Introduction In light of the urgent need to reduce fossil fuel consumption and mitigate greenhouse gas emissions, the automotive and marine sectors are increasingly exploring alternative fuels and technologies [1].This research contributes to the broader goal of developing viable transitional strategies for existing diesel engines towards cleaner and more efficient technologies, highlighting the potential of onboard hydrogen production as an immediate and effective solution.Research on natural luminosity and OH* chemiluminescence imaging of T50, an oxygenated fuel blend, in a heavy-duty CI engine modified to provide optical access, revealed that it reduced soot and nitrogen oxide emissions compared to standard diesel but slightly increased hydrocarbon and carbon monoxide emissions [24].Despite the wealth of research on hydrogen in compression ignition engines and of research on the use of optical diagnostic in CI engines, a notable gap persists in the intersection of those areas, the study of hydrogen-diesel mixtures in optically accessible engines, particularly in understanding the effects of micro-additions of hydrogen.In another study focusing on natural flame luminosity and OH* chemiluminescence of methanol and high-reactivity fuels in an optical single-cylinder diesel engine, the authors observed that the combination resulted in efficient combustion, less soot, and lower nitrogen oxide emissions.Strategies such as adjusting equivalence ratios, inlet pressures, ignition timing, and utilizing exhaust gas recirculation effectively mitigate knock, providing insights for optimizing hydrogen engine performance.However, its effectiveness is limited in detailing the subtleties of hydrogen enrichment to diesel, as hydrogen combustion does not produce soot or significant visible light, and the overall luminosity is predominantly influenced by diesel combustion and soot formation.Advanced diagnostic methods like high-speed imaging, planar laser-induced fluorescence (PLIF), and particle image velocimetry (PIV) further enrich this data by detailing temperature, pressure, and flow fields within the engine [19,20].Soid and Zainal discuss how various optical techniques can assess combustion characteristics at macroscopic and microscopic levels, providing a holistic understanding of how alternative fuels influence spray and combustion characteristics [21].A review by Marchitto on optical diagnostics stressed the need for advanced soot measurement techniques, such as Laser-Induced Incandescence and Elastic Light Scattering, for assessing soot volume fraction and size distribution [28].By leveraging optical diagnostics, researchers can delve deeper into the behavior of hydrogen in various combustion environments, providing insights essential for both engine optimization and the broader application of hydrogen as a sustainable energy source.Their experiments, using different injection pressures and timings, revealed that hydrogen significantly enhanced engine performance and reduced emissions, though with a slight increase in nitrogen oxides (NOx).Their study used a variety of fuel blends and found that hydrogen enrichment lowered Specific Fuel Consumption (SFC) and increased Brake Thermal Efficiency (BTE), with most emissions, except NOx, decreasing.Using numerical and experimental methods, they observed improved brake thermal efficiency and reduced fuel consumption with hydrogen blends despite rising NOx emissions.Kathirvel et al. [16] examined the impact of blending neem oil methyl ester (NME) with diesel (10% and 20%) and varying HHO gas concentrations on a 3.7 kW CI engine.Dronniou et al. studied dual-fuel combustion strategies with natural gas and diesel employing natural flame luminosity, OH* chemiluminescence, and PLIF techniques on a light-duty single-cylinder research optical engine [30].Liu et al.'s studies in 2020 [8] and

2022 [9] explore the advantages of hydrogen-diesel dual direct-injection (H2DDI) in compression ignition engines.The study underscores the need for optimized fuel induction strategies to maximize BTE in dual-fuel CI engines, contributing to developing more efficient and eco-friendly engines.Therefore, as storage, transportation, and dual-fuel solutions like H2DDI are being developed and optimized, onboard hydrogen production offers an immediate transitional solution for existing diesel engines if added in small quantities.Research by Taschek et al. on nozzle hole geometry and in-cylinder dynamics found significant impacts on spray and mixture formation and soot reduction.They found that low equivalence ratios led to spray-dominated combustion, while higher ratios resulted in flame propagation, which impacted heat release rates and fuel distribution, providing insights into dual-fuel combustion optimization.Lee et al. used a similar approach in a study on natural gas and diesel dual-fuel engines and showed that hydrogen blending notably decreased soot emissions during initial combustion phases.These findings offer critical insights into the combustion characteristics of ammonia and hydrogen mixtures and underscore the effectiveness of chemiluminescence in assessing flame structures and chemical reactions.Rorimpandey et al. also leveraged optical diagnostics to investigate the ignition and combustion characteristics of hydrogen and diesel-pilot fuel jets in a CVCC [42].Prabhu et al. [3] investigated the impact of biodiesel unsaturation and hydrogen induction in CI engines, exploring alternatives to diesel.Key results include improved Brake Thermal Efficiency (BTE) from 28.1-32.3% to 32.5-36%, reduced Brake Specific Energy Consumption (BSEC) from 11.1 to 8.4 MJ/kWh for diesel, and altered Exhaust Gas Temperature.Notably, the RB10 blend improved brake thermal efficiency by 3.32% compared to standard diesel, demonstrating the effectiveness of hydrogen-enriched biodiesel as an alternative fuel.Despite the promising benefits, adopting hydrogen in CI engines faces challenges such as storage, transportation, and safety, mainly due to hydrogen's low ignition energy, high flammability, high specific energy, and low density [13].In the study by Trujillo-Olivares et al. [15], the authors reported significant emissions reductions due to using oxyhydrogen gas in a diesel-fueled internal combustion engine.Producing small quantities of hydrogen onboard alleviates storage and transport challenges and brings tangible benefits in fuel consumption and emissions reduction under specific operating conditions [18].Research on natural flame luminosity in coal-to-liquid (CTL) and butanol blends on a modified single-cylinder optical engine showed that adding butanol to CTL extended ignition delay and lowered fuel reactivity.Combined with cycle data, these natural flame images offer valuable insights into hydrogen combustion behavior, showing that direct-injected hydrogen promotes initial flame kernel formation and early flame propagation.Cheng et al. used natural flame luminosity techniques to study hydrogen's addition to methane-air mixtures in tri-fuel combustion ignited by diesel pilot injection [37].The study's findings reveal that increased hydrogen levels significantly enhance NO emissions, a phenomenon closely tied to the intensification of chemiluminescence signals.This gap is significant, as most current research focuses on larger hydrogen quantities, often overlooking the nuanced impacts of small-scale hydrogen enrichment in diesel engines.To address this gap, this study aims to investigate the effects of small quantities of hydrogen on diesel combustion processes within an optically accessible compression ignition engine.This predominance can overshadow the presence of hydrogen, particularly in the later stages of combustion, known as the diffusion phase, where slower burning of fuel-rich regions occurs, and soot formation dominates.Integrating these two diagnostic methods enables a comprehensive analysis of the combustion dynamics in hydrogen-enriched diesel engines.Hydrogen's high flame propagation speed and low minimum ignition energy facilitate stable and self-sustaining flame kernels, which reduce cyclic variation and accelerate combustion [5].Lastly, Rajak et al. [12] studied hydrogen enrichment in dual-fueled compression ignition engines.In another investigation using similar techniques in the same engine in the context of partially premixed combustion under low loads, misfires were more likely with excessive premixing or unfavorable in-cylinder conditions [26].Exploring the natural flame luminosity of natural gas combustion in the dual-fuel application of an optical engine revealed that increasing its energy fraction delayed combustion start and lowered peak pressure.Further research using natural flame luminosity techniques to study natural gas substitution ratios in dual-fuel operation on a modified optically accessible engine showed that increasing these ratios reduced pressure and heat release rates.Studies by Zhang et al. on hydrogen direct injection's impact on methane combustion used natural flame optical testing to show the effects of varying hydrogen volume ratios [35].Further studies by the same group found that late hydrogen injection timings led to advanced combustion phasing, higher thermal efficiency, and increased heat release rates.The optical diagnostics were mainly instrumental in understanding how the injection sequence, timing, and ambient temperature influenced the ignition and combustion processes.This study aims to enrich the empirical understanding of the effects of small-scale hydrogen addition in CI engines and establish a solid foundation for the practical application of micro-level hydrogen enrichment in diesel-fueled engines.One promising avenue in this regard is using hydrogen in compression ignition (CI) engines to improve their performance and emissions [2].The 2020 study found that 50% hydrogen substitution improved efficiency, reduced noise, and controlled nitrogen oxide (NOx) emissions.HHO improves combustion and lowers emissions of hydrocarbons, carbon monoxide, and smoke, though it .[slightly increases NOx [2