Review

Fuel Oil Combustion Pollution and Hydrogen-Water Blending Technologies for Emission Mitigation: Current Advancements and Future Challenges

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ABSTRACT: In recent years, researchers have focused on exploring alternative fuel technologies that enhance engine performance and combustion efficiency while reducing nitrogen oxide (NO_x) and particulate matter (PM) emissions. Water-diesel emulsified fuel, which requires no engine modifications, has emerged as a critical pathway for cleaner diesel engine applications. This review systematically examines the combustion characteristics, emission performance, and energy efficiency of emulsified fuels in compression ignition (CI) engines. Studies indicate that compared to conventional pure diesel, emulsified fuels significantly optimize combustion processes through micro-explosion phenomena, shorten ignition delays, and improve combustion efficiency. Notably, NO_x and PM emissions are simultaneously reduced, effectively resolving the traditional trade-off dilemma between pollutant reduction targets. Emulsified fuel exhibits comparable power output and fuel consumption rates to those of pure diesel, while delivering enhanced environmental benefits. Additionally, innovative technologies such as hydrogen nanobubbles further enhance combustion dynamics by improving fuel atomization and radical generation, though challenges persist in stabilizing non-aqueous nanobubbles and scaling up production. Despite ongoing advancements in policy incentives (e.g., green hydrogen subsidies) and combustion mechanism research, industrial adoption of emulsified fuels still faces technical hurdles, including equipment corrosion and issues with long-term storage stability issues. In conclusion, water-based emulsified fuels and hydrogen-water blending technologies provide efficient and low-cost transitional solutions for reducing diesel engine emissions, with their multi-component synergistic optimization mechanisms laying a theoretical and practical foundation for future clean fuel development.

Keywords: Water-diesel emulsified fuel; Hydrogen-water blending; Micro-explosion phenomena; NO_x emissions; PM emissions; Synergistic optimization; Emission mitigation

1. Introduction

Fuel oil (including gasoline, diesel, aviation fuel, *etc.*), as a core component of global energy consumption, has drawn worldwide attention due to the environmental and climate impacts of pollutants (e.g., CO_2, NO_x, PM) generated by its combustion.

According to data from the U.S. Energy Information Administration (EIA), fossil fuels accounted for 83% of U.S. energy consumption in 2023, with oil consumption ranking highest at 35.4 quads (equivalent to approximately 35 million barrels per day). This consumption was primarily distributed across transportation (approximately 70%), industry (20%), and residential and commercial sectors (10%). In 2023, the U.S. consumed approximately 9 million barrels of gasoline daily, accounting for 25.7% of total petroleum use, predominantly in light-duty vehicles. Daily diesel consumption reached approximately 4 million barrels (11.3% of total petroleum use), mainly for heavy-duty transport, agricultural machinery, and industrial power generation. Aviation fuel usage stood at 1.7 million barrels per day (4.8% of total petroleum use), supporting the world's largest aviation market. In the U.S. transportation sector, fuel oil combustion contributes roughly 30% of national CO_2 emissions and 40% of nitrogen oxide (NO_x) emissions. Particulate matter (PM2.5) emitted by diesel vehicle exhaust is directly linked to respiratory diseases.

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According to data from China's National Bureau of Statistics (NBS), China's apparent petroleum consumption reached 740 million tons (approximately 16.4 million barrels per day) in 2024, with an import dependency of about 74%. The consumption structure exhibits the following characteristics:

Gasoline and diesel together accounted for 44% of total petroleum consumption in 2024. Daily diesel consumption averaged 3.5 million barrels, while gasoline consumption stood at 3 million barrels. Aviation fuel consumption reached 800,000 barrels per day, a 12% year-on-year increase due to the recovery of the aviation sector, making it a major driver of demand growth. Diesel vehicles, representing less than 10% of China's total motor vehicles, contribute 90% of particulate matter (PM) emissions and 70% of nitrogen oxide (NO_x) emissions in the transportation sector. Pollutants released during fuel oil combustion primarily include carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and unburned hydrocarbons (HC). Specific impacts are as follows:

Combustion of 1 ton of diesel releases approximately 3.1 tons of CO_2, while gasoline emits 2.3 tons of CO_2. Global oil combustion accounts for approximately 34% of energy-related CO_2 emissions, making it a primary driver of climate change. Diesel engines emit 4~6 times more NO_x than gasoline vehicles. Heavy-duty diesel vehicles account for over 70% of NO_x emissions in the transportation sector. Approximately 15–20% of PM2.5 originates from diesel combustion. Marine heavy fuel oil contains up to 3.5% sulfur. Even after the implementation of the International Maritime Organization (IMO) sulfur cap regulations, global ship fuel sulfur emissions still account for 13% of total SO_x emissions.

Despite global efforts to upgrade fuel quality standards (e.g., China's National VI standards and the EU's Euro 6), sectors such as heavy-duty transport and shipping remain heavily reliant on high-sulfur fuels. Emission reduction technologies (e.g., Selective Catalytic Reduction (SCR), Diesel Particulate Filters (DPF)) face challenges due to high costs and low adoption rates. Data from the U.S. Department of Energy shows that the carbon intensity of fuel oil consumption in the transportation sector decreased by only 2% in 2023, far below the targets set by the Paris Agreement.

In developing countries, rapid growth in fuel oil consumption (e.g., India's 4.5% annual growth rate) in industrial and transportation sectors, coupled with lagging pollution control technologies, has exacerbated air quality degradation in localized regions. While China promotes energy transition through its "dual-carbon" policy, petroleum consumption in the transportation sector still accounted for 45% of final energy use in 2023, with over 20 million diesel vehicles in operation, posing significant pollution control challenges.

The adoption of electric vehicles (EVs) and hydrogen fuel cell vehicles remains constrained by infrastructure gaps and high costs, making it unlikely for them to replace conventional fuel-powered vehicles fully in the short term. In 2023, the global penetration of new energy vehicles reached just 15%, while diesel continued to dominate sectors like heavy-duty trucks and shipping. To mitigate pollution, blending hydrogen or water into fuel oil (e.g., emulsified fuels) has emerged as a research focus. The U.S. Inflation Reduction Act subsidizes green hydrogen production, laying a policy foundation for hydrogen-blending technologies. China's Medium- and Long-Term Plan for Hydrogen Energy Industry Development explicitly supports the integration of hydrogen with traditional fuels.

High consumption and pollution from fuel oil remain central challenges in the global energy transition. Although emission reduction policies and technologies continue to advance, rigid demand for conventional fuels in heavy industries and transportation persists in the short term. Hydrogen- or water-blending technologies, which optimize combustion processes and reduce pollutant emissions, offer a feasible pathway during this transitional period.

2. Impact of Hydrogen on Fuel Oil Combustion Performance

Alteration of combustion characteristics: Hydrogen, as a fuel with a high hydrogen content, can improve the combustion characteristics of fuels when added [1]. In diesel-hydrogen dual-fuel engines, the addition of hydrogen optimizes the combustion and heat release processes of diesel engines. Qin et al. modified a single-cylinder diesel engine (original model: 185-type) equipped with a hydrogen injection system and a common-rail diesel injection system. When the hydrogen ratio (RH) was 20%, the peak in-cylinder pressure increased by 7.7% compared to pure diesel operation (8.4 MPa *vs.* 7.8 MPa); hydrogen addition significantly shortened the combustion duration (26 °CA at RH 20%, longer for pure diesel); high RH shifted the heat release center forward, with 90% of total heat release occurring 20 °CA earlier than pure diesel (at RH 50%). Additionally, the cumulative heat release increased by 3.7% (665 J *vs.* 642 J) [2]. According to OKAMOTO's research, adding hydrogen to diesel and emulsified fuel spray can increase the height and brightness of the flame [3]. Hydrogen addition also alters the equivalence ratio and temperature during combustion, thereby affecting CO_x and NO_x emissions [4]. Figure 1 illustrates changes in equivalence ratio, temperature, and CO_x/NO_x emission indices under different hydrogen addition ratios.

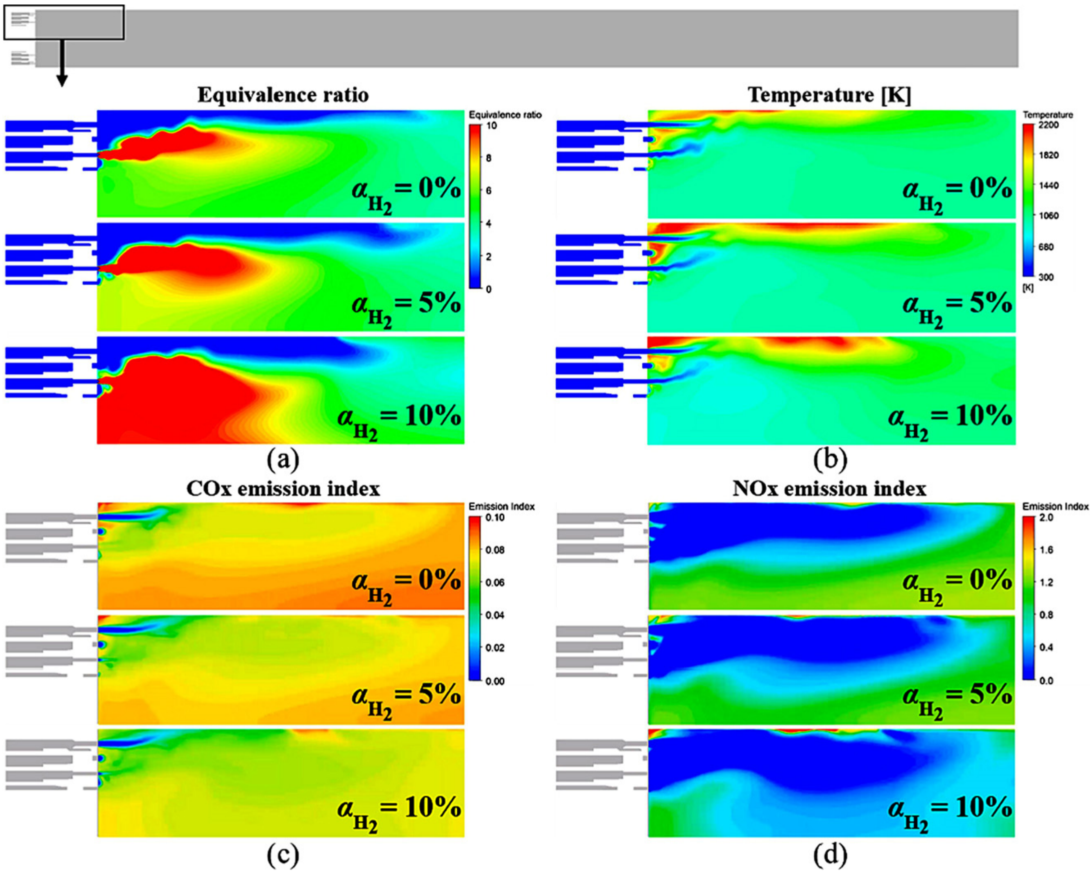

Figure 1. Spatial field of (**a**) equivalence, (**b**) temperature, (**c**) CO_x emission index, and (**d**) NO_x emission index near the outlet of the combustion chamber burner at several hydrogen mixing ratios [4].

Emission Reduction Potential: Due to the clean combustion properties of hydrogen, blending it with fuel oil can reduce harmful emissions. For example, Murugan et al. introduced hydrogen alongside hemp oil methyl ester (HOME) into a diesel engine to study its impact on engine performance and emissions under dual-fuel reactivity-controlled compression ignition (DF-RCCI) combustion mode [5]. Additionally, hydrogen can act as a gaseous additive when mixed with other fuels to enhance combustion efficiency and reduce emissions [6].

Impact on Heavy Oil Properties: For heavy fuel oil (HFO), hydrogen blending may affect its atomization characteristics [7–9]. HFO's high viscosity requires additional heating for spray combustion in boilers [10]. Hydrogen addition may alter the physicochemical properties of HFO, thereby affecting its combustion process and pollutant emissions [11–13].

Blending with other fuels: Hydrogen can be mixed with various fuels, such as diesel, gasoline, and methane, to form hybrid fuels [14–16]. The combustion and emission characteristics of these blended fuels differ from those of pure fuels, and the combustion process can be optimized by adjusting the hydrogen ratio [5]. In ammonia-fueled engines, hydrogen can be blended with ammonia to improve ammonia's combustion characteristics while controlling NO_x emissions [13].

Overall, the impact of hydrogen on the chemical properties of fuel oil is multifaceted, primarily reflected in combustion characteristics, emission behavior, and compatibility with other fuels. By strategically utilizing hydrogen, efficient and cleaner combustion of fuel oil can be achieved, reducing environmental pollution.

Direct hydrogen blending typically requires significant modifications to engines or combustion systems to accommodate hydrogen's physicochemical properties, such as high diffusivity, flammability, and explosion risks. Additionally, hydrogen storage and transportation pose major challenges. Hydrogen nanobubbles involve dispersing hydrogen as microscopic bubbles within fuel oil [17,18]. Due to their high surface area-to-volume ratio and interfacial activity, nanobubbles enhance hydrogen dispersion and stability in fuels, slow hydrogen escape rates, and extend fuel storage time. Studies demonstrate that hydrogen nanobubbles maintain prolonged stability in gasoline.

3. Blending Hydrogen Nanobubbles into Fuel Oil

3.1. The Effects of Nanobubbles on Combustion Characteristics

Blending hydrogen nanobubbles into fuel oil is a potential method to enhance combustion efficiency and reduce emissions, particularly in gasoline and diesel engines. Due to their unique physicochemical properties, hydrogen nanobubbles can improve fuel atomization and evaporation, thereby promoting a more complete combustion process [16].

In gasoline engines, the addition of hydrogen nanobubbles significantly enhances combustion characteristics. Studies indicate that hydrogen nanobubbles improve engine performance, especially under varying load conditions. For example, research by Oh et al. (2013) demonstrated that hydrogen nanobubble-blended gasoline mixtures, when adjusted to a stoichiometric air-fuel ratio at constant engine speed, improved combustion efficiency at 40%, 60%, and 80% engine loads. At 40% load, the hydrogen nanobubble-gasoline blend achieved a power output of 27.00 kW, representing a 4.0% increase compared to conventional gasoline (25.96 kW), while reducing brake-specific fuel consumption (BSFC) from 291.10 g/kWh for pure gasoline to 269.48 g/kWh. As the load increased, the blended fuel continued to exhibit superior BSFC performance over pure gasoline.

Brayek also demonstrated that using hydroxygen (a hydrogen-oxygen gas mixture) in spark-ignition engines enhances combustion characteristics and reduces emissions [19]. Brake torque increased by 3–12% at low speeds (1000–2500 rpm), with peak torque rpm delayed from 3000 rpm (pure gasoline) to 3500 rpm (HNB). Fuel consumption decreased by an average of 9.7%, with a maximum reduction of 19% (from 158 g/min to 128 g/min at 3500 rpm). HC emissions decreased by 17–32% across all speed ranges (e.g., from 253 ppm to 171 ppm at 3000 rpm). CO emissions were reduced by up to 42% (at 1500 rpm), attributed to hydrogen's carbon-free nature and oxygen's promotion of oxidation reactions. CO_2 emissions decreased by 7–9% due to hydrogen diluting the proportion of carbon-based fuel. This hydroxygen mixture contains macro- and nano-sized bubbles generated via electrolysis, eliminating the need for additional hydrogen storage systems and simplifying hydrogen utilization.

Additionally, nanobubbles may induce a "micro-explosion" during combustion, further atomizing the fuel, increasing its contact area with air, and promoting combustion. After exploring the optimization of combustion characteristics by incorporating nanoscale hydrogen bubbles into fuel oil, the research perspective can be extended to another key modification technology: the impact of water blending on fuel oil combustion. Although hydrogen and water exhibit significant differences in physicochemical properties (the former enhances micro-explosion and heat release through high diffusivity and clean combustion characteristics, while the latter relies on the micro-explosion phenomenon and temperature regulation to refine the fuel and suppress pollutant generation), both aim to address the common challenges of high pollution and inefficient combustion in traditional fuel oils.

3.2. Stability Analysis of Nanobubbles in Non-Aqueous Systems

Both viscosity and the presence of solid particles or molecular structures may influence stability of nanobubbles in fuel systems. Non-aqueous fuels (e.g., diesel) typically exhibit higher viscosity, which effectively mitigates bubble coalescence and buoyant escape, thereby enhancing stability. The high-viscosity environment concurrently suppresses the diffusion rate of gas molecules from bubbles into the surrounding liquid, thereby extending the lifespan of nanobubbles.

Furthermore, even in the absence of conventional surfactants, inherent components or impurities within the fuel may provide stabilization mechanisms. For instance, solid particles (e.g., dust, corrosion products) or complex macromolecular structures (e.g., resins, asphaltenes) can adsorb onto bubble surfaces, forming a physical barrier (protective layer) that impedes direct bubble contact and coalescence.

3.3. Feasibility of Scaling Up Hydrogen Nanobubble Generation Technology

Currently, the large-scale application of this technology in the maritime and heavy-duty truck sectors is confronted with significant economic and technological challenges. On the technological front, the core obstacles lie in the large-scale efficient generation (to meet ton/hour-level demands), long-term stability and durability under dynamic complex environments (such as waves, and high-speed airflow), and reliable system integration and maintenance under harsh working conditions (including corrosion, vibration, biofouling). On the economic front, the high initial investment (such as ship retrofitting, equipment costs) and operating costs (energy consumption, maintenance, potential consumables) are the main constraints. Moreover, the energy-saving benefits (theoretically 5–15%) are uncertain due to the lack of long-term real-ship/real-truck data, making it difficult to ensure the payback period. Although the maritime sector (with large single-ship fuel-saving benefits and ample layout space) and the heavy-duty truck sector (with a large market size) each have potential advantages, their feasibility paths depend on future breakthroughs in equipment efficiency improvement, significant cost reduction, and enhanced system stability. At this stage, it is more likely to conduct pilot verification in specific scenarios (such as near-sea/inland waterway vessels, fixed-route high-value truck fleets).

3.4. Comparative Analysis of Combustion Performance and Emission Reduction between Hydrogen Nanobubble (HNB) Technology and Conventional Emulsion-Based Fuels

Hydrogen Nanobubble (HNB) technology and traditional emulsion-based fuels (water-in-oil W/O or oil-in-water O/W) adopt different strategies to improve combustion performance and reduce emissions, thereby exhibiting distinct characteristics. HNB technology disperses hydrogen gas in the form of nanobubbles stably within the fuel, aiming to leverage the advantages of hydrogen to enhance combustion efficiency and reduce pollutant emissions [17,18,20]. Emulsion-based fuels, such as water-in-oil (W/O) or oil-in-water (O/W) emulsions, improve fuel atomization and combustion characteristics by dispersing the aqueous phase in the oil phase, or vice versa [21–23].

There are differences in combustion performance between the two. HNB technology aims to improve combustion efficiency because hydrogen has a high combustion speed and low ignition energy, which can promote the complete combustion of the fuel [17,18]. Traditional emulsion fuels can also enhance combustion efficiency; the micro-explosion phenomenon can improve fuel atomization, promote the breakup and evaporation of fuel droplets, thereby increasing combustion efficiency [21,24,25]. However, the efficiency improvement of emulsion fuels is also limited by the water content and the stability of the emulsifier.

Hydrogen exhibits a wide flammability range and a rapid flame propagation speed; HNB technology can improve ignition performance and flame propagation speed [18]. The ignition and flame propagation characteristics of emulsion fuels are affected by the water content; higher water content may reduce flame temperature and delay ignition [23].

The main advantage of emulsion fuels lies in their ability to improve atomization. The dispersion of water in oil can lead to micro-explosions, thereby enhancing atomization efficiency and allowing for more uniform mixing of fuel with air [24,26]. HNB technology may not directly improve atomization, but the presence of hydrogen nanobubbles may alter the physical properties of the fuel, such as surface tension, thereby indirectly affecting atomization.

There are also differences in emission reductions. The traditional view is that the aqueous phase in emulsion fuels can reduce combustion temperature, thereby reducing the formation of NO_x [27]. However, some studies have shown that emulsion fuels may increase NO_x emissions under specific conditions [28]. The impact of HNB technology on NO_x emissions requires further research, however the addition of hydrogen may alter combustion chemical reaction pathways, thereby affecting NO_x formation. Clean combustion technologies, by controlling the combustion process, can also reduce NO_x emissions [29,30]. For particulate matter (PM) emissions, emulsion fuels generally can effectively reduce PM emissions because micro-explosions improve combustion completeness and reduce the formation of unburned hydrocarbons. HNB technology also has the potential to reduce PM emissions; complete combustion of hydrogen can reduce soot formation. Studies have shown that controlling the combustion process can reduce soot production [31]. Additionally, if HNB technology uses hydrogen produced from renewable energy, it has the potential to reduce CO_2 emissions. The impact of emulsion fuels on CO_2 emissions depends on the fuel's composition and combustion efficiency.

4. Effect of Water Blending on Fuel Oil

The impact of water blending on fuel oil is primarily reflected in combustion characteristics and pollutant emissions. The following details the effects of water blending on fuel oil combustion and emissions:

Combustion Efficiency and Thermal Parameters: Studies by Toropov et al. show that water-fuel emulsion technology improves the combustion efficiency of fuel oil. The combustion efficiency of water-fuel emulsions (up to 250%) is significantly higher than that of conventional fuel oil (approximately 200%), peaking at an air excess coefficient of 1.65 [32]. By calculating the thermal parameters of water-fuel emulsions, it was determined that the optimal water content is 15%, where the heat generated during combustion reaches 1555 kJ/kg. Although this is slightly lower than that of pure fuel oil (approximately 1600 kJ/kg), it maintains an efficient energy output, thereby optimizing the combustion process [32]. Co-combustion studies of coal-water fuel and fuel oil indicate that, compared to burning coal-water fuel alone, co-combustion shortens the ignition delay time of fuel oil droplets [33].

Reduce Pollutant Emissions: Studies by Chelemuge et al. indicate that water blending generally reduces nitrogen oxide (NO_x) and soot emissions. For instance, increasing water content significantly suppresses Thermal-NO_x (due to reduced flame temperatures), but beyond a 20% water content, the proportion of Fuel-NO_x (related to fuel nitrogen content) increases, causing NO_x reduction rates to plateau (maximum reduction: 16%). At 10% water content, coal dust concentration decreases by 38%, attributed to the micro-explosion phenomenon enhancing fuel-air mixing [34]. Emulsifying water with fuel lowers combustion temperatures, thereby reducing NO_x generation [35]. Using a fuel-water rapid internal mixing injector, emissions from high-load combustion furnaces can be reduced without the need for surfactants or additional processing equipment [36]. Experimental studies on water-in-oil emulsified heavy fuel oil demonstrate improved combustion and reduced pollutant emissions [37].

However, water blending may introduce issues. For example, research shows that using biodiesel can increase NO emissions; however, natural antioxidants can mitigate this effect [38]. Additionally, higher water content in fuel oil may lead to equipment corrosion and operational problems. During long-term storage, water partially precipitates and forms lens-like distributions, which can potentially affect fuel quality. Thus, proper fuel oil treatment is required to minimize the adverse impacts of water [39].

It is noteworthy that while NO_x emissions decrease, particulate matter may increase under certain water concentrations. The specific reasons can be attributed to two points. First is the impact of reduced combustion temperature. Water's high latent heat of vaporization effectively lowers temperatures in the combustion zone, thereby suppressing the formation of thermal NO_x [40]. Thermal NO_x is generated through nitrogen-oxygen reactions at high temperatures, and lower temperatures directly inhibit this process. Additionally, water in emulsified fuel triggers a "micro-explosion" phenomenon during combustion [41]. When water droplets vaporize upon heating, rapid volume expansion shatters surrounding oil droplets into finer particles, improving fuel atomization. Enhanced atomization promotes uniform fuel-air mixing, elevates combustion efficiency, and reduces localized high-temperature zones, further curbing NO_x generation. However, increased water concentration may elevate particulate emissions, primarily due to incomplete combustion. Although micro-explosion improves atomization, excessive water content or unstable emulsification may impede complete vaporization and uniform fuel dispersion, compromising combustion stability [40]. Excess water vapor dilutes the oxygen concentration in the combustion zone, creating local oxygen-deficient conditions that cause incomplete combustion. This increases soot and unburned hydrocarbon production, ultimately raising particulate emissions. Furthermore, significant water content can adversely affect flame stability [42]. Unstable flames prone to extinguishing and re-ignition reduce combustion efficiency and promote particulate formation.

Numerical and experimental studies on the use of water-in-oil emulsified fuel in diesel engines indicate that water blending affects the chemical kinetics of combustion [43]. Experimental evaluations of the performance and emissions of four-stroke direct-injection diesel engines using water-fuel emulsions indicate that combustion characteristics are influenced when the water blending ratio varies within the 0–30% range [44–46].

Azimi et al. conducted similar experiments with emulsified diesel containing 0% to 10% water by volume. They found that at engine speeds ranging from 1600 to 1900 rpm, emulsified fuel with a 2% water content exhibited higher engine power, and torque values, as well as lower exhaust emissions. Overall, engine noise emissions increased with engine speed; however, emulsified diesel combustion did not result in increased noise compared to pure diesel [47].

In summary, the impact of water blending on fuel oil is multifaceted, offering potential for reducing pollutant emissions. By precisely controlling water blending ratios and optimizing combustion conditions, water-blending technology can be better utilized to achieve efficient and clean combustion of fuel oil. Fuel additives, which include gaseous, liquid, and solid types, can further improve combustion and reduce emissions [6]. Figure 2 illustrates the classification of fuel additives.

Notably, during droplet micro-explosion combustion, the synergistic interaction between hydrogen and water may exhibit unique advantages: hydrogen nanobubbles can act as nucleation sites to accelerate secondary micro-explosions of the water component, while the evaporative heat absorption of water alleviates the high-temperature tendency of hydrogen combustion. This mechanism enables simultaneous enhancement of combustion efficiency and synergistic control of NO_x and PM emissions. Such a multi-component coupling modification approach may provide a more systematic and innovative technical pathway for the clean transformation of fuel oils.

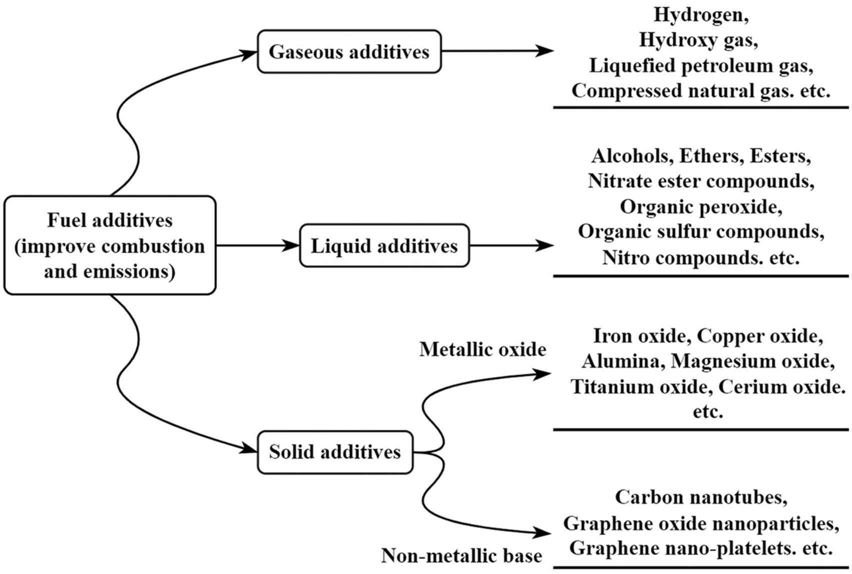

Figure 2. Classification of additives commonly used to improve engine combustion and emission performance [6].

5. Micro-Explosions during Fuel Oil Combustion

For liquid fuels blended with hydrogen or water, there are two combustion modes. The first is diffusion combustion, where hydrogen or water mist is separately injected into the combustion chamber. Since the chemical reaction rate of the fuel is much higher than the diffusion rate of fuel-air mixing, the diffusion combustion speed is limited by fuel-air mixing and heat/mass transfer rates of fuel vapor. The second is micro-explosion combustion, where hydrogen or water is pre-mixed with fuel oil and sprayed through the same nozzle. After spraying, fuel droplets containing dissolved gases or liquids with lower boiling points undergo flash boiling fragmentation, a phenomenon known as the "micro-explosion" effect. This occurs because components within the droplets nucleate and vaporize first under high-temperature conditions in the combustion chamber, generating bubbles that grow and rupture the droplet surface, breaking it into smaller droplets or causing violent oscillations [48]. To date, most researchers consider micro-explosion combustion of multi-component fuels as the dominant factor in achieving energy conservation and emission reduction [49]. Figure 3 illustrates two different combustion modes of liquid fuel mixed with hydrogen or water.

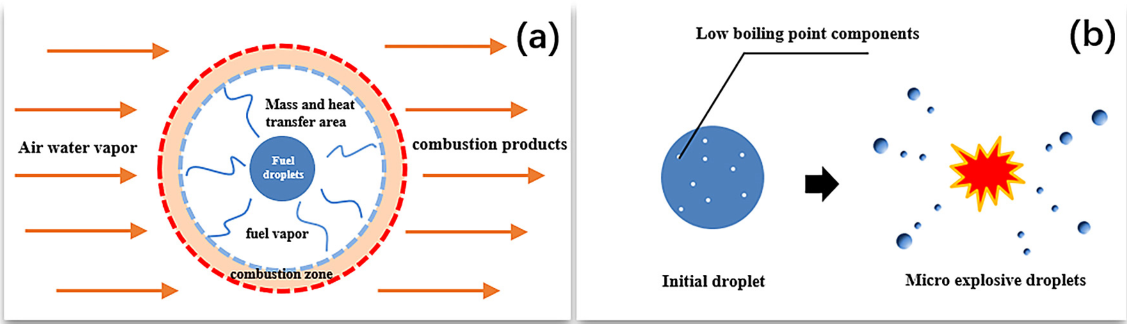

Figure 3. Droplet morphology during spray combustion, (**a**) diffusion combustion, (**b**) microburst combustion.

Currently, researchers are still unable to directly observe the micro-explosion phenomenon of spray droplets during combustion, making micro-explosion combustion a persistent research challenge. Over the past few decades, through engine performance experiments [50], visualized combustion chamber studies [51], and millimeter-scale droplet combustion experiments, the principle of micro-explosion-enhanced combustion has been deduced. It is widely accepted that micro-explosions ultimately increase the surface area and spatial uniformity of droplet clusters while enhancing the concentration of free radicals on droplet surfaces. The micro-explosion process involves heating multi-component droplets, nucleation of low-boiling-point components, vaporization of low-boiling-point components, bubble expansion, droplet surface destabilization, and droplet fragmentation. This explanation has gained broad consensus.

The above discussions are based on systems such as water-blended diesel, alcohol-blended diesel, alcohol-blended gasoline, and nanoparticle-blended diesel. For liquid fuels simultaneously blended with hydrogen and water (hydrogen-water-oil mixtures), dissolved hydrogen, dissolved water, hydrogen bubbles, and water droplets coexist in the fuel oil due to the solubility of hydrogen and water in the fuel. As proposed by Jia Ming's research group regarding the combustion fragmentation theory of binary-component droplets [52], after the mixture is injected into the combustion chamber, the hydrogen components vaporize and expand first as the temperature rises, triggering the first micro-explosion. Hassanloo and Wang simulated the combustion of nanobubble-containing dodecane using ReaxFF molecular dynamics, revealing that nanobubbles enhance fuel consumption rates by promoting intermediate and radical generation [53].

The prerequisite for the first micro-explosion is the stable existence of bubbles within fuel droplets. Jong Min Kim's team employed nanoparticle tracking analysis to measure nanobubbles, showing that hydrogen nanobubbles in gasoline maintained an average size of 159.00 ± 31.91 nm and a concentration of $11.25 \pm 2.77 \times 10^8$ particles/mL after 121 days of preparation, with no significant changes in size or concentration [18]. As suggested by Xianren Zhang's group, compared to micron- or millimeter-scale bubbles, bulk nanobubbles exhibit significantly prolonged stability in liquid fuels [54]. The intensity of the first micro-explosion depends on the expansion rate of hydrogen bubbles inside droplets: faster bubble expansion leads to stronger micro-explosions, more violent droplet fragmentation/surface oscillations, and a more pronounced combustion enhancement.

After the first micro-explosion, hydrogen nanobubbles remain embedded in the liquid fuel. According to Yarom and Marmurn (2015), nanobubbles can act as active sites for boiling and vaporization. During the second micro-explosion dominated by water components, hydrogen nanobubbles serve as nucleation sites, accelerating the micro-explosion speed of water and enhancing droplet fragmentation [55].Following the second micro-explosion, the fuel droplets transition into an aerosol state, and dissolved hydrogen is released from the droplets, forming a nearly homogeneous gas-gas mixture of hydrogen and fuel vapor. This enables dissolved hydrogen to enhance the combustion of fuel aerosols. Since this combustion process is no longer limited by liquid-phase heat/mass transfer rates, it approaches an ideal combustion state.

Directly utilizing high-speed thermal imaging or visualization techniques to experimentally observe and verify the dual micro-explosion sequences of hydrogen droplets and water droplets in a water-oil droplet system remains technically challenging and has not yet been achieved by any researchers. The microscopic mechanism of this complex phenomenon is a crucial aspect of enhancing the combustion of water-doped fuels with nanobubbles. It is also a key focus and frontier hotspot for future research.

In summary, the current limitations of this technology lie in the following three areas of research: (1) the preparation mechanism of nanobubble fuels, (2) the mechanism of nanobubble-enhanced micro-explosion combustion, and (3) the relationship between micro-explosion combustion and pollutant emissions.

5.1. Mechanism of Nanobubble Fuel Preparation

Current nanobubble mixture preparation technologies predominantly use water as the continuous phase and hydrophobic gases (e.g., air, hydrogen) as the dispersed phase. These methods typically rely on surfactants in water to enhance microbubble stability, leveraging impurities and electrical charges at the bubble surfaces to stabilize the interfaces [56]. However, fuel oils, such as diesel and fuel gases like hydrogen, lack hydrophilic polar structures, making traditional surfactant-based nanobubble preparation methods unsuitable for fuel oil systems. When Yuqian Ma replaced the oxygen-water system with an air-diesel system, nanobubble concentrations decreased significantly with shorter retention times [57]. To date, controllable preparation of nanobubbles in non-aqueous, surfactant-free systems remains a major challenge.

Guo Liang's research group at Jilin University developed nanobubble diesel using porous ceramic membrane tubes and Venturi devices. Experimental verification demonstrates that the Venturi device achieves higher peak nanobubble concentrations compared to porous ceramic membranes [58]. Certainly, the method for generating nanobubbles should be selected based on different application scenarios. There are also differences between the two methods in terms of stability and energy consumption. In terms of stability, compared to the Venturi device, which primarily produces a wide size distribution of bubbles through mechanical shearing and is prone to coalescence or dissolution due to the lack of a physical stabilization mechanism, the ceramic membrane method allows for precise control of bubble size through uniform membrane pores. The physical constraints reduce coalescence and extend bubble lifetime. The Venturi device can rapidly generate a large number of micro- and nanobubbles, making it suitable for large-scale applications. Although its stability may be relatively lower, efficiency can be improved through an optimized design [59,60]. In terms of energy consumption, the Venturi device has lower energy consumption, primarily because it relies on the kinetic energy of the fluid, with the main energy consumption being the power of the driving pump. Energy savings can be achieved through structural optimization. The ceramic membrane method, on the other hand, requires additional pressure to overcome membrane resistance, and regular cleaning increases maintenance energy consumption [61,62].

The Chinese invention patent ZL 201910467055.6 proposes an intermittent preparation device and method for nanobubble hydrogen/diesel blended fuel. By pressurizing, maintaining pressure, and depressurizing hydrogen-diesel mixtures, combustion performance in diesel engines is improved. However, fluctuating decompression rates in the pressure release flow field can cause rapid coalescence and growth of nanobubbles. Due to the Ostwald ripening effect, larger bubbles tend to merge with nanobubbles [63], further reducing nanobubble concentrations—a phenomenon observed via in-situ transmission electron microscopy by Jong Bo Park [64]. Thus, vaporization and nucleation of dissolved gases serve as the primary energy source for nanobubble generation. These dissolved gases may form nanobubbles or larger micron/millimeter-scale bubbles, with the pressure release flow field determining the energy efficiency of nanobubble formation.

In addition, Xu et al. conducted research on pressure gradients in swirl flow fields [65,66]. In swirling flow fields, dissolved gases can undergo controlled depressurization, and under the centrifugal force of swirling flow, oversized bubbles can be rapidly separated. This approach circumvents the issue of low nanobubble concentrations resulting from Ostwald ripening. Laboratory research on swirling flow field-enhanced nanobubble diesel preparation has yielded reliable experimental results.

5.2. Nanobubbles Enhance the Micro-Burst Combustion Mechanism

Currently, single-droplet combustion experiments are the most mature and reliable method for studying micro-explosion combustion. By placing fuel droplets in controlled temperature and pressure environments and employing diagnostic techniques such as high-speed cameras, temperature measurement systems, and optical testing, researchers can quantitatively study the evaporation and combustion processes of droplets. Internationally, Bar-Kohany et al. used single-droplet micro-explosion experiments to reveal that the superheating degree and nucleation time during the combustion of water-blended fuels depend on heating rates and nucleation site density, with bubble growth rates determining droplet expansion and fragmentation intensity [67]. Antonov et al. proposed that micro-explosions and expansion shorten the heating, evaporation, and ignition times of fuel components, improving combustion efficiency, reducing fuel consumption, and enabling smoother injection in combustion chambers. They also suggested that the viscosity, surface tension, and interfacial tension of emulsified fuels dominate micro-explosion rates [68]. Sazhin et al. developed a mathematical model for heat and mass transfer during single-droplet micro-explosions, achieving results consistent with experimental combustion of water-blended kerosene [69]. Domestically, Deqing Mei et al. investigated the enhancement of micro-explosion combustion by nanoparticles through single-droplet experiments. While nanoparticles inhibited droplet evaporation, they intensified micro-explosion at ignition, overall promoting fuel combustion [70]. Jigang Wang's research group further explored micro-explosion types in adjacent droplet combustion, concluding that micro-explosions also enhance combustion of neighboring droplets [71,72].

Currently, research has not yet established a direct quantitative correlation between nanobubble size and the intensity or timing of micro-explosions. However, existing literature provides information on the mechanisms of micro-explosions, influencing factors, and the characteristics of nanobubbles, which can serve as a basis for understanding the potential connection between the two. Factors such as fuel type, droplet diameter, water content, and ambient temperature all affect the effectiveness of micro-explosions.

Although there is currently a lack of quantitative models directly linking nanobubble size to micro-explosions, future research could explore several directions: using coupled CFD-PBM (Computational Fluid Dynamics–Population Balance Model) models to simulate the effects of nanobubbles of different sizes on the internal temperature distribution of droplets, as well as bubble growth and breakage processes; considering the significant influence of the physical property parameters of different fuels (such as surface tension, viscosity, boiling point, *etc.*) on micro-explosions; conducting experiments to precisely control the size of nanobubbles and measure their impact on micro-explosions, thereby verifying the accuracy of the models; and employing high-speed photography, pressure sensors, and other technologies to capture the dynamic processes and intensity of micro-explosions.

5.3. The Influence of Micro-Explosion Combustion on Pollutant Emissions

Studying pollutant emission patterns during spray combustion, building on single-droplet micro-explosion combustion, is the final step to confirm energy conservation and emission reduction. Compared to single-droplet combustion, spray combustion involves more complex processes such as air entrainment and spray penetration/distribution. The impact of micro-explosions on non-combusting sprays can be analyzed using high-speed micro-particle tracking velocimetry (micro-PTV) and optical schlieren methods. For spray combustion, flame chemiluminescence imaging and the two-color method are typically employed. Diesel spray flame self-emission primarily originates from two sources: soot luminosity (incandescence of soot particles) and chemiluminescence (light emission from chemical species). In conventional pure diesel combustion, soot luminosity dominates chemiluminescence by orders of magnitude, allowing soot luminosity to approximate flame radiation intensity. However, water-blended low-temperature combustion strategies limit the applicability of the two-color method based on soot luminosity. Flame chemiluminescence imaging, which measures the excited-state transitions of combustion product radicals like OH, combined with the two-color method, can identify high-temperature reaction zones and flame positions. Youxin Ge compared spray characteristics of micro-nano bubble-laden fuel and conventional diesel using a spray schlieren optical platform. As the concentration of pre-mixed gaseous nanobubbles in the fuel increased, spray penetration decreased, while spray cone angle, spray width, and spray projection area gradually increased [58].

It is particularly noteworthy that the impact of the hydrogen-to-water mixing ratio on combustion efficiency and pollutant emissions is complex and influenced by various factors. Achieving the optimal hydrogen-to-water mixing ratio that minimizes NO_x and particulate matter emissions while maximizing combustion efficiency requires a comprehensive consideration of fuel properties, combustion technologies, and emission control strategies. There is currently no universal model for the optimal hydrogen-to-water ratio that applies to all types of combustion devices. The design, operating conditions, and application scenarios of different combustion devices all require specific analysis and adjustment. In practical research, it may be more reasonable to formulate targeted models of the hydrogen-to-water ratio based on factors such as combustion kinetics, thermodynamics, and emission characteristics. In the future, the combination of numerical simulation and experimental research can be used to optimize combustion process parameters, thereby achieving clean and efficient combustion.

In summary, through the three aforementioned research aspects, it is expected to reveal the mechanisms by which hydrogen nanobubbles enhance micro-explosion combustion. By preparing high-concentration hydrogen nanobubble fuels, conducting micro-explosion combustion experiments, and performing spray combustion tests, the project seeks to achieve synergistic reductions in NO_x and PM concentrations. This will provide a multi-component combustion approach that enhances combustion via hydrogen-water blending to reduce pollutant emissions, addressing the long-standing.

6. Conclusions

With the global push for energy transition and pollution/carbon reduction goals, hydrogen-water blending technology has emerged as a critical research direction for the cleaner utilization of traditional fuels due to its significant potential in improving combustion efficiency and reducing pollutant emissions. The equipment discussed in this study innovatively integrates hydrogen blending, water blending, and nanobubble technologies, offering a novel technical pathway to resolve the "efficiency-pollution" paradox in fuel oil combustion. Future breakthroughs in hydrogen-water blending applications may focus on the following directions:

Current nanobubble preparation technologies are predominantly water-phase-based, while the nonpolar nature of fuel oil and hydrogen poses greater challenges for bubble stability. Developing non-aqueous nanobubble generation theory requires breaking away from traditional surfactant-dependent models and exploring gas-oil interface dynamics, dissolved gas nucleation mechanisms, and energy dissipation patterns in swirling flow fields. By establishing multi-scale physicochemical models, this theory would reveal the generation, stabilization, and coalescence mechanisms of nanobubbles in fuel oil, providing theoretical support for preparing high-concentration, long-lifetime nanobubble fuels. Such theoretical advancements would not only fill gaps in physicochemical research but also accelerate the engineering application of fuel oil nanobubble technology.

From single-droplet combustion experiments to spray droplet group combustion tests, systematic studies are needed on the heat/mass transfer characteristics, as well as the chemical reaction pathways of hydrogen-water-oil ternary blended fuels. Utilizing high-speed microscopic imaging, molecular dynamics simulations, and flame chemiluminescence diagnostics, researchers must clarify the synergistic effects between the first micro-explosion (driven by hydrogen nanobubbles) and the second micro-explosion (dominated by water components). This will uncover mechanisms by which droplet fragmentation, elevated free radical concentrations, and homogeneous mixing enhance combustion rates. A key focus lies in resolving the competitive relationship between NO_x and PM generation during micro-explosions. By optimizing hydrogen/water ratios, bubble sizes, and spray parameters, the trade-off challenge of "reducing NO_x while increasing PM" can be resolved, achieving coordinated pollutant control.

Guided by non-aqueous phase theory, the equipment efficiently prepares high-concentration, highly stable hydrogen nanobubble fuels by controlling the decompression process of dissolved gases through swirling flow fields, overcoming bubble coalescence caused by Ostwald ripening in traditional methods. Future optimizations of swirling parameters and decompression rates can further enhance nanobubble dispersion and storage stability in fuel oil, laying the foundation for large-scale applications. Advancing interdisciplinary research on non-aqueous nanobubble theory and hydrogen-water-oil combustion mechanisms will help overcome cost and large-scale production bottlenecks. With synergistic progress in fundamental science and engineering technologies, hydrogen-water-blended fuel systems are poised to serve as a “bridging technology” for transitioning traditional energy to clean energy, injecting new momentum into global green and low-carbon transformation.

Author Contributions

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