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Editorial

New Fuels and Advanced Combustion Modes for Innovative Internal Combustion Engines: An Overview

Davide Lanni * and Enzo Galloni

Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, 03043 Cassino, Italy
* Correspondence: davide.lanni@unicas.it

Abstract: Internal combustion engines (ICEs) currently account for approximately 25% of global power generation. Notably, this technology still plays a crucial role in a large segment of the transportation sector. In this editorial, a short overview of the latest developments and current research trends related to internal combustion engines is presented. Furthermore, the 11 contributions of this Special Issue are introduced. They cover three main topics: the use of new fuels for internal combustion engines for both automotive and railway applications; testing of additives for ICEs fed with conventional fuels; and CFD simulation applied to the analysis and design of ICE components.

Keywords: internal combustion engines; carbon-free fuels; e-fuels; biofuels; fuel additives; CFD engine modeling; advanced combustion modes

1. Introduction

Today, the energy sector faces the pressing challenge of mitigating greenhouse gas and pollutant emissions. This situation necessitates the adoption of innovative technologies alongside enhancements to conventional ones, such as internal combustion engines. Transitioning from ICEs to technologies that do not rely on combustion presents significant technical and economic hurdles. Achieving this transition on a global scale within a short timeframe appears to be a tough challenge. Additionally, it is essential to conduct a thorough evaluation of the impact of all technologies, taking into account their complete life and usage cycles.

The pollutant emissions from ICEs that comply with current regulations have shown a notable decrease in recent years [1]. However, the greenhouse gas emissions produced by burning traditional fossil fuels still require substantial examination. Thus, in order to reduce the environmental impact of ICEs, several solutions are currently under study.

The use of carbon-free fuels (hydrogen and ammonia [2]), low-carbon fuels (methane, methanol, etc.) [3], e-fuels [4], and biofuels [5] can strongly contribute to reducing both the greenhouse gas and pollutant emissions of ICEs.

In particular, in recent years, both hydrogen and ammonia have been receiving particular attention from researchers, since, if produced starting from renewable energy sources, they drastically reduce the environmental impact of engines if compared to traditional fuels. Hydrogen is suitable for both spark-ignition [6–9] and compression-ignition engines [10]. The expected improvements in the next generation of hydrogen internal combustion engines suggest that their thermodynamic efficiency will be similar to that of current fuel cell powertrains [11]. Ammonia, which is also a hydrogen carrier [12], presents advantages in terms of storage over hydrogen but also issues when burned in internal combustion engines. Several studies assessed both its combustion characteristics and emissions in spark-ignition engines, highlighting the critical issues of using neat ammonia as a single fuel [13–15]. Different techniques to improve ammonia combustion in spark-ignition engines have been proposed, such as hydrogen enrichment [16–18], multiple spark strategies [19,20] and plasma ignition [21]. Ammonia can also be used in compression ignition

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engines in dual-fuel mode, even if advanced injection strategies and aftertreatment systems are needed to improve both engine performance and emissions [22].

The use of fuel additives is a way to improve performance and reduce the emissions of ICEs fed with conventional fuels, particularly in regard to existing vehicle fleets. If coupled with alternative fuels, fuel additives can play a significant role in promoting the shift toward cleaner and more sustainable energy sources in the transportation sector [23]. However, achieving a balance between cost and performance is essential to ensure their widespread adoption [23].

Considering both conventional and non-conventional fuels, advanced combustion strategies can improve the energy conversion efficiency in internal combustion engines.

Homogeneous charge compression ignition (HCCI) has gained recognition and undergone extensive testing, research, and analysis as a promising "green" engine technology in contemporary times [24]. Nevertheless, challenges such as ignition control, difficulties with cold starts, and the need for consistent fuel/air mixture preparation, among other limitations, continue to pose significant obstacles [24].

Reactivity-controlled compression ignition (RCCI) demonstrated significant commercial potential for automotive applications in the short to medium term [25]. Nevertheless, the implementation of accurate feedback control systems is essential to regulate engine parameters, thereby reducing cycle-to-cycle variability and ensuring reliable and safe operation [25].

Pre-chamber ignition, also known as turbulent jet ignition (TJI), allows the use of both stoichiometric and lean air-fuel mixtures in ICEs. The passive TJI system provides low-cost technology and stoichiometric operation, enhancing combustion and potentially improving fuel consumption by 2–3% [26]. In contrast, the active TJI system operates under lean-burn conditions with an air-excess value up to 2, offering greater efficiency and lower NO_x emissions, but at higher costs and complexity [26]. Several significant challenges remain to be thoroughly resolved, including the design and integration of hardware in current cylinder heads, ensuring satisfactory combustion stability at low loads such as idle and catalyst light-off, and implementing lean aftertreatment for the active configuration [26].

Water injection (WI) has garnered significant interest in recent years across various engine types as a promising method to lower in-cylinder and exhaust temperatures, reduce knock events, enhance combustion timing, and reduce NO_x emissions [27]. In particular, WI has significant potential to enhance the thermal efficiency of spark-ignition engines, mainly because of its ability to effectively suppress knock and provide cooling benefits [28]. Water can be injected into the intake ports (port water injection, PWI) [29,30] or directly into the combustion chamber (direct water injection, DWI) [31,32]. DWI is capable of removing a larger quantity of heat in comparison to PWI; however, the latter facilitates a more uniform distribution of water near the cylinder walls [33]. The fundamental thermophysical and chemical kinetic effects of adding water on combustion processes and emissions require further exploration, particularly concerning various methods of WI and different engine configurations. Moreover, there is a scarcity of research focused on the long-term effects of water injection in ICEs [27].

The presented short overview shows that ICEs are still widely studied and developed. They may still play an important role in the near future in order to increase the transport sector's sustainability.

In this scenario, this Special Issue presents seven research articles assessing the use of new fuels for internal combustion engines (Section 2), two studies related to experimental investigations on additives for ICEs fed with conventional fuels (Section 3), and two contributions (a research article and a review) focused on the CFD simulation applied to the analysis and design of ICE components (Section 4).

2. New Fuels for ICEs

Lanni et al. [34] employed a one-dimensional (1D) numerical method to assess the performance and operational limits of a downsized port fuel injection spark ignition

(PFI SI) engine running on pure ammonia. The investigation covered both throttled and unthrottled operation and also evaluated the impact of different geometrical compression ratios. The findings revealed that ammonia's low laminar flame speed leads to longer combustion durations and optimal spark timing that is more advanced than in conventional SI engines, with knock consistently mitigated. Long combustion durations and high exhaust gas temperatures limited both the maximum allowed engine speed and the lowest achievable load. However, higher compression ratios allowed for an increase in the engine's maximum speed.

The work of Tutak et al. [35] examined the co-combustion of hydrogen with diesel and biodiesel (RME) in a compression-ignition engine under maximum load, with hydrogen content up to 34%. Hydrogen minimally affected ignition delay but reduced combustion duration, especially with biodiesel. A hydrogen content of 12% provided optimal energy efficiency, with better results when using RME. However, the hydrogen–RME engine showed slightly less stability. Emissions analysis revealed reductions in CO, CO_2, and soot, but increases in NO and HC emissions.

Tutak et al. [36] also evaluated the operation of a cooperative fuel research spark-ignition engine using ammonia and dimethyl ether (DME) as fuels. DME facilitated ignition and improved combustion, with just a 10% energy share of DME contributing to proper combustion. The addition of DME reduced both ignition delay and combustion duration. Even minimal DME inclusion ensured high repeatability of IMEP (indicated mean effective pressure), staying below 5%. With an 18% energy share of ammonia, the engine achieved the maximum efficiency.

Arsie et al. [37] presented preliminary findings from the H2-ICE project, focusing on hydrogen fuel utilization and hybrid powertrain integration for urban buses. A robust methodology has been developed, including validated high-fidelity CFD models to assess various injection methods (port fuel injection and direct injection) and optimize combustion efficiency. Two Waste Heat Recovery (WHR) systems were tested. The development of catalytic systems for the Selective Catalytic Reduction (SCR) of nitrogen oxides (NO_x) using hydrogen has been completed, along with a control strategy utilizing an Artificial Neural Network (ANN) model. Two Energy Management System (EMS) methodologies were evaluated to meet a target fuel consumption of 0.1 kg/km.

Kolahchian et al. [38] employed a 1D engine modeling approach to evaluate hydrogen as a fuel for railways, using a turbocharged diesel engine as a reference. Modifications to the turbocharger and injection systems allow the engine to run on hydrogen while retaining original performance. Results show a reduction in traction power from 600 kW to 400 kW and nearly double the energy consumption during typical missions compared to diesel. However, a Life Cycle Assessment indicates a 56% reduction in equivalent CO_2 emissions when using photovoltaic-based green hydrogen, lowering emissions from 4.27 to below 2 kg CO_2 equivalent per kilometer. This suggests that engines with moderate modifications can effectively reduce carbon emissions in non-electrified railway segments.

The research of Capatano et al. [39] experimentally assessed the potential of low- and zero-carbon fuels, such as methanol, methane, and hydrogen, in a spark-ignition engine. Results showed that alternative fuels reduced CO and CO_2 emissions, with the reduction varying by fuel type. Methanol had higher total hydrocarbon (THC) emissions but lower nitrogen oxides (NO_x) emissions compared to gasoline. Methane and hydrogen further lowered THC emissions, while NO_x emissions were influenced by operational conditions. Particle emissions were affected by fuel properties, engine conditions, and lubricating oil type, particularly with hydrogen, which produced significant particle emissions despite lacking carbon atoms.

The safety aspects related to the use of hydrogen in an engine-based combustion system were evaluated by Gill et al. [40]. Their methodology utilizes the FMESA (Failure Mode and Effects Severity Analysis) framework with specialized tabular scales to evaluate failure severity, aiming to reduce epistemic uncertainty in hazard severity and risk models. This approach modifies traditional methods like FMEA/FMECA (Failure Mode and Effect

Analysis/Failure Mode, Effects and Criticality Analysis) and includes the development of new failure severity scales specific to hydrogen systems. The article reviews relevant literature, discusses the FMESA method and its mathematical framework, presents failure severity scales, shares experimental findings, and quantitatively analyzes the severity of different failure modes in the hydrogen combustion system.

3. Additives for ICEs Fed with Conventional Fuels

Chivu et al. [41] investigated the performance, emissions, and fuel consumption of a 1.6 L four-cylinder direct-injection diesel engine using blends of commercial diesel and pine tree turpentine (up to 30% of turpentine). Key findings indicate that the biofuel had minimal overall performance impact, but a blend with 15% turpentine increased torque by up to 7.9% at low load and 6.8% at high load, with power output rising by 9% at low speeds and 5% at high speeds compared to baseline diesel. While efficiency and greenhouse gas emissions improved, pollutant emissions varied; hydrocarbons and particulate matter responses differed, but NO_x emissions increased by 30% at high loads and 20% at low loads, mainly due to enhanced engine performance rather than turpentine's higher oxygen content.

The study of Marchitto et al. [42] assessed the effects of two performance packages on exhaust emissions and fuel efficiency in five vehicles from the current Italian fleet, including three Euro 4 vehicles (two passenger cars and one light commercial vehicle) and two Euro 6 diesel vehicles. Considering the worldwide harmonized light vehicles test cycle (WLTC), the results indicated a 1.2% reduction in fuel consumption for the Euro 6 diesel passenger car and 8.1% for the Euro 4 diesel passenger car, along with similar trends in CO_2 emissions and significant reductions in total hydrocarbons, carbon monoxide, and particulate matter across all vehicles.

4. CFD Simulation for the Analysis and Design of ICE Components

Martos et al. [43] developed a CFD model to simulate throttle valve operation and identify optimal exhaust backpressure for effective low-pressure exhaust gas recirculation in Euro 6 compliant engines. The model examines flow control dynamics for integrating these valves with thermoelectric generators that convert residual thermal energy into electricity. The results indicate consistent pressure drop values across different scenarios, with over 90% agreement between model and experimental results, leading to a correlation for estimating exhaust gas mass flow rates based on easily measurable parameters.

The perspective review of Jeong et al. [44] highlighted that CFD technology is widely used in industry and academia to improve pre-chamber designs, but it faces challenges in predictive accuracy, particularly in turbulence modeling, which impacts mixing, combustion, and wall heat transfer. They concluded that, to unlock the full potential of CFD as a sophisticated design tool rather than merely a predictive one, it is crucial to enhance CFD methodologies with specifically tailored, physics-based numerical models. Furthermore, to acheive high-fidelity CFD modeling of pre-chamber engines, it is imperative to identify and rectify the primary sources of uncertainty prior to implementing refinements and enhancements related to both turbulence and combustion models.

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