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The use of hydrogen to supply combustion engines – part 2

ARTICLE INFO

Received: 28 April 2025

Revised: 6 October 2025

Accepted: 23 November 2025

Available online: 14 January 2026

The present study reviews the state-of-art regarding the application of H₂ in the automotive industry. This part focuses on dual-fuel (DF) internal combustion engines (ICEs) supplied with fuel and H₂. This is a continuation of the earlier part, which focused on out-of-engine studies on the effect of H₂ combustion processes, ICEs supplied with H₂, and vehicles powered by fuel cells (FCs). Using H₂ in diesel engines via the DF strategy enables a decrease in diesel fuel consumption and a reduction in harmful exhaust emissions. Using H₂ in diesel engines powered by diesel/biodiesel mixtures also allows for reducing reliance on fossil fuels. Also, incorporating nanomaterials or oxygen-containing compounds into diesel fuel formulations may enhance the combustion efficiency of H₂-powered diesel engines, thereby increasing thermal efficiency and reducing fuel consumption. However, additional studies are required on this subject.

Key words: hydrogen, dual-fuel engine, combustion engine, emission

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1. Introduction

Nowadays, hydrogen (H₂) is increasingly used to power internal combustion engines (ICEs) in both mobile and stationary applications. Developments in the transport and energy sectors have heightened interest in using fuels derived from renewable sources rather than fossil ones.

The present study reviews the state-of-art in the application of H₂ in the automotive industry. This part focuses on dual-fuel (DF) ICEs supplied with conventional fuel and H₂ and continues the earlier part that examined out-of-engine H₂ combustion studies, ICEs operating solely on H₂, and vehicles powered by fuel cells (FCs).

2. Dual-fuel combustion engines supplied with conventional fuel and hydrogen

According to [8], in case of a gas shortage, DF ICEs can operate on gaseous fuel with a diesel pilot or solely on diesel. Converting an existing diesel ICE to dual-fuel operation is relatively straightforward and requires only minor modifications. Because of the excellent anti-knock properties of H₂, the original cylinder geometry can be retained and the compression ratio (CR) preserved.

According to [17], DF ICEs are recommended when using H₂-enriched compressed natural gas (HCNG) with an H₂ mass fraction of 0–50%; when NH₃ or pure H₂ is used, compression-ignition (CI) ICEs are preferable for environmental reasons.

Several studies have confirmed the positive role of exhaust-gas recirculation (EGR) in DF ICEs fueled with conventional fuel and H₂.

Purayil et al. [70] observed that H₂-gasoline DF ICEs use H₂ as the main fuel and gasoline as the auxiliary fuel. Such engines exhibit high thermal efficiency at low and partial loads, but their power output declines at high loads. The optimal configuration combines H₂ direct injection

with gasoline port-fuel injection (PFI), which mitigates abnormal combustion but increases emissions. Using EGR reduced emissions by up to 77.8% at an EGR rate of 18%; higher rates, however, induced combustion instability.

Alrazen et al. [3] reported that the air–fuel (A/F) ratio, engine speed and load significantly influence the performance and emissions of diesel ICEs enriched with H₂. Brake thermal efficiency (BTE), brake power (BP), brake mean effective pressure (BMEP), and specific energy consumption (SEC) all depend on operating conditions when H₂ is introduced. Increasing the H₂ fraction decreases unburned hydrocarbons (UHCs), CO, CO₂, particulate matter (PM), and smoke, whereas NO_x rises; this increase can be controlled through injection strategies, EGR, water injection, or exhaust after-treatment.

Banerjee et al. [9] reported that initiating H₂ dual-fuel combustion with a diesel pilot improves conventional diesel performance while reducing regulated emissions, even though H₂ enrichment tends to raise NO_x. Because H₂ has a wide flammability range, high diffusivity, and low ignition energy, DF combustion tolerates higher EGR rates than conventional diesel. Extensive EGR alleviates NO_x-PM trade-offs without compromising performance and can obviate complex NO_x after-treatment.

Dimitriou and Tsujimura [27] demonstrated that the use of H₂ in compression ignition (CI) engines markedly reduces HC, CO, CO₂, and smoke – often by more than 50% under optimal conditions. Higher H₂ fractions raise the heat-release rate and BTE but also elevate in-cylinder temperature, sharply increasing NO_x, especially at high loads. EGR reduces NO_x in proportion to the EGR rate but may raise smoke, CO, and HC owing to lower O₂. Combining H₂ with optimized EGR simultaneously cuts all emissions relative to pure diesel operation, yet NO_x remains the principal challenge.

Rosha et al. [74] reviewed many studies on H₂ addition to diesel or biodiesel (BD) pilots in DF CI ICEs and concluded that:

- H₂'s higher laminar flame speed, shorter ignition delay, and lower minimum ignition energy accelerate flame propagation and kernel development
- BTE and BP generally improve with greater H₂ energy share owing to shorter combustion duration, higher heat-release rate, and higher peak pressure; however, knocking increases, BMEP falls in fuel-rich mode, and rises modestly under lean burn
- Because H₂ is carbon-free, CO, CO₂, and HC emissions fall at all loads, whereas NO_x increases due to higher temperature.

Arjun et al. [7] reported that the addition of Brown (HHO) gas, a mixture of H₂ and O₂ produced by electrolysis, to ICEs raised BP by 2–5.7% and BTE by 10.3–34.9%, reduced brake-specific fuel consumption (BSFC) by 20–30%, and cut CO and HC by 18% and 14%, respectively. NO_x responses varied among studies.

Thiyagarajan et al. [96] investigated H₂ addition to various BD/vegetable oils on CI ICE performance. BTE, BSFC, in-cylinder pressure and heat release rate, as well as UHCs, CO, NO_x, and smoke emissions, were thoroughly assessed. H₂ inclusion generally enhances ICE performance compared to BD/vegetable oil, though it remains comparable to or lower than diesel. H₂ addition improved BTE and fuel efficiency in CI ICEs, regardless of the fuel type utilized. This results from the higher heating value and faster combustion characteristics of H₂. H₂ combustion enhances burning efficiency, leading to higher heat release rates and maximum pressures. The high auto-ignition temperature of H₂ limits its exclusive use in CI ICEs. H₂ can serve as fuel in CI ICEs alongside pilot fuel, with the knock limitation for H₂ being approximately 20%. All emissions, except NO_x, exhibited a downward trend with H₂ inclusion. H₂ significantly reduces CO₂ emissions based on the carbon content in the molecular structure of BD or vegetable oil. Since H₂ is carbon-free, emissions of HC, CO, and smoke are consequently reduced. However, the decrease depends solely on the quantity of H₂ introduced and the type of fuel used. H₂ combustion increases NO_x emissions regardless of the fuel type used. To mitigate this effect, various after-treatment systems, such as selective catalytic reduction (SCR), exhaust gas recirculation (EGR), selective non-catalytic reduction (SNCR), and non-selective catalytic reduction (NSCR), have been suggested.

Following an extensive analysis of HHO production through various generators and its application in heating and power contexts, Paparao and Murugan [68] found that HHO can serve as an alternative fuel in SI ICEs either independently or in combination with gasoline or similar fuels. Thermal efficiency increased while BSFC decreased with HHO use in SI ICEs. CO, HC, and CO₂ emissions decreased in SI ICEs powered by HHO fuel throughout the entire operating range. Furthermore, gaseous HHO can be utilized in CI ICEs operating in dual-fuel (DF) configuration. When HHO was employed in CI ICEs in DF mode, BTE improved and BSFC decreased. CO, HC, and smoke emissions decreased, while NO_x increased throughout the entire ICE operating range.

When examining various efficiency reports and emission characteristics of CI ICEs powered by HHO, Ridhuan et al. [4] discovered that HHO gas enhanced brake power (BP) and torque. In all cases, an improvement in brake thermal efficiency was observed. This was because HHO gas contains H₂, which has a higher calorific value than fossil fuels. Simultaneously, BSFC was reduced, and the combined effects of H₂ and oxygen facilitated complete combustion, enhancing combustion efficiency when HHO gas was introduced. HHO gas inclusion improved BP, brake torque (BT), and BTE while reducing BSFC and lowering CO and HC emissions. The increase in CO₂ emissions indicated complete combustion. Consequently, utilizing HHO gas in CI ICEs improved ICE efficiency and reduced exhaust emissions.

Hosseini et al. [38] reported that HHO enrichment serves as a practical solution to enhance diesel ICE performance while minimizing exhaust emissions. HHO also addresses storage and safety concerns associated with H₂ use in diesel ICEs. HHO can boost BTE of diesel ICEs and reduce BSFC by increasing the calorific value of air-fuel (A/F) mixtures and improving combustion efficiency. HHO addition can enhance heat release rates and in-cylinder pressure of diesel ICEs due to increased flame speed and diffusivity of monoatomic H₂. HHO inclusion in diesel fuel may reduce ignition delays by creating a uniform air-fuel mixture. HHO incorporation may lead to notable decreases in CO, CO₂, UHC, smoke, and particulate matter (PM) emissions from diesel ICEs. This effect may be attributed to the presence of H₂ and oxygen in carbon-free HHO, which accelerates fuel oxidation processes and ensures complete combustion. HHO gas may successfully address the negative impacts of adding gaseous fuel to diesel fuel, such as reduced efficiency metrics and increased CO and UHC emissions.

Akal et al. [2] evaluated H₂ application as a fuel for vehicles and as an additional fuel source. They discovered that due to the elevated self-ignition temperature of H₂ fuel, it is better suited for use in gasoline ICEs. Incorporating H₂ into gasoline in specific ratios can further increase compression ratios (CRs), enhancing ICE efficiency and performance. In numerous studies, depending on the quantity of H₂ incorporated into fuel, ICEs have demonstrated improvements in both performance and fuel efficiency. Moreover, due to the structural characteristics of ICEs, gasoline ICEs are better positioned to utilize H₂ enrichment in terms of emissions and BSFC levels. When H₂ fuel was added to the LPG ICEs, there was a slight decrease in torque and power. When the quantity of H₂ supplied to the LPG system was increased, the BSFC and harmful emissions from these ICEs decreased. However, gaseous fuels and H₂ fuel reduce volumetric efficiency since they occupy more space in the ICE cylinder compared to gasoline. This can be addressed by designing various combustion chambers, increasing the cylinder capacities of ICEs that will utilize H₂ fuel, and incorporating variable valve timing and different valve designs. In diesel ICEs, different outcomes were noted based on the quantity of H₂ added to the fuel and the ICE speed. Although the torque and power outputs of certain ICEs increased with H₂ utilization, other ICEs experienced

a decline in torque and power values as speeds increased. Due to H₂'s elevated ignition temperature, it is unsuitable for direct application in diesel ICEs. Consequently, in numerous studies, various techniques were employed to inject H₂ into the cylinder. In various studies where H₂ fuel was added to diesel ICEs, a reduction in CO₂ emissions and soot production in exhaust emissions was noted, although an enhancement in NO_x emissions was also recorded. Many ICEs utilizing H₂ achieved reduced BSFC and harmful exhaust emissions.

Wang et al. [104] noted that H₂ fuel is beneficial as a fuel for automotive ICEs due to its advantages of wide flammability limits and high flame speed. Its introduction can significantly enhance the combustion and emission properties of ICEs. Regardless of ICE type, efficiency can be enhanced through targeted H₂ doping methods and specific H₂ doping ratios. Nevertheless, the optimal mode and proportion vary based on operating conditions. The performance of H₂ ICEs and H₂ blended ICEs is highly influenced by H₂ injector positions and H₂ injection control strategies.

Deheri et al. [22] noted that H₂, as a fuel with higher flame speed and lower ignition energy, enhances peak cylinder pressure and heat release rate. H₂ use as a fuel cause knocking in CI ICEs and increases NO_x emissions due to its rapid flame propagation. Combustion parameters like maximum in-cylinder pressure and heat release rate can be enhanced by up to 30%, while combustion duration and ignition delay can be reduced by 4 to 5%, by introducing biogas (BG) and H₂ into the cylinder alongside advanced injection timing and increased CRs. Diethyl Ether (DEE) serves as a beneficial additive alongside these alternative fuels to enhance combustion properties. DF mode reduced NO_x and smoke emissions by up to 60%, while HC and CO emissions may increase by up to 30%. However, these emissions can be controlled by employing control techniques and adding additional components with the pilot fuel.

Das et al. [19] also reported that H₂ in producer gas (PG) is the key element affecting ICE performance. A higher percentage of H₂ in producer gas enhances combustion efficiency and peak cylinder pressure (PCP). Nevertheless, a higher amount of inert gases, such as CO₂ and N₂, in PG inhibits pre-flame development that leads to knocking. Incomplete combustion during DF mode led to increased emissions of HC and CO compared to diesel mode. Utilizing BD as a pilot fuel enhances combustion efficiency of both gaseous and liquid fuels by supplying adequate O₂, leading to decreased levels of HC and CO. Moreover, H₂ incorporation in PG decreases the amount of carbon particles in the fuel and increases the average gas temperature, thereby reducing CO. Regarding producer gas use, a higher quantity of H₂ increases NO_x emissions.

H₂ use in diesel ICEs does not necessarily require significant modifications to the internal combustion engine (ICE). In their comprehensive review, Hosseini et al. [38] explained that H₂ can be utilized in existing CI diesel ICEs in DF configurations with minor adjustments. The specific physicochemical traits of H₂, including its higher calorific value, flame speed, and diffusivity, can significantly enhance the efficiency and combustion properties of diesel ICEs. Being a carbon-free fuel, H₂ can also reduce harmful

emissions from diesel ICEs, such as CO, UHC, PM, soot, and smoke. Nevertheless, diesel ICEs running on H₂ experience knocking combustion and elevated NO_x emissions. This review thoroughly examines the impact of H₂ or gaseous fuels containing H₂ (such as syngas (SG) and HHO gas) on the performance of DF diesel ICEs. H₂ can effectively decrease all carbonaceous emissions from diesel ICEs. Real-time H₂ injection control can eliminate its disadvantages in diesel ICEs. H₂ cannot enhance all performance metrics and exhaust emissions of diesel ICEs simultaneously. Nevertheless, modifying pilot fuel through additives, mixing H₂ with other gaseous fuels, changing ICE settings, improving operational conditions, adapting ICE design, utilizing HHO gas, and implementing exhaust gas catalysts may facilitate the development of safe, efficient, and cost-effective H₂-powered diesel ICEs.

H₂ inclusion in diesel fuel may enhance the BTE of diesel ICEs and reduce the BSFC rates. This may result from the increased heating value and faster burning of gaseous H₂. H₂ might also offset the reduced calorific value of BD while addressing its primary limitations, such as decreased BTE and increased BSFC. Increased H₂ addition levels may enable more uniform charge combustion, resulting in improved combustion characteristics. However, introducing H₂ above a specific threshold, especially under high ICE loads, could lead to knocking issues. The H₂ inclusion rate that results in knocking varies among ICEs, fuels, and operating conditions. Thus, a definitive guideline for the optimal H₂ inclusion rate cannot be established [38].

Selected characteristics of DF ICEs powered by diesel fuel, reviewed by Hosseini et al. [38], are shown in Fig. 1. The studied ICEs operated at speeds with a mean value of 1724 rpm and a standard deviation (SD) of 528. The displacement of such ICEs had a mean value of 1674 cm³ and a high SD of 2325 cm³. ICE minimum loads reached the mean value of 27.3% and SD of 34%, while maximum loads reached the mean value of 82% and SD of 32%. ICE load can vary between 0 and 100%. The ICE's minimum CR reached a mean value of 16.41 and SD of 4.72, while the maximum CR reached a mean value of 16.49 and SD of 4.78.

The effect of load, EGR and H₂ supply on BTE and BSFC for DF ICEs ignited by diesel fuel is shown in Fig. 2. For the data presented in Fig. 2a, 16% and approximately 65% of the analyzed cases exhibited missing data for BTE and BSFC, respectively. 13.5% showed reductions, approximately 3% and none showed no effect, and about 68% and 21.6%, respectively, showed increases. For the data presented in Fig. 2b, 28.5% and 71.4% of the analyzed cases exhibited missing data for BTE and BSFC, respectively. No cases showed reductions or no effects, and approximately 71.5% and 58.6%, respectively, showed increases. For data in Fig. 2c, 25% and 87.5% of analyzed cases exhibited missing data for BTE and BSFC, respectively; 12.5% and none showed reductions, no cases showed no effect; and about 62.5% and 12.5%, respectively, showed increases.

Integrating H₂ into pure diesel fuel may enhance the BTE of diesel ICEs [37, 46, 71, 72]. Incorporating H₂ into pure diesel fuel can result in a more complete combustion process due to its higher flame temperature and faster flame speed compared to conventional diesel [35, 47, 62, 112].

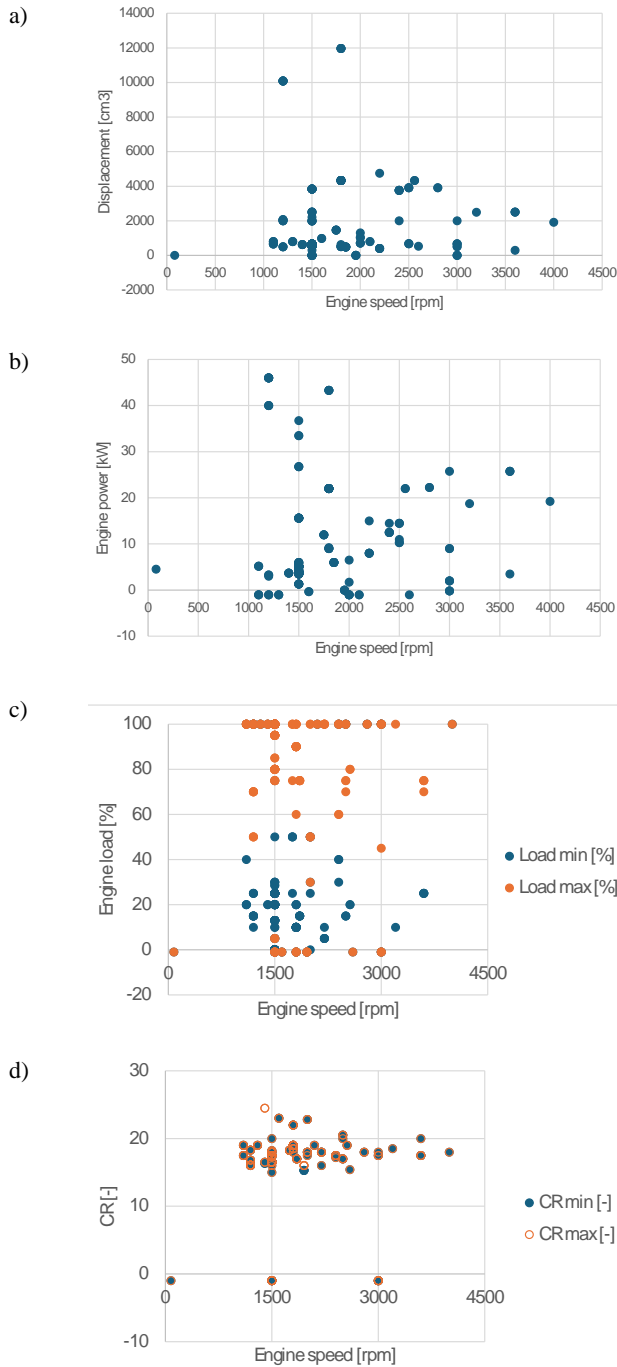


Fig. 1. Selected characteristics of DF ICEs ignited by diesel fuel speed (negative values correspond to missing data); a) displacement versus ICE speed, b) ICE power from 1-cylinder versus ICE, c) ICE load versus ICE speed, d) ICE CR versus ICE speed based on data from [38]

H₂ can improve the combustion of diesel fuel because its premixed flames possess wider flammability limits than hydrocarbon fuels, thereby enhancing the BTE of diesel ICEs [78]. H₂ can also shift the peak heat release closer to the injection (TDC) point, resulting in improved cycle efficiency of diesel ICEs [78]. Nonetheless, utilizing H₂ in a diesel ICE does not always guarantee an improvement in BTE. Although H₂ has higher energy content per unit mass compared to diesel fuel, factors such as the air-fuel (A/F) ratio and ICE design can significantly affect BTE. A factor

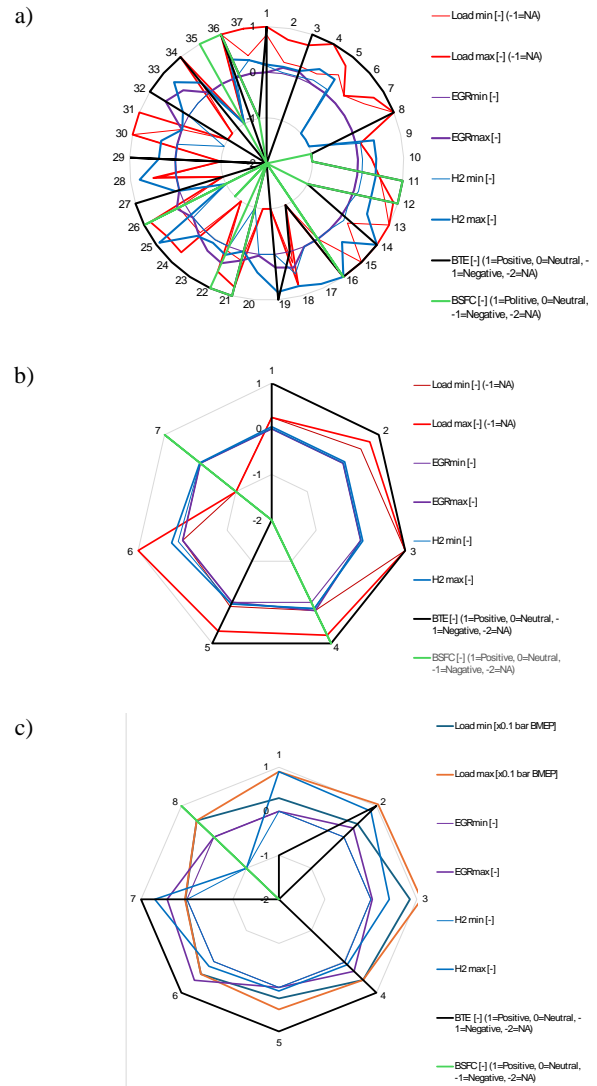


Fig. 2. The effect of load, EGR and H₂ supply on BTE and BSFC for DF ICEs ignited by diesel fuel; a) for ICE load [%], EGR [%], and H₂ supply [%], b) for ICE load [%], EGR [%], and H₂ supply [lpm] approximately converted to [%], c) for ICE load [x0.1 bar BMEP], EGR [%], and H₂ supply [%], based on data from [38]. There are shown minimal and maximal limits for load (Load min and Load max, respectively), EGR (EGRmin and EGRmax, respectively) and H₂ supply (H₂ min and H₂ max, respectively) in the Figure

that can enhance the BTE of diesel ICEs is the high energy content of H₂. This effect arises from H₂'s elevated calorific value, which drives the H₂-diesel combustion process toward completion, resulting in better ICE efficiency [47, 112]. Although higher calorific fuels generate more heat during combustion, this does not necessarily ensure complete combustion.

The completeness of the combustion process depends on the A/F ratio and the mixing of fuel and air within the combustion chamber. Moreover, incorporating H₂ into diesel fuel can improve A/F mixture homogeneity due to its gaseous state [23, 47], resulting in rapid energy release and enhanced combustion [79].

Incorporating H₂ into diesel fuel can enhance diesel ICE BTE through various mechanisms. One approach is to achieve a leaner equivalence ratio and reduce combustion

duration [55]. However, the effect of H₂ addition on the equivalence ratio may vary depending on specific ICE operating conditions and the amount of H₂ introduced. Although injecting H₂ via the inlet port may slightly reduce airflow, leading to a leaner mixture equivalence ratio, increasing H₂ percentage can also result in a richer mixture. Nevertheless, with increased H₂ addition rates, the overall A/F ratio can be maintained at or near stoichiometric to avoid efficiency reduction caused by higher H₂ levels. Also, the heat capacity ratio (adiabatic index) of H₂ exceeds that of hydrocarbon fuels, potentially enhancing diesel ICE BTE. Additionally, the rapid combustion rate of H₂ may reduce heat loss to the surroundings, further improving BTE [108]. However, increasing H₂ beyond a certain threshold may cause knocking [80]. The short quenching distance of the H₂ flame increases the likelihood of flame contact with combustion chamber walls, resulting in increased convective heat transfer and reduced BTE at high H₂ content [112]. Therefore, the precise influence of H₂ addition on BTE depends on specific ICE configuration and operating conditions.

While some studies indicate that H₂ addition to diesel fuel improves combustion efficiency, others suggest the opposite [28, 87], Varde and Frame [100] proposed that incorrect piston positioning relative to peak in-cylinder pressure due to H₂-diesel mixing may reduce diesel ICE BTE. This issue may be resolved by adjusting diesel fuel injection timing, either advancing or retarding it, to optimize combustion timing and mitigate negative impacts on ICE performance. Although H₂ addition into the intake air increases heat absorption by H₂ molecules, it does not necessarily reduce flame temperature. H₂ addition may lower oxygen availability for combustion, potentially reducing combustion efficiency [67]. It is essential to note that H₂ has a higher molar heat capacity than nitrogen, which can increase the overall heat capacity of the mixture. Nonetheless, H₂ addition often leads to an increased overall equivalence ratio, raising combustion temperature. Conversely, low BTE in H₂-diesel dual-fuel operation can be attributed to heat losses resulting from the short flame quenching distance and the high thermal conductivity of H₂, which increases convective heat losses and reduces overall efficiency [26]. Heat loss rates also rise when H₂ is mixed with diesel due to increased wall heat flux, lowering BTE [65].

H₂ addition to diesel under varying ICE loads may result in differing efficiency trends [21, 102].

H₂ addition can reduce BTE under low loads because diesel injection rates decrease, possibly resulting in insufficient pilot fuel to fully combust added H₂. At higher ICE loads, BTE improvements are observed due to increased pilot diesel injection, providing adequate ignition energy for gaseous fuel combustion [57]. H₂ may enhance diesel combustion at higher loads due to the broader flammability limits of its premixed flames, resulting in improved A/F mixture combustion. Additionally, increasing H₂ supplementation at higher loads can increase in-cylinder pressure thanks to its rapid combustion and wide flammability limits [25]. These factors, when combined, can improve BTE in H₂-diesel dual-fuel operation at high loads. In dual-fuel ICEs, H₂ and diesel fuel are injected separately.

The H₂ inclusion rate is typically independent of ICE load and speed, regardless of the injection method, allowing the adjustment of the H₂-to-diesel ratio to ensure consistent combustion and improved efficiency.

The comparative BSFC metric represents fuel consumption per unit brake power (BP) output [109]. Two approaches determine BSFC in diesel ICEs running on H₂ fuel. The first divides the combined mass flow rates of H₂ and diesel by generated power [21, 45, 66]. The second converts the H₂ mass flow into an equivalent diesel amount based on lower heating values, then sums the diesel and converted H₂ mass flows before dividing by the power output [42, 43]. Both express BSFC in g/kWh or kg/kWh. The second method is considered more practical and reliable, as the first may be misleading for fuels with different densities and energy contents [75].

Many studies [14, 46] demonstrated that H₂ addition to intake air reduces BSFC due to its high diffusivity and flame speed, facilitating uniform mixing and improved combustion, increasing BP while reducing BSFC [23, 45, 47, 90]. However, excessive H₂ introduction may increase BSFC due to oxygen limitation, causing incomplete combustion [45].

Although some studies show H₂ improves diesel ICE efficiency, others dispute this [42, 87]. This can occur because H₂ addition reduces available oxygen in the combustion chamber, impairing combustion [45]. Mismatches between diesel injection timing and H₂ addition can cause suboptimal combustion timing and insufficient combustion duration, lowering BP and raising BSFC. Brake Specific Energy Consumption (BSEC) is a more reliable efficiency metric, as it is unaffected by fuel characteristics [33]. H₂ addition may improve BSEC by accelerating combustion reactions and enhancing mixture homogeneity [20, 23, 46, 95]. However, excessive H₂ can reduce local oxidant concentration and combustion efficiency [29]. Some studies report BSEC increase due to the mismatch between diesel ICE combustion and gaseous H₂ [48], and increased H₂ mass flow may exacerbate this [108].

The elevated flame temperature of H₂ can increase peak in-cylinder pressure and heat release rates in diesel ICEs. H₂ addition can shorten combustion duration owing to rapid flame speed and faster A/F mixing. However, H₂ inclusion may lengthen ignition delay due to low cetane number and higher auto-ignition temperature. Due to its carbon-free nature and enhanced mixture uniformity, H₂ can significantly reduce emissions of CO, CO₂, HC, PM, smoke, and soot. Nonetheless, H₂ may increase NO_x emissions due to higher in-cylinder peak pressure and temperature [38].

The effect of load, EGR, and H₂ supply on particulate matter (PM), hydrocarbons (HC), NO_x, CO, and CO₂ emissions for DF ICEs excited by diesel fuel is shown in Figure 3. For data in Fig. 3a, 10.1%, 5.4%, 2.7%, 1.1%, and 30% of analyzed cases exhibited missing data for PM, HC, NO_x, CO, and CO₂ emissions, respectively; 8.1%, 21.6%, 43.2%, 8.1%, and 2.7%, respectively, showed reductions; 2.7%, 1.1%, 8.1%, none, and none, respectively, showed no effect; and 78.3%, 62.1%, 45.9%, 81%, and 67.5%, respectively, showed increases. For Fig. 3b, 14.2% of cases had missing data for PM, HC, NO_x, CO, and 28.5% for CO₂ emissions; 14.2% showed reductions for PM, HC, NO_x, and

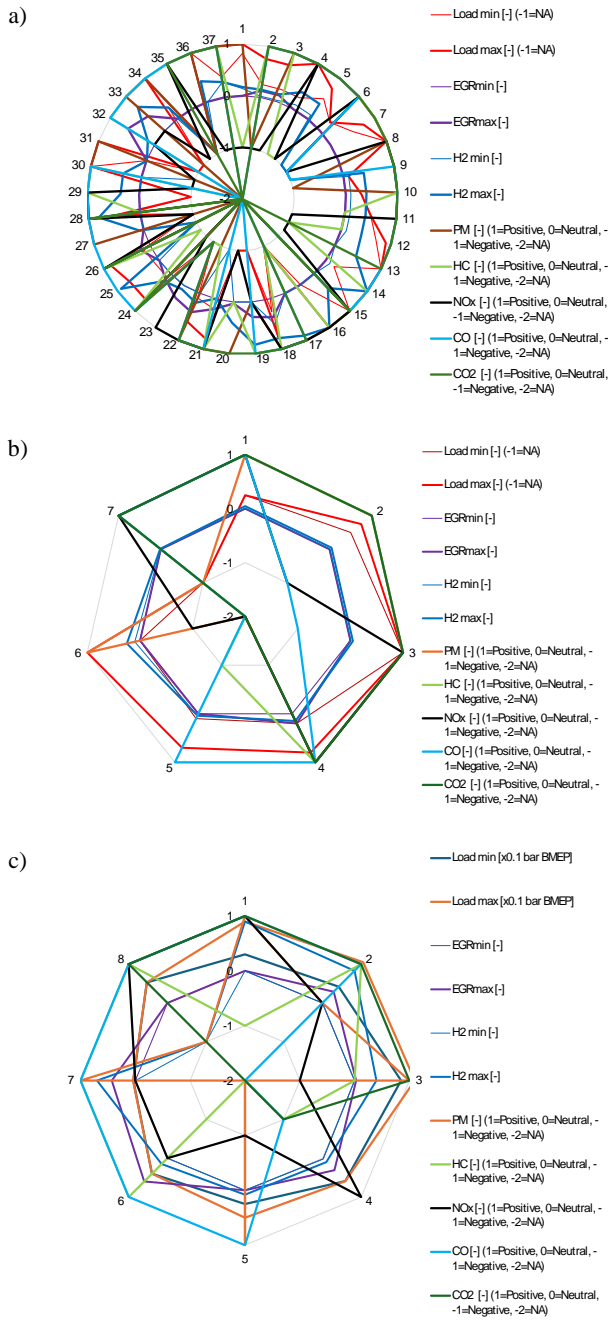


Fig. 3. The effect of load, EGR and H₂ supply on PM, HC, NO_x, CO and CO₂ emissions for DF ICEs ignited by diesel fuel; a) for ICE load [%], EGR [%], and H₂ supply [%], b) for ICE load [%], EGR [%], and H₂ supply [lpm] converted approximately to [%], c) for ICE load [$\times 0.1$ bar BMEP], EGR [%], and H₂ supply [%], based on data from [38]. There are shown minimal and maximal limits for load (Load min and Load max, respectively), EGR (EGRmin and EGRmax, respectively) and H₂ supply (H₂ min and H₂ max, respectively) in Figure

CO, none for CO₂; none showed no effects; and 71.4%, 71.4%, 57.1%, 57.1%, and 71.4% showed increases. For Figure 3c, 25%, 12.5%, none, 12.5%, and 37.5% had missing data for PM, HC, NO_x, CO, and CO₂; 12.5%, 25%, 25%, 12.5%, and 12.5% showed reductions; 12.5%, 12.5%, 37.5%, none, and none showed no effect; and 50%, 50%, 37.5%, 75%, and 50% showed increases.

The amount of soot released from the diesel ICE depends on the equilibrium between soot production and its

oxidation [105]. H₂ addition to diesel fuel may reduce soot emissions [1, 5]. H₂ can effectively unify the A/F mixture, enhancing combustion efficiency and reducing soot emissions [46]. Incorporating H₂ into diesel fuel may lower carbon levels or increase the H/C ratio of the fuel, thereby reducing soot emissions [61]. By decreasing the proportion of diesel fuel in the mixture, soot oxidation may be enhanced while initial soot formation is reduced [94]. Smoke is an apparent byproduct of incomplete combustion. H₂ addition to diesel fuel may reduce smoke emissions due to the carbon-free nature of gaseous H₂ or an increased H/C ratio in the A/F mixture [81, 83]. The combustion of H₂ generates water and does not produce smoke emissions [80]. The high diffusivity of H₂ may improve A/F mixture uniformity and increase O₂ availability, further reducing smoke emissions [66]. The intense flame produced during H₂ combustion can oxidize carbon particles arising from diesel combustion [82]. The formation of a premixed H₂-air charge during DF operation may eliminate the source of smoke emissions from diesel ICEs [101]. However, excessive H₂ induction may increase smoke emissions by creating an overly rich A/F mixture [78].

PM consists of carbon-based substances resulting from the incomplete combustion of hydrocarbon fuels [80]. PM is a complex pollutant that includes both soluble and insoluble fractions, as well as dry components [98, 106]. Soot, classified as an insoluble fraction, constitutes a significant portion of PM (slightly over 50%) [98]. The remainder of PM (~50%) comprises unburned hydrocarbons (UHCs), partially oxidized hydrocarbons, unburned or partially burned lubricating oil, wear particles, and sulfates (SO₄²⁻) derived from the fuel [60, 98]. The majority of soot consists of elemental carbon, which adsorbs organic compounds such as polycyclic aromatic hydrocarbons and their derivatives, sulfates, nitrates (NO₃⁻), metals, and various trace elements [13]. PM particles exist in both liquid and agglomerated solid forms. Primary particles in the liquid phase are typically volatile organic compounds and sulfates, ranging in size from 5 to 50 nm. Agglomerated particles mainly consist of soot, volatile and nonvolatile organic fractions, metallic residues, and sulfates, with sizes ranging from 50 to 500 nm [36]. Soot aggregates primarily from inside the combustion chamber, while PM is generated outside it [36]. PM may decrease with H₂ enrichment due to the absence of carbon in H₂ and a reduced diesel fuel injection rate [57]. Adding H₂ to diesel fuel may increase flame temperature and improve hydrocarbon combustion, reducing PM generation [67]. Replacing diesel fuel with H₂ can create a more uniform A/F mixture, reducing fuel-rich zones and lowering PM emissions. Incomplete combustion in fuel-rich zones near injector sprays can result in PM formation [58]. Adding H₂ may decrease both particle size and concentration due to its inhibitory effect on hydrogen abstraction and acetylene (C₂H₂) addition processes [114].

Furthermore, it appears that the agglomeration of additional particles into larger clusters can be reduced by incorporating H₂ into ultra-low-sulfur diesel [115]. H₂ addition may also alter the nanostructure of primary particles emitted from the diesel ICE. A shift from a “turbostratic interlayer” to an “onion-like” structure was observed with H₂

addition at 1200 and 1800 rpm under 30% load. Moreover, the "shell-core" structure can transition to a "shell-amorphous" structure with H₂ addition at 1200 and 1800 rpm under 70% load. Compression ignition (CI) diesel ICEs generate PM mainly due to non-uniform combustion resulting from localized fuel-rich zones within the combustion chamber [15]. H₂ can promote a more uniform A/F mixture, reducing PM emissions. H₂ addition may also lower PM emissions from ICEs running on biodiesel (BD) due to a reduced proportion of carbon-containing BD in the A/F mixture [12, 63, 113]. The product of H₂ combustion is water, not PM [15]. The main factors influencing PM oxidation in CI ICEs are the O₂ concentration and temperature inside the cylinder.

UHC compounds are typically found in low-temperature regions of the combustion chamber, such as near cylinder walls, where the temperature is insufficient for complete combustion of the A/F mixture [22]. Incorporating H₂ may reduce UHC emissions from diesel ICEs due to the absence of carbon in H₂ fuel [10]. Introducing H₂ into the intake air may extend the ignition delay, allowing for better A/F mixing prior to ignition [58]. Gaseous H₂ can fully homogenize the A/F mixture due to its high diffusivity [46], improving combustion efficiency and reducing UHC emissions. The wide flammability range and short quenching distance of H₂ may also improve the combustion of A/F mixtures [108]. The rapid burning rate of H₂ can enhance diesel combustion, leading to lower UHC emissions [82]. H₂ addition may increase in-cylinder temperature, enhancing UHC oxidation after combustion [47].

However, H₂ incorporation into diesel fuel may also increase UHC emissions [20, 42]. This may occur if the pilot fuel supply is insufficient to fully ignite the gaseous fuel [26], or if H₂ reduces the O₂ concentration in the A/F mixture, resulting in incomplete diesel fuel combustion [66]. Rapid H₂ combustion may consume most of the available O₂, leading to incomplete oxidation of diesel injected late in the cycle [100]. The high burning speed of H₂ may also increase UHC emissions due to flame quenching [81]. Extending the ignition delay under fuel-lean conditions with H₂ addition may also result in incomplete combustion [114].

The formation rate of NO_x in diesel ICEs largely depends on O₂ concentration, A/F mixture residence time, and in-cylinder temperature. Atmospheric N₂ and O₂ can undergo various chemical reactions, forming NO_x in high-temperature regions [39]. Conventional diesel combustion produces high levels of NO_x and soot due to diffusive flame characteristics [48]. Low-temperature combustion can reduce both NO_x and soot emissions from diesel ICEs [51], [76]. Various low-temperature combustion strategies, such as homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and reactivity-controlled compression ignition (RCCI), have been developed and studied [51]. RCCI can operate over a wide load range, achieving near-zero NO_x and soot emissions by adjusting fuel blends and injection strategies [49, 50, 111]. RCCI ICEs control in-cylinder reactivity to manage the combustion phase [51]. In this dual-fuel process, at least two fuels with different reactivities are used [30, 49]. A/F homogeneity is achieved by introducing low-reactivity

fuels (e.g., methanol, natural gas, gasoline, ethanol) through the intake port, while ignition is initiated by direct injection of a high-reactivity fuel (e.g., diesel, biodiesel, dimethyl ether) [11, 34].

In RCCI diesel combustion, combustion chamber regions are cooler compared to conventional diesel, significantly reducing heat transfer from the piston bowl and improving BTE [44]. While RCCI offers attractive features, its CO and UHC emissions are typically higher than in standard diesel combustion [34]. When H₂ is added to low-reactivity fuels, RCCI ICEs produce much lower CO and UHC emissions, as shown by Kakoei and Gharehghani [41]. However, H₂ addition beyond a certain threshold may increase NO_x and soot emissions by raising in-cylinder temperature.

H₂ addition to diesel fuel may increase NO_x emissions [20], [107]. The high calorific value of H₂ can elevate peak in-cylinder pressure and temperature, leading to higher NO_x emissions [77]. The rapid flame speed of H₂ can promote complete combustion, further increasing pressure and temperature [85]. H₂ addition may also raise local temperatures earlier in the expansion phase, accelerating NO_x formation [100]. The increased ignition delay due to H₂ addition can create a more homogeneous A/F mixture before ignition, raising in-cylinder temperature and contributing to higher NO_x emissions [58]. NO_x emissions from H₂ port injection can exceed those from H₂ induction [101]. Port injection can improve combustion and volumetric efficiency while increasing combustion temperature [101].

However, H₂ incorporation into diesel fuel may also reduce NO_x emissions if the engine operates with a leaner mixture [83]. A very lean equivalence ratio can lower peak combustion temperature, reducing NO_x emissions [81]. H₂ can promote a more uniform A/F mixture, eliminating fuel-rich zones and allowing temperature to rise more gradually, thus reducing NO_x production [1]. NO_x reduction may also occur at high H₂ supplementation rates if combustion duration increases, lowering the heat release rate [28]. Water vapor (H₂O) generated from H₂ oxidation may lower in-cylinder temperature and further reduce NO_x emissions [108]. H₂ addition may reduce the amount of diesel fuel consumed during the diffusive combustion phase, which is a major source of NO_x [108].

H₂ introduction into the intake air can reduce CO emissions [20, 112] due to a lower C/H ratio in the fuel mixture [32]. The high diffusivity of H₂ promotes a homogeneous combustible mixture, enhancing combustion and reducing CO emissions [42, 77]. The rapid flame speed of H₂ enhances combustion and increases in-cylinder temperature, thereby further reducing CO emissions [66, 77]. This reduction may also be linked to the ability of H₂ to operate at lean equivalence ratios [84], [112]. However, H₂ addition to diesel fuel under certain conditions may increase CO emissions. This can occur if H₂ reduces O₂ availability, leading to incomplete oxidation [26]. Elevated in-cylinder temperature from H₂ addition may promote CO₂ dissociation into CO and O [56]. The rapid H₂ reaction rate may deplete O₂ in the combustion chamber, leaving less for CO oxidation. O₂ may be consumed in H₂ oxidation and radical formation [10]. H₂O from H₂ oxidation may also participate in the steam reforming of diesel hydrocarbons, increasing CO

emissions [10]. H₂ addition may increase CO production under high engine loads due to reduced O₂ and shorter reaction times [82]. However, CO emissions may decrease when H₂ is blended with diesel under low loads, due to ample O₂ in leaner A/F mixtures [82].

H₂ incorporation into diesel fuel may lower CO₂ emissions [52, 112], due to the carbon-free nature of H₂ [66]. Furthermore, increasing the overall H/C ratio of the fuel blend by adding H₂ can shorten combustion duration and improve combustion efficiency [61, 77]. The high diffusivity of H₂ may also create a more uniform premixed combustible mixture [20], driving combustion toward completion [77]. The rapid flame speed of H₂ can improve fuel blend combustion efficiency, potentially reducing CO₂ emissions [20]. However, under high engine loads, H₂ addition may reduce CO₂ emissions due to combustion instability and O₂ deficiency [80].

Sutkowski and Mareczek [93] examined the MUZG and WUZG systems designed for managing the combustion of H₂-based fuels. These systems enable operation even with pure H₂ while effectively controlling combustion parameters, such as preventing knock, regulating combustion temperature, and controlling flame speed, among others. This is achieved by early detection of knock or misfire signals, monitoring exhaust temperature, and implementing corrective actions in the next engine cycle if deviations are detected. The WUZG system also enables independent monitoring of each cylinder with its individual mixture composition, or temporary deactivation of a cylinder if combustion becomes unstable, thereby potentially preventing cylinder failure. The system logs engine operation and can detect even minor deviations from target performance, enabling preventive measures to be taken before damage occurs. This prevents scenarios where engine power is limited or the engine must be shut down due to operational faults. The integrated MUZG/WUZG system offers enhanced operational flexibility, allowing transitions between different fuel supply systems. MUZG is prioritized for fuels with low pressure and low H₂ content, while WUZG is preferred for higher-pressure or higher-H₂ fuels. The system can be expanded to accommodate additional hydrocarbon gases blended with H₂. MUZG is applicable to bi-fuel engines operating on both liquid and gaseous fuels (e.g., biodiesel and biomethane), whereas WUZG can be used in dual-fuel engines that combine biodiesel with H₂ or alcohols.

Longwic et al. [54] examined the acceleration of a diesel ICE fueled by both diesel and H₂ on a test bench equipped with a 1.3 Multijet diesel, H₂ storage, and measurement instruments (Table 1). Empirical tests included ICE assessment at idle and at specific speeds using a chassis dynamometer, as well as vehicle acceleration in selected gears from predefined engine speeds. They found that supplying both diesel and H₂ to the intake manifold increased the mean indicated pressure at idle by approximately 144% compared to diesel-only operation. The amount of heat release, peak combustion pressure, and maximum rate of pressure rise also increased. However, for engine operating conditions other than idle, there was a decrease in heat output, heat release rate, combustion chamber pressure, and mean indicated pressure. In these tests, the H₂ flow was

controlled to ensure no gas accumulation and prevent possible explosions in the intake manifold under any operating condition. Stock diesel fuel injection timing maps were not modified. Currently, it appears that H₂ supplied to the intake manifold can improve engine performance at idle. However, to achieve safe and noticeable improvements under other conditions, both the H₂ amount and diesel fuel quantity must be adjusted according to the engine's operating parameters.

Longwic et al. [53] tested a diesel engine powered by various fuels using a specialized H₂ injection system with dedicated control software. Control parameters included H₂ injection pressures of 1.5, 1.8, and 2.0 MPa and injector opening durations of 2.5, 3.0, and 3.5 ms.

Analysis of the engine operating in diesel-H₂ dual-fuel mode demonstrates that rapidly changing in-cylinder combustion parameters can be effectively monitored. As H₂ injection duration and pressure increase, the amount of air required for proper combustion also rises. The control system responded by reducing the amount of diesel fuel injected per cycle as additional H₂ was provided. However, the range of H₂ pressure and injection duration was limited, so the reduction in diesel fuel quantity was nearly the same across the tested range. Proper regulation of the diesel-H₂ ratio is essential for stable engine operation under load.

Research on a diesel engine operated with H₂ enabled the identification of control parameters for integrating renewable fuel to reduce fossil fuel consumption, specifically diesel. Operating the test vehicle on a dynamometer in 4th gear at 2600 rpm, optimal fast-variable cylinder parameters were achieved with an injector activation time of 3.5 ms at 0.20 MPa. Modified control strategies resulted in an average 21.5% reduction in diesel consumption.

Noga and Moskal [64] examined the suitability of a pressure-sensing glow plug (PSG) for monitoring combustion in an H₂-powered engine (Table 1). The combustion characteristics of H₂ in spark-ignition (SI) engines differ significantly from those of conventional fuels, making cylinder pressure monitoring essential for optimizing power, efficiency, and minimizing NO_x emissions, which are the primary pollutants in H₂ engines. A PSG was selected for its cost-effectiveness, availability, and durability. Initial tests were conducted on a small single-cylinder SI engine coupled to a 48 V generator. Tests were run at various speeds and generator loads using gasoline with a research octane number (RON) of 95. To simulate H₂ combustion and achieve faster pressure rise, tests were also performed with unaltered light gasoline (lower RON). Comparing the PSG signal with that of a reference pressure transducer installed in the cylinder allowed characterization of PSG behavior under different conditions. Pressure waveforms from both sensors varied according to engine speed and load. The developed transfer functions from the PSG signal to actual in-cylinder pressure may be applied to other engines, allowing cost-effective combustion monitoring in H₂ SI engines after appropriate calibration.

Cupał and Szwaja [18] studied producer gas combustion in SI and DF CI engines using a diesel pilot (15% of nominal amount), with compression ratios (CR) of 8, 12 (SI engine), and 17 (CI engine) (Table 1). The study focused on

combustion instabilities, including cycle-to-cycle variability and knock phenomena. H₂ combustion was also investigated for comparison. The authors found that producer gas is knock-resistant, even with 16% H₂ content. However, significant cycle-to-cycle variability was observed when producer gas was burned in the SI engine. The DF CI engine could operate more efficiently and stably with producer gas, with no misfires or knock. On the other hand, H₂ combustion in the DF engine resulted in heavy knock, making it unsuitable as a primary fuel. Conversely, gases with high H₂ content are generally not prone to knock, especially when CO₂ is present in quantities similar to H₂, as this greatly increases resistance to knocking.

Tira et al. [97] examined the performance of diesel ICEs fueled with biogas (BG) and H₂ (Table 1). In these experiments, simulated BG (60% CH₄ and 40% CO₂ by volume) and H₂ (2% by volume) were introduced into the intake manifold, while diesel fuel was injected into the cylinder as a pilot ignition source. The results showed that BG and H₂ reduced PM levels compared to pure diesel combustion. Specifically, total PM decreased by up to 39% and smoke by 33%. A slight increase in particle count was observed, with particle size distribution shifting toward the nucleation mode, which is advantageous for after-treatment systems. However, BTE decreased with the addition of gaseous fuel.

Siadkowska and Barański [89] investigated (direct H₂ injection) in a four-cylinder, four-stroke DF ADCR ICE (Table 1). Analyzed parameters included mean effective pressure, peak pressure, crank angle at peak pressure, and heat release. Both early and late direct H₂ injection timing strategies were tested. The authors found that:

- Significant statistical differences were observed in burning process parameters between early and late injection, based on the Student's t-test ($\alpha = 0.05$): for IMEP (56%), peak pressure (88%), heat released (56%), and crank angle at peak pressure (56%)
- In 94% of measurement points, the coefficient of variation for IMEP remained below 5%, indicating stable combustion progression
- Changing direct H₂ injection timing from early to late affects only the combustion process; the degree of this influence depends on H₂ dosage and initial torque. At the highest H₂ dosages, the maximum load threshold of the test setup was nearly reached, resulting in engine knocking, which may account for the observed instabilities.

Depczyński et al. [24] examined the effects of H₂ as an additive to gasoline in ICEs within a hybrid powertrain, focusing on efficiency and environmental sustainability (Table 1). Their study centered on evaluating fuel consumption and CO₂ emissions during the NEDC driving cycle. A mathematical model was developed incorporating H₂ addition and hybrid powertrain operation during the NEDC cycle. They found that a 2% increase in H₂ content in gasoline reduced BSFC by 2.8–3.5%, depending on engine speed. The hybrid system enabled effective energy recovery during braking, enhancing overall system efficiency.

Shadidi et al. [86] investigated the effects of using H₂ as an auxiliary fuel in both SI and CI ICEs on engine efficiency and emissions. Utilizing H₂ as a fuel reduces torque, power, and brake thermal efficiency (BTE), while simulta-

neously increasing brake specific fuel consumption (BSFC). H₂ use significantly lowers CO, UHC, CO₂, and soot emissions; however, NO_x emissions increase.

Stepień [92] reviewed the unique physical, chemical, and operational properties of H₂ used as an ICE fuel, focusing on H₂ port fuel injection (PFI) and direct injection (DI) technologies. The author compared various fuel injection and ignition strategies, highlighting the benefits of combining selected solutions. Potential risks of improper H₂ combustion – such as pre-ignition, delayed ignition, knocking, and backfiring – were analyzed. Special attention was given to optimizing the air-fuel ratio for combustion quality, NO_x emissions, and engine efficiency, as well as exhaust gas treatment. Required modifications to adapt conventional ICEs for H₂ operation were also discussed. It was found that H₂ represents a promising alternative fuel for SI ICEs, significantly improving efficiency and reducing emissions to a fraction of the levels of conventional fuels. However, its use has notable drawbacks, including elevated NO_x emissions, reduced durability, and reliability concerns.

Fabiś et al. [29] studied the relationship between combustion noise and operational parameters of an ICE powered by LPG, CNG, and CNG-H₂ mixtures in comparison to a gasoline-fueled ICE. Indicators of various resonances within the combustion chamber and related vibration signals from the engine's cylinder block were examined for a single combustion cycle. A four-cylinder, 1.6 dm³ SI ICE modified to operate on LPG, CNG, and CNG-H₂ mixtures with H₂ volumetric fractions of 5, 10, 15, 20% to 30% was evaluated. For comparison, gasoline was used as the reference fuel. The authors found that fluctuations in in-cylinder pressure significantly affect the vibration signal from the engine block. For CNG-H₂ mixtures of 20% and 30% H₂, a distinct reduction in combustion noise was observed compared to the other fuels studied.

Sharma and Dhar [88] investigated how different compression ratios (CRs) influence the maximum possible H₂ energy share in a DF ICE. A numerical model was used to examine combustion and emission characteristics with H₂ introduced via port fuel injection (PFI). They found a trade-off between maximum H₂ energy share and CR. The knock-limited maximum H₂ energy share increased from 20% to 45% as the CR was reduced from 19.5 to 14.5. With increasing H₂ energy share, emissions – except for NO_x – typically decreased across all tested CRs.

Jamrozik et al. [40] reported that investigating DF combustion with diesel and H₂ (0–30%) showed that adding up to 30% H₂ increased peak combustion pressure by 13%, increased heat release rate by 46%, and raised the maximum rate of pressure rise by 35% under full load conditions. Although efficiency improved with H₂ concentrations up to 25%, engine stability decreased at higher H₂ levels, and NO_x and HC emissions increased. Therefore, careful optimization of H₂-diesel mixtures is essential to enhance efficiency while managing emissions [91].

Pham et al. [69] examined the efficiency, combustion, and emission characteristics of ICEs using alternative fuels (H₂, NG, BD) in DF CI ICEs. Due to differing fuel properties, DF operation typically improved brake specific energy consumption (BSEC) compared to standard diesel operation.

Table 1. The characteristics of selected dual-fuel internal combustion engines powered by H₂

Refs	Model ICE type	Combustion system	H ₂ supply method	Bore × stroke [mm]	Displacement [dm ³]	CR [-]	Max power [kW]/ Speed [rpm]	Max torque [Nm]/ speed [rpm]
[54]	Fiat Qubo 1.3 MultiJet 4-cylinders, vertical 4-stroke forced air cooled diesel	Multipoint injection system	H ₂ is supplied from the cylinder to the inlet channel via tubing. Pressure controlled by a valve and measured with a manometer. Flow rate measured by a Vogtlin mass flow meter in the line supplying H ₂ to the system	69.6 × 82	1.248	16.8:1	55/4000	190/1500
[18]	Deutz F2L511 2-cylinders, 4-stroke, air cooled, diesel	6-hole injector for adjustable diesel fuel dosing. One cylinder modified to operate in SI mode	H ₂ or producer gas supplied via an injection system mounted on the inlet manifold or via a mixer	100 × 105	1.650 (unmodified), 0.825 (modified)	8:1; 12:1 (1 cylinder modified to operate at SI mode); 17:1 (diesel)		
[97]	Lister-Petter TR1 1-cylinder, Bowl-in-piston, air cooled diesel	3-hole direct injection. Pilot liquid fuel injected near the end of the compression phase	Bottled H ₂ supplied via the intake manifold (~2% of air intake). H ₂ premixed before entering the combustion chamber	98.4 × 101.6	0.773	15.45:1	8.6/2500	39.2/1800
[89]	Andoria-Mot ADCR ICE 4-cylinder, 4-stroke DF diesel ICE		The glow plugs replaced by injectors for compressed H ₂		2.636	17.5:1		
[64]	WEIMA 168FA 4-stroke, SI, 1-cylinder, air cooled		Unmodified light gasoline as a solvent to simulate H ₂ supply		0.163		3.8/3600	
[24]	VAZ-21081 ICE, 4-stroke, 4-cylinder, gasoline	distributed FI system	H ₂ supplied as a part of hybrid system	76 × 60.6	1.1	9:1	39.7/5600	77.9/3600
[8]	1-cylinder, air-cooled, (DI), 4-stroke HATZ D-series DI diesel ICE		H ₂ fed into the mixer in the intake manifold. Diesel fuel flow rate controlled by a modified original diesel FI system					

However, the overall efficiency of DF ICEs – measured by BTE and volumetric efficiency – remained considerably lower. DF operation significantly increased in-cylinder pressure and heat release rate while prolonging the ignition delay. Emission characteristics revealed a trade-off between NO_x and HC emissions: NO_x, PM, and smoke decreased, depending on engine load, blend ratio, and injection timing. However, HC and CO emissions in DF ICEs were several times higher than in conventional diesel engines.

Tutak et al. [99] studied a DF ICE running on diesel and NG, with H₂ enrichment to improve the NG component. They found that increasing H₂ levels improved combustion efficiency, reducing combustion duration by 30% and halving the time to 50% mass fraction burned. The maximum H₂ energy share was determined to be 19%; beyond this, engine stability declined due to increased cycle-to-cycle variability and knocking.

Rorimpandey et al. [73] emphasized the role of injection sequence, timing, and ambient temperature on combustion. Injecting the pilot diesel before H₂ cooled and delayed H₂

ignition. In contrast, injecting H₂ first improved air–gas mixing, but lean combustion occurred if H₂ was injected later, especially at low ambient temperatures.

Bakar et al. [8] explored the effects of varying H₂ flow rates on combustion, efficiency, and emissions in a DF diesel ICE. Tests conducted at various engine speeds and H₂ flow rates revealed that specific flow rates had a significant impact on engine efficiency and emissions. In particular, BTE increased at lower flow rates due to shorter combustion duration and improved phasing, while higher flow rates increased CO, CO₂, and smoke emissions.

Numerous studies indicate that increasing the H₂ proportion in DF ICEs improves combustion efficiency and reduces emissions, but requires careful management to prevent engine instability and increased NO_x emissions.

These studies highlight the influence of CR, injection timing, and H₂ flow rate on efficiency, demonstrating that while H₂ enhances fuel efficiency and reduces emissions, careful integration is essential to ensure engine stability and prevent combustion-related issues.

Wagemakers and Leermakers [103] reported that using H₂ or SG in DF combustion generally increases NO_x emissions, likely due to higher fire temperatures and burning speeds. HC and CO emissions also tend to increase in DF combustion, primarily due to incomplete combustion of mixtures trapped in crevices. Efficiencies of various gaseous fuels are similar, with minor gains observed for H₂ and LPG, and slight reductions for NG and SG.

Hosseini et al. [38] explained that although SG is low in carbon, its use in diesel ICEs may reduce thermal efficiency and increase BSFC, mainly due to the low volumetric calorific value and high CO₂ content of SG. Nanoparticles and oxygenated additives may help compensate for this by promoting complete combustion, though further research is needed. Adding less energetic SG reduces peak heat release rate and in-cylinder pressure in diesel ICEs. The high specific heat capacity and CO₂ content of SG may also extend ignition delay. Reduced burning rates and adiabatic flame temperature may result in longer combustion duration.

Adding SG to diesel/BD fuel may increase CO, CO₂, and UHC emissions from diesel ICEs. CO in SG and high charge dilution can lead to incomplete combustion. Oxygenated additives to diesel/BD may raise CO₂ emissions due to enhanced oxidation. These additives may also increase UHC emissions, as higher heat of vaporization can lower in-cylinder temperature. Adding nanoparticles to diesel/BD could reduce UHC emissions by promoting oxidation, but further research is required [38].

Integrating SG into diesel/BD fuel may reduce NO_x emissions from diesel ICEs. SG may lower concentrations of N₂ and O₂ in the intake air, decreasing the likelihood of thermal NO_x formation. SG may reduce PM emissions by decreasing the liquid fuel injection rate, which is more prone to sooting. However, adding SG may also increase soot/smoke emissions by lowering in-cylinder O₂ concentration and causing incomplete combustion. Conversely, some studies suggest that SG can lead to more homogeneous fuel mixtures and lower local air-fuel equivalence ratios, thus reducing soot/smoke emissions [38].

Ando et al. [6] evaluated the performance of low-heating-value gases from gasification and two-stage pyrolysis/reforming in a naturally aspirated single-cylinder SI ICE with CRs of 9.4 and 11.9. The gas from gasification was rich in H₂ (lower heating value of 3.83 MJ/Nm³), while the two-stage pyrolysis gas was rich in CH₄ (lower heating value of 4.2 MJ/Nm³). A gas mixer replaced the carburetor to control the air–fuel ratio. Both fuels achieved similar BTE to CNG. The H₂-rich gas enabled stable engine operation at λ up to 2.00. Compared to both CNG and CH₄-rich pyrolysis gas, NO_x and HC emissions were significantly lower for the H₂-rich gas. The CH₄-rich gas also exhibited very low NO_x levels.

Chintala and Subramanian [16] reported that PM emissions can be notably reduced while improving thermal efficiency by using H₂ in DF ICEs (diesel-H₂). In H₂ DF ICEs, HC, CO, and smoke emissions approach zero, while CO₂ and CH₄ emissions from CI ICEs are substantially reduced. However, the maximum H₂ energy share in DF ICEs at rated load is limited to 6–25% due to elevated peak cylinder pressures and pressure rise rates, which can cause

knocking and autoignition of the H₂-air mixture. In addition, NO_x emissions in DF mode are 29–58% higher than in conventional diesel mode due to high localized in-cylinder temperatures. Appropriate optimization strategies can increase the maximum H₂ energy share to 79% while reducing NO_x emissions to levels comparable to those of conventional diesel operation.

Mehra et al. [59] observed that incorporating H₂ into CNG (HCNG) ICEs enhances BTE and significantly reduces cycle-to-cycle variations (CCV) and BSFC due to H₂'s combustion characteristics. HCNG is safer than pure H₂ due to its lower energy content. Under certain conditions, the thermal efficiency of HCNG ICEs is notably higher than that of CNG ICEs, without increasing harmful emissions. However, adding H₂ to natural gas increases NO_x emissions due to higher combustion temperatures. This can be mitigated by lean combustion or three-way catalyst (TWC) systems. Using EGR with TWC reduces combustion temperature, directly lowering NO_x emissions. THC, CO, CO₂, and CH₄ emissions decrease notably with H₂ addition. However, H₂ also increases the engine's tendency to knock due to peak cylinder temperatures and high ignitability. H₂ enables higher CRs without combustion instability compared to CNG, further enhancing BTE. For SI ICEs, optimal performance is achieved with 20–30% H₂ enrichment. HCNG ICEs offer better fuel efficiency than conventional CNG ICEs, and direct fuel injection (DFI) systems further reduce BSFC compared to PFI.

According to [110], blending H₂ with natural gas in SI ICEs shifts the lean limit toward a leaner mixture, increasing combustion speed and temperature. Even a small addition of H₂ by volume catalytically improves hydrocarbon ignition, and in pure CNG, the required spark advance can be reduced due to H₂'s high flame speed. HCNG mixtures improve engine efficiency, especially at low loads, but with increasing H₂ content from 10% to 30%, NO_x emissions rise by 4–20% due to higher in-cylinder temperatures. Implementing about 10% EGR for HCNG blends can significantly reduce NO_x emissions and BSFC compared to natural gas. Maximum brake torque can be achieved under leaner combustion conditions by increasing H₂ content.

Hosseini et al. [38] explained that H₂ can address issues associated with using gaseous fuels (e.g., biogas, methane, CNG, NG, LPG) in diesel ICEs, including extended ignition delay, reduced engine efficiency, slower burning rates, and increased CO and UHC emissions. H₂ can improve efficiency metrics of diesel ICEs running on biogas by offsetting the low calorific value of CO₂-rich biogas and optimizing its combustion. Similarly, increasing H₂ levels can enhance efficiency in diesel ICEs running on CH₄ by accelerating combustion. Notably, CH₄ can compensate for some limitations of H₂ combustion (e.g., short quenching distance). H₂ can offset the low flame speed of CNG and NG, enhancing their combustion in diesel ICEs. H₂ can improve the BTE of LPG-fueled diesel ICEs by stabilizing the LPG flame in lean mixtures. H₂ enrichment can raise the heat release rate and in-cylinder pressure in ICEs with biogas, methane, CNG, and NG by increasing mixture calorific value and laminar flame speed. Adding H₂ may extend the combustion duration of diesel ICEs powered by

natural gas and methane by widening flammability limits. Enriching CNG and LPG with H₂ shortens combustion duration by accelerating the burning rate.

Significantly, methane (CH₄) can mitigate certain limitations of hydrogen (H₂) combustion, such as its minimal quenching distance. H₂ can effectively offset the low flame speed of compressed natural gas (CNG) and natural gas (NG), thereby enhancing their combustion in diesel internal combustion engines (ICEs). H₂ has the potential to improve the brake thermal efficiency (BTE) of diesel ICEs fueled by liquefied petroleum gas (LPG) by stabilizing the LPG flame in lean gaseous air-fuel (A/F) mixtures. H₂ enrichment can increase the heat release rate and in-cylinder pressure of diesel ICEs fueled by biogas (BG), methane, CNG, and NG by raising the calorific value and laminar flame speed of the A/F mixture. Adding H₂ may extend the combustion duration of diesel ICEs powered by natural gas and methane by broadening the flammable limits of the A/F mixture. Enriching CNG and LPG with H₂ shortens the combustion duration of diesel ICEs by accelerating the burning rate of the A/F blend [38].

The use of H₂ can reduce combustion duration in diesel ICEs by increasing the burning rate of the A/F mixture [38].

The inclusion of H₂ in BG extends the ignition delay in diesel ICEs due to a decrease in the oxygen content of the intake mixture. Conversely, the addition of H₂ to CH₄, CNG, and LPG may reduce the ignition delay in diesel ICEs due to enhanced combustion kinetics [38].

Emissions of CO and unburned hydrocarbons (UHC) from diesel ICEs can be significantly reduced by enriching BG, CH₄, CNG, NG, and LPG with H₂. This reduction is largely attributed to the partial substitution of carbon-rich fuels with H₂, which accelerates the combustion rate of the gaseous fuel. Incorporating H₂ into BG, CH₄, CNG, and NG may lower CO₂ emissions from diesel ICEs by reducing the carbon-to-hydrogen (C/H) ratio of the gas mixtures. However, H₂ may increase NO_x emissions from ICEs using BG, CH₄, CNG, or NG-diesel blends due to a rise in peak in-cylinder pressure and temperature. Introducing H₂ to LPG may positively reduce NO_x emissions from diesel ICEs by decreasing the extent of high-temperature zones around the diesel flame. Incorporating carbon-free H₂ into BG, CH₄, and CNG can reduce smoke and soot emissions from diesel ICEs. The high diffusivity of H₂ promotes thorough homogenization of the combustible mixture, improving combustion efficiency and reducing smoke emissions [38].

Emerging Indirect Regenerative Evaporative Technology (IRET), also known as the Maisotsenko cycle (M-cycle), may offer complementary benefits for H₂- and diesel-powered combustion engines [116]. When applied to the engine inlet system, this technology can significantly lower inlet air temperature and enhance charge cooling, potentially mitigating knocking, improving power density, and further reducing NO_x emissions [31] – even at high H₂ enrichment rates. The IRET's unique ability for both sensible and latent cooling with minimal water usage is particularly promising for high-efficiency, low-emission engine applications, especially under demanding or transient operating conditions. Recent R&D on Maisotsenko-powered cycles [116] suggests that when integrated with advanced engine management

systems, these cooling techniques could enable more aggressive optimization of H₂ supply, EGR rates, and injection strategies, while maintaining combustion stability and minimizing particulate formation. Their adaptability to variable engine loads and ambient conditions makes them a viable candidate for next-generation engine architectures aiming to maximize renewable fuel utilization (e.g., H₂, biodiesel) and minimize environmental impact. Further experimental and numerical research is encouraged to evaluate the real-world performance and durability of such integrated systems, especially in scenarios with high combustion temperatures and aggressive emission control demands.

3. Summary

The present review enabled the current state-of-the-art to be obtained relative to dual-fuel (DF) internal combustion engines (ICEs) supplied with fuel and hydrogen (H₂). The benefits and challenges of using such engines were discussed.

The reviewed ICEs operated within a relatively narrow speed range, 1724 ± 528 rpm. The displacement of such ICEs was in a wide range of 1674 ± 2325 cm³. Additionally, ICE minimal loads spanned a wide range of values, from 27.3% ± 34%, and similarly, maximum loads reached values in the range of 50–100%. Of course, the ICE load could vary between 0 and 100%. The ICE's CR did not vary too much. The minimum CR reached values varied in the range of 16.41 ± 4.72, while the maximum CR values varied in the range of 16.49 ± 4.78; thus, variations in CR values are significant.

It should be noted in particular that for many of the analyzed engine cases, there is a lack of data regarding the effect (especially the combined one) of load, EGR, and H₂ supply on BTE and BSFC. For a slightly smaller number of such engine cases, there was a lack of data regarding the effect (especially the combined one) of load, EGR, and H₂ supply on PM, HC, NO_x, CO, and CO₂. Furthermore, comparing data for these engines was difficult because engine load was reported in either percent or bars, and H₂ supply in percent or L/min, necessitating categorization of the data into three different groups. This necessitates the development of a standard for collecting and presenting data from the tested DF ICEs.

For analyzed cases of common effect of varying load, EGR and H₂ supply on BTE and on BSFC, respectively it was found that up to 13.5% of the cases related to their lowering, almost no cases related to no effect on them, as well about 62.5–71.5% and 12.5–58.6% of the cases, respectively, related to their enhancing.

For analyzed cases of common effect of varying load, EGR and H₂ supply on PM, HC, NO_x, CO and CO₂ emissions, respectively it was found that below: 14.2%, 25%, 43.2%, 28.5% and 12.5% of the cases, respectively related to their lowering, while below 12.5%, 12.5%, 37.5%, none and none of the cases, respectively related to no effect on them, and similarly related to their enhancing. Especially positive is the role of EGR in DF ICEs.

The application of H₂ in diesel engines via the dual-fuel (DF) strategy represents a promising pathway to reduce diesel consumption, lower carbonaceous emissions, and decrease dependence on fossil fuels. The review highlights that H₂-DF combustion can significantly reduce CO, CO₂,

HC, and PM emissions, while maintaining or improving brake thermal efficiency (BTE) under optimized conditions. However, the technology faces two major technical challenges: elevated NO_x emissions and increased susceptibility to knocking, both of which are strongly influenced by H₂ concentration, engine load, and pilot fuel properties.

To address NO_x emissions, a range of strategies – including exhaust gas recirculation (EGR), selective catalytic reduction (SCR), water injection, urea dosing, external cylinder cooling, and Lean-NO_x traps – have proven effective, with EGR offering a particularly attractive solution due to H₂'s tolerance for high dilution rates. Combustion stability and knock resistance can be managed by carefully adjusting the maximum H₂ inclusion rate for each engine configuration and operating scenario, though further research is needed to establish universal guidelines.

The use of H₂ in combination with biodiesel (BD) further reduces reliance on fossil fuels, but the optimal BD/H₂ blend ratio and injection strategy remain to be systematically defined. While H₂ drastically reduces total particulate

matter (PM), it may increase the number of ultrafine particles, posing potential health and environmental risks that warrant further investigation.

Incorporating nanomaterials and oxygenated compounds into diesel fuel formulations has the potential to further enhance combustion efficiency and reduce emissions. However, the long-term impacts of these additives on engine durability, emissions, and aftertreatment systems require a comprehensive study. Lifecycle assessments (LCA) are also necessary to evaluate the full environmental benefits and trade-offs of H₂-DF engines, including resource use and end-of-life considerations for advanced materials.

Ultimately, integrating H₂-DF engines with hybrid electric systems may provide additional efficiency gains and enhanced transient performance. Future research should focus on system optimization, health impacts of ultrafine particles, durability of novel materials, evaluation of the viability of advanced evaporative technologies (IRET) [116] and the development of robust, adaptive control strategies for a wide range of applications.

Nomenclature

A/F	air-fuel	DF	dual fuel
BD	biodiesel	DI	direct injection
BG	biogas	EGR	exhaust gas recirculation
BSFC	brake specific fuel consumption	FI	fuel injection
BP	brake power	ICE	internal combustion engine
BT	brake torque	LPG	liquefied petroleum gas
BTE	brake thermal efficiency	PFI	port fuel injection
CI	compression ignition	SG	syngas
CNG	compressed natural gas	SI	spark ignition
CR	compression ratio	UHC	unburned hydrocarbons

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