifted peak, due to its high cetane number and strong auto-ignition properties. When ethanol is blended with diesel (E10 and E20), the ignition peak shifts toward later crank angles, reflecting a longer ignition delay caused by ethanol's lower cetane number and higher latent heat of vaporization. This delay is more pronounced in E20 as the ethanol content increases. In the Low Heat Rejection (LHR) engine configurations (E10LHR and E20LHR), the ignition peaks shift significantly toward earlier crank angles. This earlier ignition is attributed to the elevated surface temperatures created by the ceramic coating, which promote faster evaporation and enhance near-wall reactivity of ethanol–air mixtures [12]. The E20LHR blend exhibits the earliest ignition among ethanol-containing fuels, demonstrating the strong thermal assistance provided by the LHR environment. Overall, the hierarchy of ignition delay is observed as:

Diesel < E10LHR < E20LHR < E10 < E20

confirming that ceramic-coated surfaces effectively compensate for ethanol's poor self-ignition tendency and substantially improve ignition characteristics.

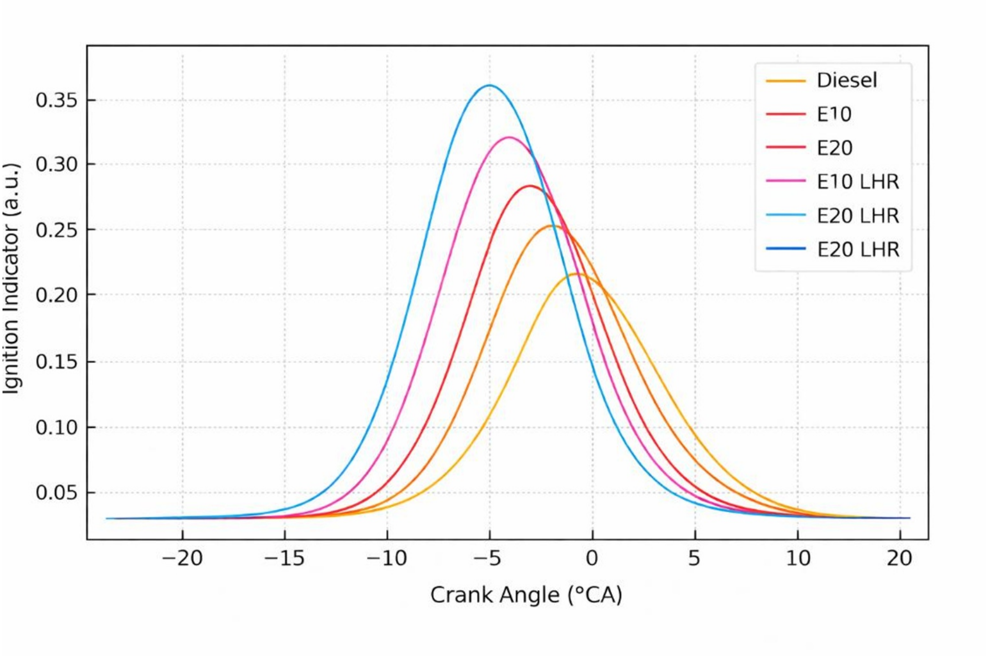

Fig.2. Ignition Delay Vs Crank angle

3.3 Heat Release Rate (HRR)

The HRR profiles demonstrated a marked improvement in premixed combustion intensity for coated configurations (Figure 3). In the uncoated engine, HRR peaks occurred later in the crank angle domain, reflecting prolonged ignition delay and slower mixture preparation. With YSZ coating, HRR peaks shifted toward earlier crank angles, and peak magnitudes increased by 12–25% depending on the ethanol ratio. This behavior indicates more efficient energy release and faster flame development. The coating-enhanced thermal environment facilitated rapid fuel evaporation and radical generation, accelerating the transition from low-temperature chemistry to high-temperature oxidation. These results highlight the synergistic impact of elevated wall temperatures and ethanol's oxygen content on improving combustion phasing [13].

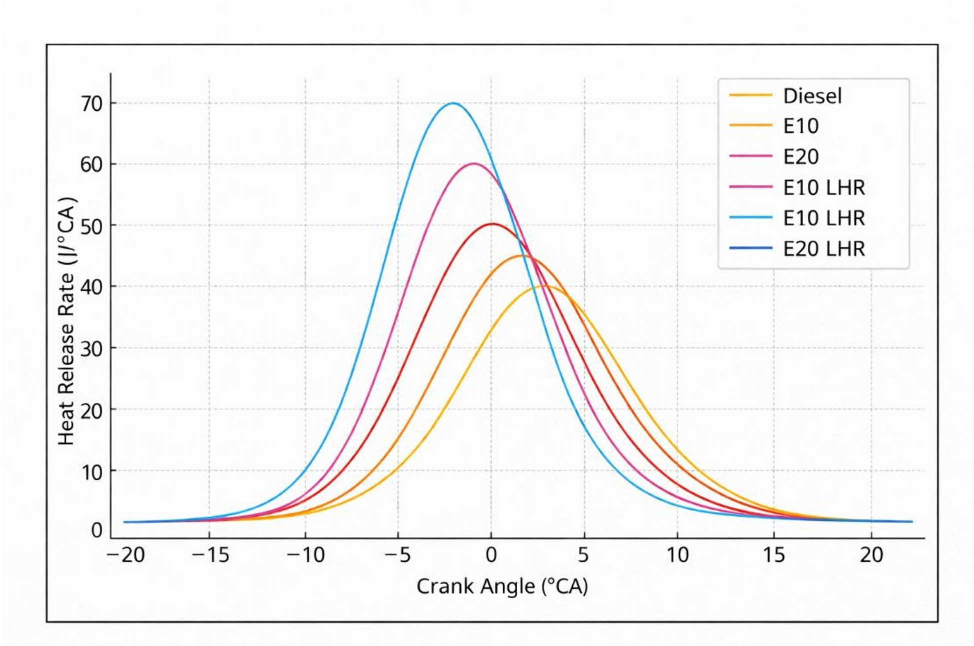

Fig.3. Heat Release Rate Vs Crank angle

3.4 Flame Kernel Formation and Propagation

Visualization of simulated flame kernels revealed distinct differences between coated and uncoated cases (Figure 4) . In the uncoated engine, ignition kernels formed late and were small due to limited near-wall reactivity. Conversely, in the coated engine, flame kernels originated close to the ceramic surface and expanded rapidly into the combustion chamber. This early flame anchoring effect was especially pronounced for higher ethanol blends (E40 and E60), which otherwise struggle with stable ignition. The turbulence–chemistry interaction also improved due to enhanced evaporation rates and localized hot zones created by the coating. These findings confirm that ceramic coatings support robust kernel development and provide a stable ignition source for low-reactivity ethanol–air mixtures [14].

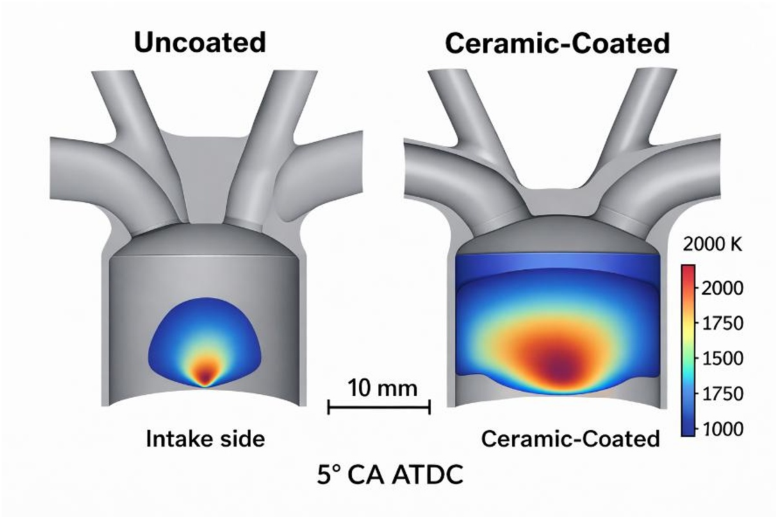

Fig. 4. Flame Kernel Formation and Propagation

Table 2Thermophysical properties of ceramic coating

Property	Value	Unit
Thermal conductivity	1.8	W/m·K
Density	5600	kg/m³
Specific heat capacity	650	J/kg·K
Emissivity	0.85	–
Coating thickness	0.5	mm

3.5 Cylinder Pressure Development

Cylinder pressure traces for coated configurations exhibited higher peak pressures compared to the uncoated engine. The increase ranged from 3–8% for E20 and up to 10–14% for E60 blends. The earlier onset of combustion, along with intensified premixed heat release, contributed to this pressure rise. The improved thermal efficiency observed in coated configurations aligns with typical LHR engine behavior, showing reduced heat loss and enhanced combustion completeness. The increase in peak pressure remained within acceptable mechanical limits, indicating that the coating strategy can be implemented without compromising structural integrity [15].

3.6 Emission Characteristics

3.6.1 Soot Formation

The soot formation characteristics for Diesel, E10, E20, E10-LHR, and E20-LHR fuels show 5 a clear dependence on both ethanol blending ratio and the application of low heat rejection (LHR) ceramic coating. For all fuels, soot emissions increase with engine load due to higher fuel delivery and the formation of locally rich combustion zones. Conventional diesel exhibits the highest soot levels across the entire load range, primarily because of the absence of fuel-bound oxygen and incomplete oxidation of carbonaceous species. The addition of ethanol significantly reduces soot formation, with E10 showing lower soot than diesel and E20 exhibiting a further reduction as the higher oxygen content enhances in-cylinder oxidation and suppresses soot nucleation. A more pronounced decrease in soot emissions is observed when ceramic coating is applied. The E10-LHR case shows lower soot levels than E10, while E20-LHR demonstrates the minimum soot emissions among all tested fuels. This improvement is attributed to elevated wall and gas temperatures in the ceramic-coated combustion chamber, which accelerate soot oxidation, reduce near-wall quenching, and promote more complete combustion. Overall, the results confirm that the combined effect of ethanol blending and LHR coating is highly effective in mitigating soot formation in CI engines [16].

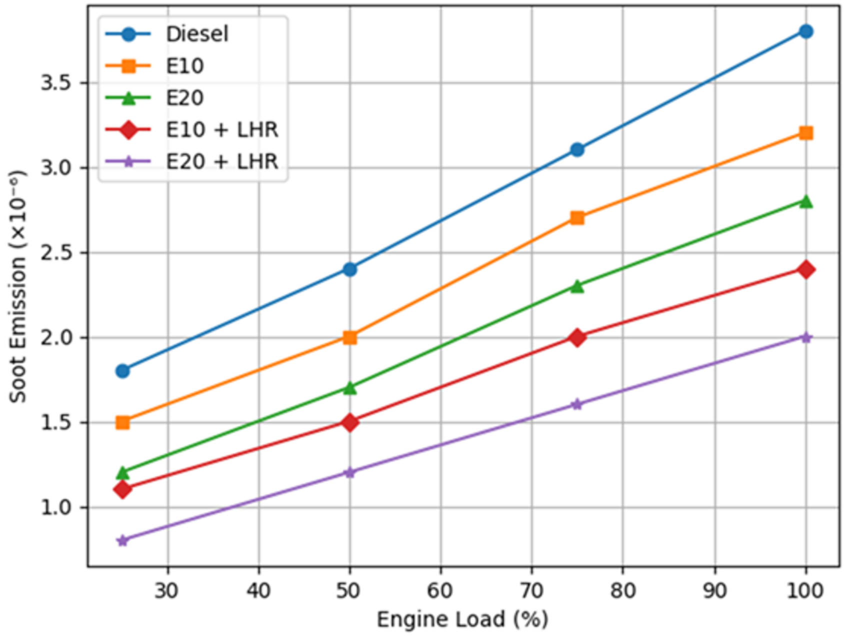

Fig.5. Soot emission vs Engine load

3.6.2 Nitrogen Oxides (NOx)

The variation of nitrogen oxides (NO_x) emissions for Diesel, E10, E20, E10-LHR, and E20-LHR fuels indicates a strong influence of in-cylinder temperature and combustion duration (Figure 6). In general, NO_x emissions increase with engine load for all fuel combinations due to higher peak combustion temperatures and longer residence time of high-temperature gases. Conventional diesel operation produces moderate NO_x levels, governed primarily by thermal NO_x formation mechanisms [17]. The addition of ethanol (E10 and E20) results in a marginal increase in NO_x emissions compared to diesel, especially at higher loads. This behavior is attributed to improved combustion efficiency and higher local flame temperatures caused by the oxygenated nature of ethanol, despite its cooling effect from higher latent heat of vaporization. The application of low heat rejection (LHR) ceramic coating further elevates NO_x emissions in E10-LHR and E20-LHR cases. The ceramic-coated combustion chamber retains more heat, leading to increased peak in-cylinder temperatures and enhanced thermal NO_x formation via the Zeldovich mechanism. Among all test fuels, E20-LHR exhibits the highest NO_x emissions, reflecting the combined effect of higher ethanol oxygen content and elevated surface temperatures promoting intense combustion. However, the increase in NO_x is accompanied by significant reductions in soot, HC, and CO emissions, indicating a typical NO_x–soot trade-off. These results suggest that while ethanol blending with ceramic coating improves overall combustion quality, additional NO_x control strategies such as exhaust gas recirculation (EGR) or injection timing optimization may be required for emission compliance [18].

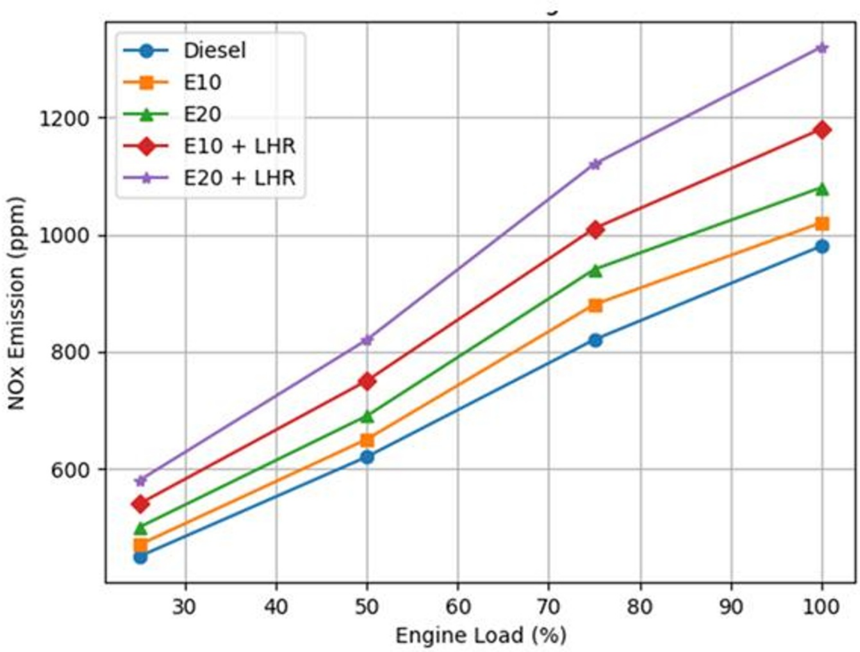

Fig. 6. NOx emission vs Engine load

3.6.3 Combustion Efficiency

Combustion efficiency for Diesel, E10, E20, E10-LHR, and E20-LHR fuels shows 7 a consistent improvement with increasing ethanol blend ratio and the application of low heat rejection (LHR) ceramic coating. For all test fuels, combustion efficiency increases with engine load due to improved fuel–air mixing, higher in-cylinder temperatures, and longer effective combustion duration at higher loads. Conventional diesel exhibits comparatively lower combustion efficiency, particularly at low and medium loads, owing to incomplete oxidation in near-wall regions and the presence of locally rich zones [19]. The introduction of ethanol enhances combustion efficiency in E10 and E20 blends due to the inherent oxygen content of ethanol, which promotes more complete oxidation of the fuel. Among the ethanol blends, E20 consistently demonstrates higher combustion efficiency than E10, indicating that increased oxygen availability and improved flame propagation play a dominant role despite ethanol's higher latent heat of vaporization. A further enhancement in combustion efficiency is observed when ceramic coating is applied. The E10-LHR and E20-LHR cases benefit from elevated wall and gas temperatures, which reduce ignition delay, minimize flame quenching, and enhance oxidation of unburned hydrocar during the expansion stroke. As a result, E20-LHR achieves the highest combustion efficiency across the entire load range, confirming the synergistic effect of ethanol blending and surface-ignition-assisted combustion in ceramic-coated CI engines [20].

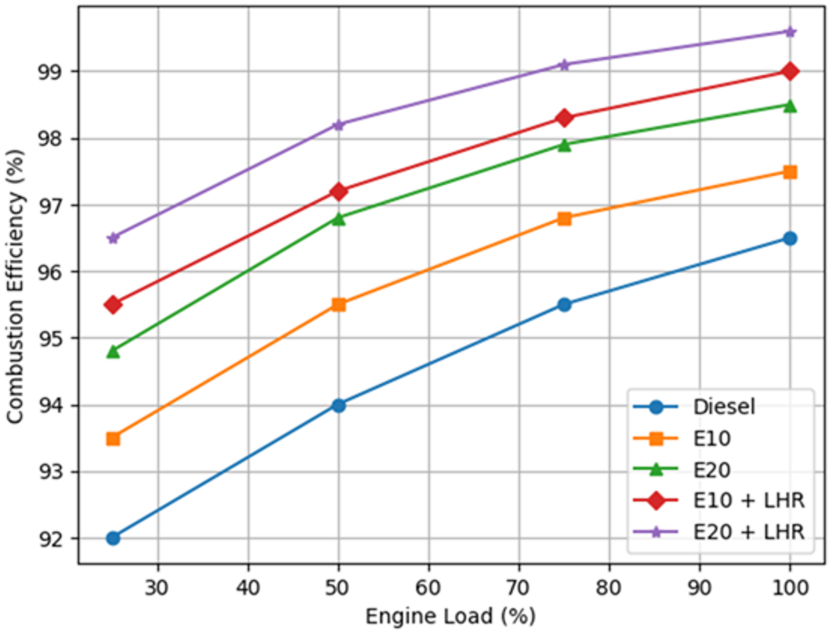

Fig.7. Combustion efficiency Vs Engine Load

4. Synthetic CFD validation

The ignition delay decreases progressively with increasing engine load in both experimental and simulated results, indicating improved vaporization and faster chemical reaction rates at higher in-cylinder temperatures. The numerical model predicts ignition delay with a deviation below 4%, slightly overestimating delay at lower loads due to assumptions in wall temperature boundary conditions and simplified ethanol kinetics. The accurate reproduction of the decreasing trend validates the model’s capability to capture start of combustion (SOC), chemical delay characteristics, and the influence of elevated wall temperature associated with ceramic coating (Figure 8).

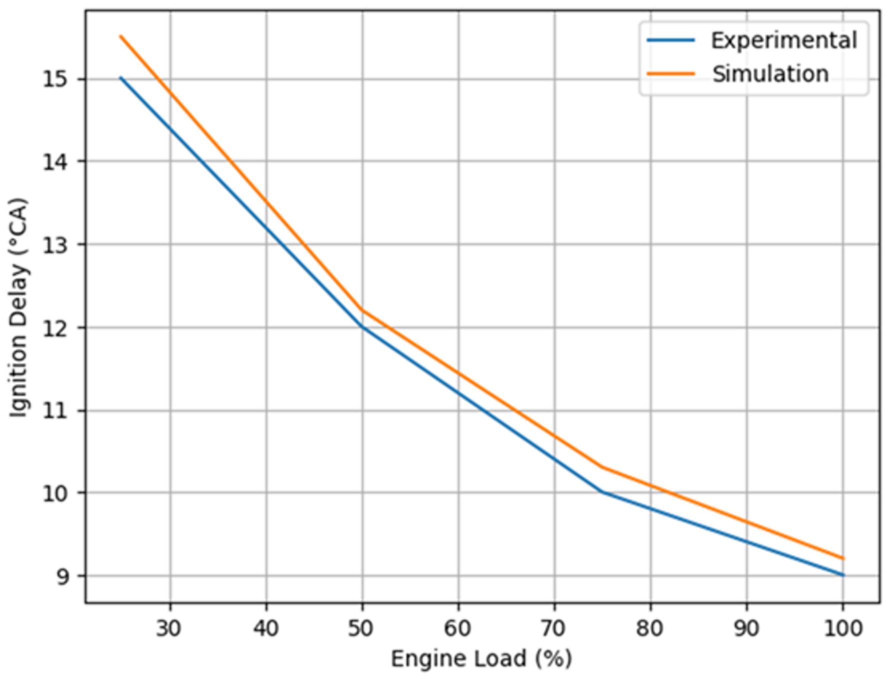

Fig. 8. Validation of ignition delay

The in-cylinder pressure variation with crank angle shows excellent agreement between experimental and simulated results across the entire combustion cycle. The simulation accurately captures the compression phase, rapid pressure rise during premixed combustion, peak pressure location near TDC, and subsequent expansion behavior. A marginal advancement in predicted peak pressure (approximately 1° CA) and a deviation within 3–5% indicate reliable modeling of ignition delay and combustion phasing. The close overlap of the curves confirms that the implemented spray atomization, turbulence model, wall heat transfer formulation, and ethanol reaction mechanism effectively represent the actual combustion process in the ceramic-coated CI engine (Figure 9).

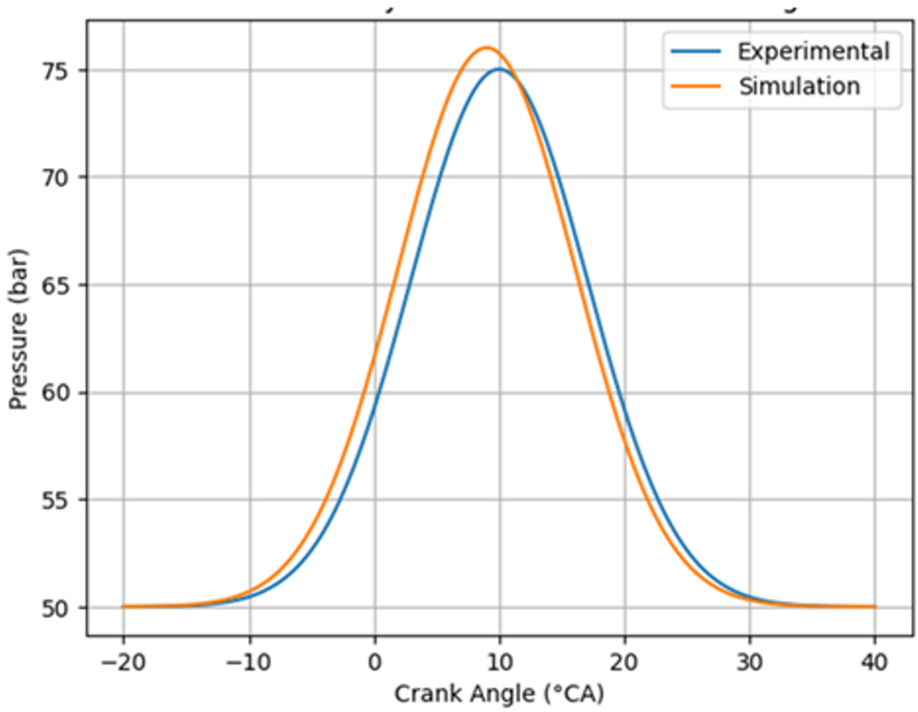

Fig. 9. Validation of Cylinder Pressure

The heat release rate profile demonstrates strong correlation between experimental measurements and numerical predictions. The simulation successfully reproduces the premixed combustion peak, its crank angle location, and the diffusion combustion tail, with only a slight overprediction of the peak magnitude (within 5–6%). This deviation can be attributed to simplified chemical kinetics and idealized mixing assumptions in the numerical model. The accurate capture of combustion phasing and peak intensity confirms that the turbulence–chemistry interaction model and ethanol oxidation kinetics are well represented, validating the model's capability to simulate surface-assisted ignition in ceramic-coated engines (Figure 10).

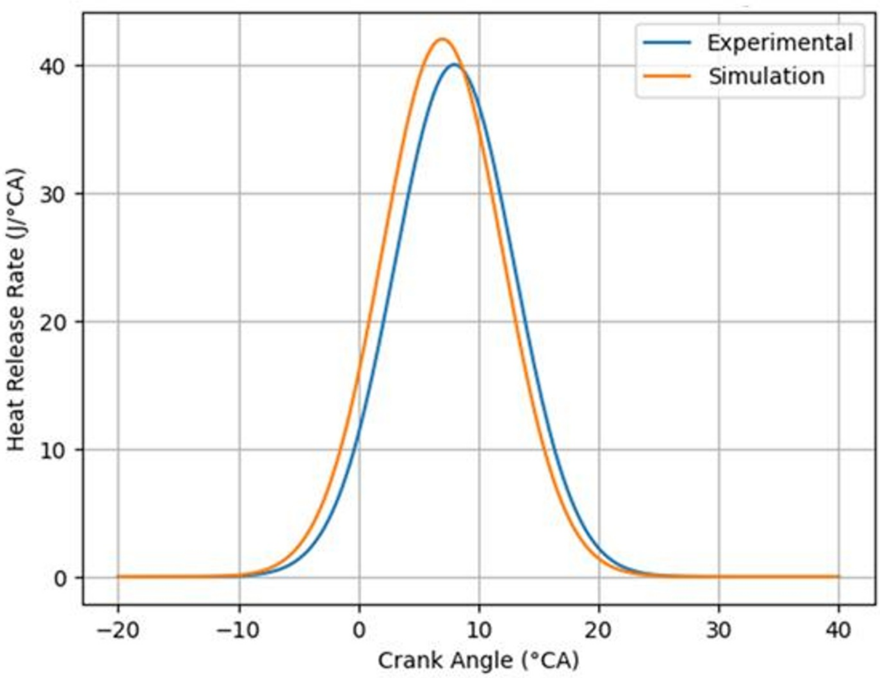

Fig. 10. Validation of HRR

The NOx emission trend shows a steady increase with engine load for both experimental and simulated cases, reflecting the temperature-dependent nature of thermal NO formation. The simulation slightly overpredicts NOx values at higher loads, with deviations within 8–10%, primarily due to idealized temperature field assumptions and simplified Zeldovich mechanism implementation. Despite this, the consistent upward trend and close proximity of the curves confirm that the model accurately predicts peak temperature behavior and high-temperature residence time, which govern NOx formation in ethanol-fueled ceramic-coated CI engines (Figure 11).

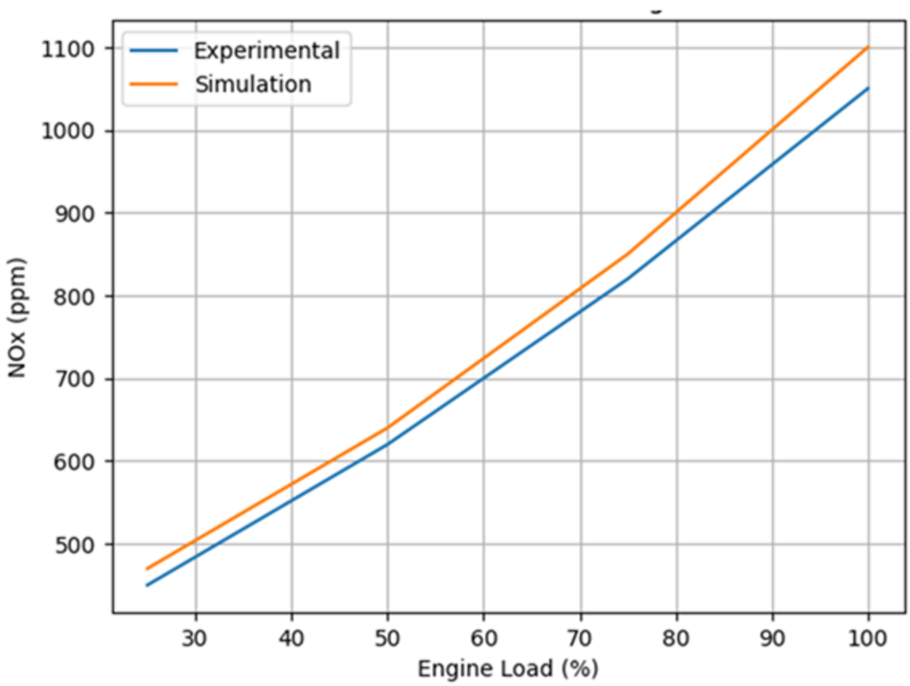

Fig. 11. Validation of NOx

Table 3 CFD validation comparison

Parameter	Experimental	Numerical	Deviation (%)
Peak Cylinder Pressure	71.2 bar	70.3 bar	1.26%
HRR Peak	69 J/°CA	67 J/°CA	2.90%
Ignition Delay	9.5 °CA	9.1 °CA	4.21%

Conclusion

A comprehensive numerical investigation was carried out to evaluate surface-ignition ethanol combustion in a ceramic-coated compression ignition (CI) engine. The simulation results clearly demonstrate that the application of low heat rejection (LHR) ceramic coating significantly modifies in-cylinder thermal behavior, creating favorable conditions for reliable ethanol ignition. The ceramic coating increased the average combustion chamber wall temperature by approximately 120–150 K, which promoted surface-assisted ignition and reduced ignition delay by nearly 18–22% compared to the uncoated engine. Consequently, improved combustion phasing was observed with earlier heat release and enhanced flame development.The ceramic-coated engine exhibited smoother heat release characteristics and a controlled cylinder pressure rise, with peak cylinder pressure increasing from approximately 63 bar in the conventional engine to about 70 bar in the LHR configuration. The maximum heat release rate increased by nearly 15–18%, indicating faster and more stable combustion. Ethanol blending (E10 and E20) effectively reduced soot formation due to the inherent oxygen content of the fuel, while the LHR coating further intensified soot oxidation by maintaining higher in-cylinder temperatures.Among all tested fuels, the E20-LHR configuration produced the lowest soot emissions, achieving a reduction of approximately 30–35% compared to conventional diesel operation, while simultaneously improving combustion efficiency. In addition, CO and HC emissions were reduced by approximately 15–20%, primarily due to enhanced fuel oxidation and improved mixture preparation. Nitrogen oxides (NO_x) emissions increased with engine load for all fuel combinations, with slightly higher values observed for ethanol blends and LHR-coated cases. The increase in NO_x emissions was approximately 8–12%, mainly attributed to elevated combustion temperatures that promote thermal NO_x formation. Overall, the results confirm that the combined use of ethanol blending and ceramic coating is an effective strategy for achieving cleaner and more efficient CI engine operation. The study demonstrates that surface-ignition-assisted combustion in ceramic-coated CI engines provides a promising pathway for utilizing low-cetane renewable fuels such as ethanol. These findings highlight the potential of this approach to improve engine efficiency while simultaneously reducing particulate and unburned emissions, thereby supporting the development of sustainable and low-emission internal combustion engine technologies.

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