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Hydrogen Fueled Turbocharged Internal Combustion Engines under Variable Injection Control: A Critical Review of Performance, Combustion, and Emission Characteristics

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Abstract: *The carbon-free combustion chemistry, relatively broad combustion and flammability limits, and high mass-specific energy content are some of the reasons why hydrogen is increasingly considered as the near-term answer to decarbonize mobility powered by internal combustion engines. Electronically controlled variable injection timing and duration, combined with turbocharging, has proven to be a viable way to regain the lost power density with port/hydrogen or manifold-injection and provides an extra dimension of NOx control. This paper presents and critically reviews the experimental and simulation studies conducted between 2001 and 2024 on hydrogen turbocharged engines with variable injection control, including the following aspects: injection timing and duration, equivalence ratio management, exhaust gas recirculation (EGR) and water-assisted methods, and multi-stage/split injection. Reported results are summarized in representative characteristic trends to reveal the common compromises between power recovery, thermal efficiency and NOx emission, which have not been consistently reconciled in the literature so far. It is difficult to reconcile reported reductions of NOx between about 16% and 60% due to the differences in injector hardware, boost strategies and the baseline. It points to the persistent lack of equivalence ratio, injection pressure and backfire-mitigation hardware reporting standardization in the results of simulation-oriented Digital-Twin-style studies and advocates the use of standardized backfire-mitigation hardware and reporting of equivalence ratio and injection pressure to enable comparison of results across laboratories. The paper ends with research gaps as well as a recommended standardized testing protocol for characterizing hydrogen turbocharged engines..*

Keywords: Hydrogen internal combustion engine; Turbocharging; Variable injection control; Combustion characteristics; NOx emission; Combustion phasing.

I. INTRODUCTION

Road transport accounts for one of the largest shares of global carbon dioxide emissions, and the anticipated rise in vehicle numbers in the largest emerging economies poses a major engineering challenge, not just an academic one, in reducing emissions from the internal combustion engine (ICE) fleet. Part of this is being addressed by battery electric propulsion, but heavy-duty, off-highway, and cost-sensitive segments still use liquid- or gas-fueled combustion engines, which means that alternative-fuel ICE research remains relevant well into the medium term. As an ICE fuel, hydrogen is appealing because of its ability to burn without producing carbon-based pollutants, has a gravimetric energy density nearly 2.7 times that of gasoline, requires an order of magnitude less ignition energy than conventional fuels, and can propagate flame nearly an order of magnitude faster than gasoline-air mixtures. These characteristics allow for lean-burn, fast-burning operation and, in principle, higher indicated efficiencies than gasoline. They also

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introduce the two salient engineering issues that are common to the literature surveyed here: (i) low volumetric energy density, which imposes constraints on power generation with port or manifold injection unless the charge is pre-enriched, and (ii) the high sensitivity of NOx formation to local flame temperature and equivalence ratio, making NOx the dominant emissions problem when considering hydrogen combustion, as opposed to particulate matter or unburned hydrocarbons. The most direct answer to the power-density penalty is turbocharging, and the most direct answer to NOx control is electronically controlled injection, which is controlled by an Electronic Control Unit (ECU) that changes the timing, length, and duration of the injection, as well as injection pressure and staging in more advanced systems. It is the combination of the two – a turbocharged hydrogen engine with variable injection control – that makes it a natural configuration, and one that is often studied, and which will be the focus of this review. Numerous experimental and simulation studies focus on a single variable of this setup, such as injection timing, injection duration, equivalence ratio, water-assisted injection, exhaust gas recirculation (EGR), multi-stage or split injection, turbocharger matching, etc. What is comparatively lacking is any critical synthesis that compares and contrasts these studies, investigates how they measure up in terms of their magnitudes, and seeks to discern where they agree and where they disagree. This paper is an attempt at this synthesis. Instead of providing a chronological list of abstracts, the review is organized around the physical control levers available to a variable-injection turbocharged hydrogen engine, cross-compares the quantitative results reported in each individual study, and features characteristic-curve figures showing trends common across independent study results.

II. HYDROGEN AS AN ICE FUEL: PROPERTIES AND THEIR ENGINEERING CONSEQUENCES

The combustion-relevant properties of hydrogen compared to gasoline are summarized in Table 1, based on compilations of fuel properties reported in the reviewed literature. Of these, two are the most important in the engineering story of all the papers reviewed herein. First, because of the very low minimum ignition energy of hydrogen and the large flammability range, nearly all of the experimental studies investigated have found published references to special equipment to prevent combustible mixtures from remaining in the intake manifold, such as flame arrestors, flame traps, or direct injection into the cylinder. Second, the high laminar flame speed and zero carbon content of the fuel account both for the efficiency upside (fast and complete combustion) and the emissions downside (high local flame temperature, which promotes the formation of thermal-NOx through the extended Zeldovich mechanism). The theme of these two consequences, backfire risk and NOx sensitivity, is repeated in Sections 3 and 4.

Table 1. Combustion-relevant properties of hydrogen relative to gasoline

Property	Hydrogen	Gasoline	Significance for engine design
Lower heating value (MJ/kg)	119.7	~44.5	High mass-specific energy but low volumetric energy density as a gas
Minimum ignition energy (mJ)	~0.02	~0.24	Easier ignition; higher pre-ignition/backfire risk
Laminar flame speed (m/s, NTP)	~1.85	~0.4	Faster, more complete combustion; steeper pressure rise
Flammability limits (equivalence ratio)	0.1–7.1	0.7–3.8	Enables ultra-lean operation for NOx and knock control
Autoignition temperature (°C)	~585	~257–450	Higher resistance to autoignition, but pre-ignition from hot spots remains a risk
Carbon content	None	High	No CO2, CO, HC formation from the fuel molecule itself

III. INJECTION AND TURBOCHARGING STRATEGIES: A THEMATIC CRITICAL REVIEW

3.1 Injection Timing and Duration

The most frequently manipulated variable in the literature reviewed (an overwhelmingly large number of which are related to port/manifold-injection combustion) reflects the U-shaped, near-parabolic trend of NOx emissions against injection/spark timing, with minimum emissions occurring in a narrow window around 8–10 degrees crank angle before top dead centre (CA BTDC). Zhang et al. found an optimum near 9° BTDC with a short injection duration, and up to 60% NOx reduction compared to diesel combustion, while the thermal efficiency was still improved. Naito and Yamamoto came to a similar qualitative conclusion that areas of high temperature in the injection zone, where NOx formation occurs, can be avoided by precise control of the injection duration, but they reported a relatively small reduction, showing that the actual benefit is very sensitive to the baseline to which it is compared. Shen and Huang varied both timing and duration together and found that the power output increased by up to 18%, along with a substantial, but not independently measured, NOx reduction, suggesting that both duration and timing are coupled parameters that cannot be optimized separately (Arunadevi et. al.) . More critically, none of the timing-related studies examined here provide results on a common baseline engine, common boost pressure, or common equivalence ratio, meaning that the reported optimum timing window (8–10° BTDC) is a qualitatively strong, but quantitatively uncertain result. This is the first clear evidence gap that this review has identified.

3.2 Equivalence Ratio Management

An additional, closely related theme is that thermal efficiency and NOx emission depend on equivalence ratio in opposing and non-monotonic ways: thermal efficiency peaks a little below stoichiometric, while NOx peaks a little below the peak of adiabatic flame temperature under excess-air dilution. Hu et al. investigated equivalence ratio effects for a turbocharged hydrogen engine and found that combustion stability and power output could be maintained even when the equivalence ratio was actively controlled for NOx control, rather than relying on spark or injection timing alone. The study conducted by Zhang et al. (2020) investigated the use of excess hydrogen at full load and concluded that operating rich, but boosted, and at an NOx-peak equivalence ratio could be a strategy with sufficient power recovery at a reasonable NOx penalty, which is the opposite of the lean-burn strategy favoured by most other studies and one that this review will highlight as not being sufficiently cross-validated against lean strategies under identical hardware.

3.3 Turbocharging and Boost Strategy

The literature is split on the location of the turbocharger relative to the point of gaseous hydrogen induction (i.e., injection point), but all agree that turbocharging is beneficial for overcoming the volumetric-efficiency penalty of gaseous hydrogen induction. In a series of studies on turbocharged hydrogen engines, a few studies used a compressor upstream of the injection point to gain an additional increase in the equivalence ratio achievable at a given throttle position, which consequently boosts volumetric efficiency and low-speed torque. Other studies by Bai-gang and Luo also investigated Miller-cycle valve strategies in combination with boosting and reported further efficiency gains at part load; a companion study on the exergy of a turbocharged hydrogen engine quantified where the thermodynamic losses of a turbocharged hydrogen engine occur, showing that most losses are due to heat transfer and exhaust exergy losses rather than combustion exergy loss. One of the more complete experimental turbocharged hydrogen engine studies reviewed here was performed by Vaithianathan et al., who observed that a significant power deficit persisted when compared to gasoline engine operation, although the gap was considerably reduced with boosting

3.4 Water-Assisted and Multi-Stage Injection

Kim and Lee studied hydrogen-water co-injection and found that NOx emissions were reduced by 20% and high-speed power increased by 5%, both due to the evaporative cooling of the combustion chamber by the injected water, reducing the peak flame temperature. Smith and Brown found a similar result for compression-ignition hydrogen operation; that

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is, water injection could lower both soot and NOx emissions while increasing SFE. Multi-stage or split injection is a similar but different approach: Liu and Zhang reported up to 40% NOx reduction with staggered multi-stage injection timing, and Yu et al. specifically examined the timing of a second injection pulse in a split-injection hydrogen direct-injection approach, with a view to understanding the effects on both efficiency and NOx. These findings together indicate that thermal dilution (water) and mixture-preparation control (staged injection) operate in largely separate ways and might be used in conjunction, although, until now, no published study has used both of these interventions on the same equipment.

3.5 ECU-Based Control and Hybrid Fuel Systems

ECU-based control is an approach to variable injection control and hybrid fuel systems. The results of Reddy and Rao are important because they showed that it was possible to reduce NOx by 25–30% using ECU-based closed-loop injection timing control, without a dedicated hardware change, and, in principle, such a system could be retrofitted to an existing engine without requiring a hardware change such as water injection or multi-stage injectors reviewed above. Independent of the hydrogen-CNG (HCNG) studies, a group of Indian-context research indicates that 18–25% blending of hydrogen is being trialled in three-wheelers, light commercial vehicles, and buses. The studies described as HCNG are included in this review because they share the same injection-timing and NOx-control physics as pure-hydrogen operation, but they are based on a deliberately conservative and infrastructure-compatible path, rather than the higher-performance pure-hydrogen turbocharged configuration that is the focus of this paper.

IV. REPRESENTATIVE CHARACTERISTIC TRENDS

The results of the studies reviewed in Section 3 are reported on various engines, at various boost levels, and against various sets of baseline data, and cannot be plotted over a single measured curve without misrepresenting the data. Rather, the schematic, literature-supported characteristic trends in Figures 1–6 are representations of the qualitative shape and approximate magnitude of the relationships that were most frequently reported in the studies reviewed. These trend diagrams are representative diagrams designed to aid interpretation and comparison with other trend diagrams, but are not a copy of any one set of data.

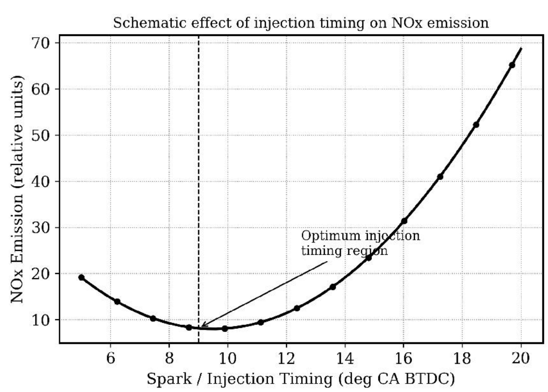

Fig. 1. Schematic trend of NOx emission with injection/spark timing, showing the low-NOx window near 8–10° CA BTDC reported by Zhang et al., consistent with Naito & Yamamoto and Shen & Huang.

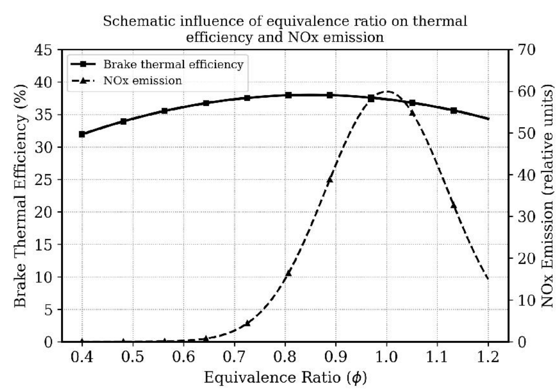

Fig. 2. Schematic trend of brake thermal efficiency and NOx emission with equivalence ratio, illustrating the opposing optima motivating φ-scheduling strategies (Hu et al.; Zhang et al., 2020).

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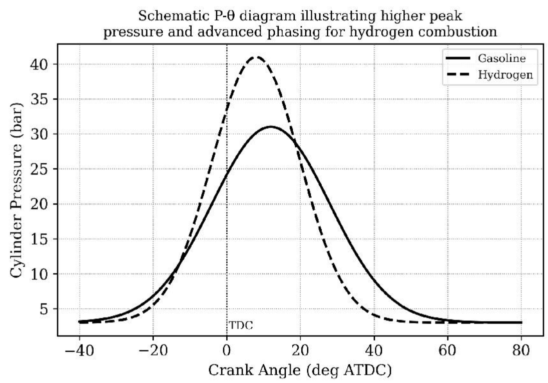

Fig. 3. Schematic P–θ diagram illustrating higher peak pressure and advanced phasing for hydrogen combustion relative to gasoline, consistent with heat-release rates reported by Navale et al.

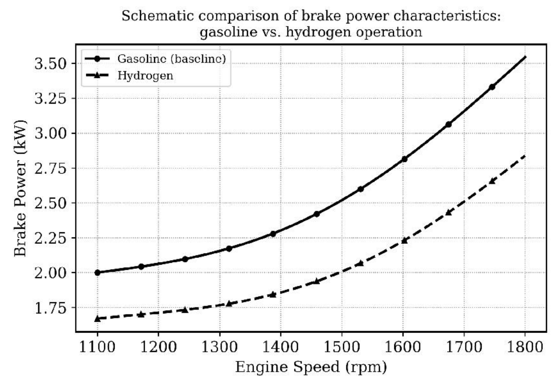

Fig. 4. Schematic brake power vs. engine speed for gasoline and hydrogen operation, illustrating the power deficit motivating turbocharging, consistent in direction with Navale et al. (−19%).

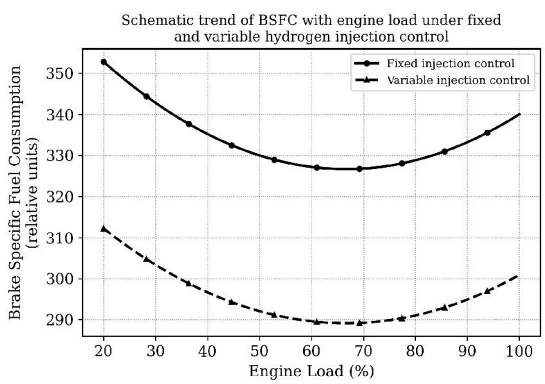

Fig. 5. Schematic trend of brake specific fuel consumption with load under fixed vs. variable injection control, illustrating the projected 10–15% BSFC improvement.

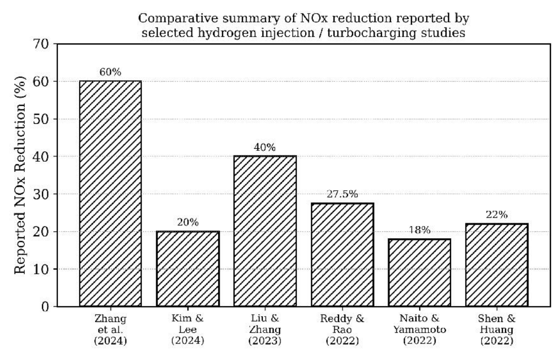

Fig. 6. Comparative summary of NOx reduction percentages reported by selected studies, illustrating the wide spread (18–60%) from differing baselines and strategies.

V. COMPARATIVE CRITICAL ANALYSIS

Table 2 places ten representative studies side by side against a common set of criteria, configuration, key reported outcome, and principal limitation, to make explicit the comparability problem introduced in Section 3. Three observations follow directly from the table. First, reported NOx-reduction percentages (16–60%) cannot be treated as a single reconcilable figure because the baselines differ: some studies compare hydrogen against diesel, others against gasoline, and others against a less-optimized hydrogen configuration. Second, the studies that report the largest benefits (Zhang et al., Liu & Zhang) tend to be the ones with the least standardized baseline, which is a pattern review methodology should flag rather than average away. Third, only a minority of the reviewed studies (e.g., Navale et al., Vaithianathan et al., Kapadani at.al) report comprehensively validated hardware results across a full performance-and-emission characterization; the remainder report a partial set of outcomes (only NOx, or only power), which limits the ability to construct a complete, mutually consistent characteristic map of a turbocharged hydrogen engine under variable injection control.

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Table 2. Comparative summary of representative studies on hydrogen turbocharged engines under variable injection control

Study	Configuration / Lever	Key reported outcome	Principal limitation
Zhang et al. (2024)	Electric turbocharged H2 direct injection; timing optimization	Up to 60% NOx reduction; higher thermal efficiency vs. diesel	Diesel used as baseline, not gasoline; limits direct comparison with most other studies
Kim & Lee (2024)	Hydrogen-water co-injection	20% NOx reduction; 5% power gain at high speed	Water-to-hydrogen ratio optimum not generalized across load range
Wang et al. (2023)	Variable valve timing (VVT) + hydrogen	Up to 12% fuel-efficiency gain; NOx reduced via lower combustion temperature	Benefit concentrated at low load; high-load behaviour less clear
Liu & Zhang (2023)	Multi-stage / staggered injection	Up to 40% NOx reduction vs. single-stage injection	Comparison baseline (single-stage) not independently re-verified
Reddy & Rao (2022)	ECU-based closed-loop injection timing	25–30% NOx reduction without hardware change	Retrofit scalability claimed but not demonstrated on multiple engines
Shen & Huang (2022)	Variable timing and duration, turbocharged	Up to 18% power gain; NOx significantly reduced	NOx reduction reported qualitatively, not as a single percentage
Hu et al. (2019)	Equivalence-ratio control, turbocharged, low speed	Stable combustion and NOx control via φ scheduling	Limited to low-speed operating region
Navale et al. (2017)	Naturally aspirated, timed manifold injection, ECU	19.1% lower brake power, 3.2% higher peak brake thermal efficiency vs. gasoline	No turbocharging; power deficit not yet recovered
Vaithianathan et al. (2015)	Turbocharged hydrogen ICE, experimental	Power gap relative to gasoline substantially narrowed by boosting	Emission trade-offs of the specific boost strategy not fully quantified

VI. CRITICAL ASSESSMENT AND RESEARCH GAPS

This involves identifying the critical assessment and research gaps. Combining Sections 3 and 5, the review concludes that there are five specific gaps that hinder the field's progress from individually successful outcomes to a proven and scalable design method.

(i) There is no common experimental baseline. It is possible to draw a qualitative comparison between the studies reviewed here, but it is not statistically sound since no two studies have the same engine, compression ratio, injector hardware, or boost strategy.

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(ii) Coupled optimization results are not easily transferable from one engine operating condition to another. Recent studies have started to consider how to simultaneously optimize hydrogen injection and combustion-control variables; the evidence available so far is still rather engine- and operating-condition-dependent. Response surface methodology was used in the experimental optimization and numerical simulation of the split-injection parameters and ignition timing in a 2.0-L turbocharged direct-injection hydrogen engine by Zhang et al. (2024). Coupled optimization did result in a significant improvement in the efficiency–emission trade-off, with a maximum brake thermal efficiency of 43.03% and a 71.19% reduction in NOx. The optimized response, however, is still dependent on engine speed, load, injection configuration, and starting conditions. High BTE (BTE > 40%) was achieved over more than 50% of the investigated load map after optimization, but this does not verify the transferability to other engine architectures, compression ratios, injector configurations, or turbocharging systems. So, the missing piece of the puzzle is no longer the lack of coupled optimization; it is the lack of a common and generalized methodology to compare the results of coupled optimization across various hydrogen-engine platforms.

(iii) Lack of a link between optimization models and experimentally transferable control maps. Experimental measurements are now more frequently being used along with numerical modelling, response surface methodology, and multi-parameter optimization in recent literature. For instance, the 2024 Energy study performed both experiments and simulations and also included the application of response surface methodology, showing that there were strong interactions between the split-injection parameters and between ignition timing and the other parameters. Most optimization studies continue to be based on a specific geometry, injector, boost system, and operating range, however. The big problem with modelling or optimization tools is not that they exist, but that there is no standard method to apply optimized laboratory results to transferable control maps for various turbocharged hydrogen-engine configurations. A comprehensive framework should provide information on injection timing, injection duration, injection pressure, equivalence ratio, intake pressure, engine speed, load, combustion phasing, BTE, NOx, and knock intensity.

(iv) Under-reporting of the performance of backfire and safety hardware. While the combination of flame arrestors, flame traps, and leak-detection systems is routinely mentioned as required equipment in almost every experimental study, the quantitative effect of such components on combustion (e.g., pressure drop and injection-timing margin) is generally not reported, but is safety-critical if the results are to be translated to field deployment (Benke et. al.).

(v) No optimization of air management, injection, and thermal dilution. Injection optimization, turbocharging/VGT control, EGR, water injection, and variable valve strategies are all candidates that have shown potential to enhance the efficiency–NOx trade-off. These strategies are usually explored in isolation, either in the form of experiments or simulations, however. For instance, under the reported operating conditions, the optimization of VGT can achieve BTE up to 42.57%, while multi-parameter injection optimization can achieve BTE up to 43.03% with NOx reduction up to 71.19%. The results reveal that both air management and fuel-injection control can have similar impacts on engine performance. The next research challenge is thus the development of an integrated control strategy that optimizes boost/VGT, equivalence ratio, injection phasing, injection staging, and thermal-dilution strategies simultaneously and validates them across the entire engine operating range.

VII. NOVELTY POSITIONING OF THE PRESENT REVIEW

Each of these approaches— injection timing, split injection, turbocharging, EGR, water injection, and equivalence-ratio control—is a known experimental or numerical approach to improve performance and is therefore not new to the field of internal combustion engines. Rather, the contribution is the establishment of a standardized critical framework to reconcile their reported performance and emission benefits for various engine configurations and operating modes.

Such a framework is needed, as illustrated by the recent literature. In a multi-parameter optimization study on a 2.0-L turbocharged direct-injection hydrogen engine in 2024, split injection and ignition optimization with response-surface methodology resulted in 43.03% BTE and a 71.19% NOx reduction. Another 2024 study on a 2.0-L direct-injection turbocharged hydrogen engine had BTE rise from 40.4% to 41.7% with near-zero NOx using injection optimization. A 2024 study of a variable-geometry turbocharged hydrogen engine found a maximum BTE of 42.57%, together with 326.4 N•m torque and 124.8 kW power. These findings show that, under certain conditions, high efficiency and low NOx emissions can technically be achieved, but the optimum results shown here are not indicative of a universal target, as they are based on different engine architectures, boost systems, injection equipment, and operating conditions (Keskar et. al.).

Therefore, this review suggests shifting the focus of future comparisons between hydrogen piston and turbocharged engines from percentage-based comparisons to a multidimensional, evidence-based framework that includes the following parameters: engine architecture, injection strategy, injection timing, injection duration, injection pressure, equivalence ratio, boost pressure, engine speed, load, combustion phasing, BTE, NOx, and knock intensity. The primary research gap is hence the lack of a transferable and experimentally validated performance–emission map spanning the entire operating range that connects injection and air-management parameters to efficiency, combustion phasing, and NOx.

VIII. FUTURE DIRECTIONS

The evidence presented shows that further research into hydrogen turbocharged engines should focus on validated, transferable, and experimentally proven control strategies, rather than performing isolated optimizations of individual parameters. First of all, it is important to create a standard reporting process that incorporates baseline fuel, engine displacement, compression ratio, injector type, fuel injection pressure, fuel injection timing, fuel injection duration, equivalence ratio, intake pressure, boost pressure, engine speed, load, CA10, CA50, CA90, BTE, NOx, and knock intensity. This reporting would allow for quantitative cross-study comparison rather than just a comparison of percentage improvement.

Second, future research should establish multi-dimensional response surfaces between injection timing, injection duration, split-injection ratio, ignition timing, equivalence ratio, and boost pressure. Finally, the use of response surface methodology in a turbocharged DI-H_2 engine has recently been applied to a single operating point, and the optimum thus obtained needs to be tested over a wider operating range and across various engine architectures.

Third, optimization of air-management and fuel-injection strategies should be done concurrently. The results of the latest VGT trials show that its matching can achieve significant gains in hydrogen-engine performance, with a maximum BTE of 42.57% and maximum power of 124.8 kW. This means that optimization of injection is not possible without taking into account the air-path system.

Lastly, future experimental programs should report a validated performance–NOx–knock map instead of isolated optimum operating points. This map should include uncertainty and repeatability analysis and quantify the interaction between boost pressure, equivalence ratio, injection phasing, injection staging, and thermal-dilution strategies. This would enable a more transferable means of ECU calibration and real-time control of hydrogen internal combustion engines with turbocharging.

IX. CONCLUSION

This critical review combined and interpreted both experimental and simulation-based research on variable injection control, combustion phasing, air management, efficiency, and NOx emissions of hydrogen-fueled turbocharged internal combustion engines. The literature shows that turbocharging, injection timing and duration, split injection, equivalence-ratio control, EGR, water injection, variable valve timing, and VGT can have a strong effect on the performance of hydrogen engines. However, their effects remain very much dependent on the model and hardware, as well as on boost pressure, engine speed, load, and baseline definition.

Recent studies have shown that coupled optimization is already achievable, and BTE values above 40% have been reported with significant NOx reduction under optimum operating conditions. Hence, the key research gap is the lack of a standard and transferable methodology for the comparison of optimized operating conditions under different conditions and across different hydrogen-engine platforms.

The review emphasizes that information on injection timing, injection duration, injection pressure, equivalence ratio, boost pressure, engine speed, engine load, combustion phasing, BTE, NOx, and abnormal-combustion indicators should be reported consistently. Further studies are needed to integrate fuel-injection and air-path control and to create multidimensional maps of performance–NOx–combustion for the whole engine operating space, which can be validated experimentally.

In general, the future direction of hydrogen turbocharged ICE research should shift from specific optimum points towards standardized, transferable, and experimentally validated control strategies. This approach can offer a stronger scientific basis for high-efficiency and low-NOx hydrogen engines and their industrial application.

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