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Numerical investigation of intake flow dynamics in hydrogen-fueled engines

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This paper presents a computational fluid dynamics (CFD) study of hydrogen injection in a modified intake system of a small industrial internal combustion engine. Two injector positions (8 mm and 12 mm from the valve stem axis) and two injection profiles were evaluated for their impact on in-cylinder mixture formation. The results indicate that injector placement significantly affects hydrogen jet penetration and turbulence interaction. A more gradual injection profile produced better mixture homogeneity. The 8 mm configuration with Profile B demonstrated the most uniform distribution, which is favorable for combustion stability and NO_x emission reduction. These findings support the need for integrated optimization of intake geometry and fuel delivery strategies in hydrogen engines.

Key words: *hydrogen combustion, intake manifold, injector positioning, fuel-air mixing, piston geometry*

1. Introduction

The growing interest in hydrogen as a sustainable fuel for internal combustion engines has intensified the need to understand the complex dynamics of fuel-air mixture formation and in-cylinder flow behavior [43, 50]. Hydrogen internal combustion engines (H2-ICEs) are increasingly regarded as a promising pathway to decarbonize the transport sector. These engines utilize hydrogen fuel in a conventional combustion process, offering near-zero carbon dioxide emissions and significantly lower levels of particulates and unburned hydrocarbons. When combined with direct injection (DI) and advanced ignition systems, H2-ICEs can achieve peak thermal efficiencies of up to 50% and average driving cycle efficiencies above 35%, especially in hybrid vehicle configurations [3, 7, 9].

Applications of H2-ICEs range from heavy-duty trucks and city buses to retrofitted power units in hybrid drivetrains. Positive ignition (PI) concepts with DI and jet ignition (JI) provide high power density and efficient lean-burn operation. However, port fuel injection (PFI) systems – although easier to retrofit – require careful control to avoid backfire and pre-ignition events [10, 24, 51]. Similarly, Yang et al. [49] showed that in Reactivity Controlled Compression Ignition (RCCI) engines, split-injection parameters have a key influence on multi-stage heat release and engine efficiency, emphasizing the need for precise tuning of the injection strategy.

Despite these advantages, H2-ICEs face several technical challenges. Key among them are elevated NO_x emissions due to high combustion temperatures, material degradation from hydrogen exposure, and the need for redesigned thermal systems to handle hydrogen-specific intake air and heat transfer characteristics [4, 32]. Recent studies also demonstrate that water injection can significantly reduce NO_x formation and improve torque and combustion stability at high loads [33].

Therefore, adequate air-fuel mixing, injection strategy, and combustion chamber geometry management are critical to ensure stable operation and emission compliance. These aspects are particularly relevant to developing small-displacement engines, where compact design constraints amplify the effects of mixture formation on overall performance.

Hydrogen's unique properties – including high diffusivity and flame speed – make it attractive but pose challenges such as backfire risk and mixture stratification [5].

Achieving a homogeneous hydrogen-air mixture is one of the most critical aspects of ensuring efficient and stable combustion in H2-ICEs. Mixture stratification can lead to local hot spots, increased NO_x formation, and incomplete combustion. As a result, understanding the dynamics of fuel-air mixing is essential for developing low-emission hydrogen engines. As emphasized by Vasudev et al. [45], accurate modelling of fuel-air stratification remains a critical challenge in low-temperature combustion strategies, which justifies the use of detailed Computational Fluid Dynamics (CFD) analyses even before ignition.

Recent studies show that injection timing strongly influences mixture quality, with early injection events (e.g., –120°CA aTDC) promoting better distribution across the combustion chamber [27]. Dual injection strategies and in-cylinder flow patterns, especially tumble and swirl, have also enhanced mixture homogeneity [34]. Although high injection pressures can accelerate mixing, their effect is often less significant than proper timing and piston geometry [2, 47, 52].

CFD simulations and optical diagnostics, such as tracer-based laser-induced fluorescence (TLIF), have enabled detailed characterization of hydrogen jet penetration and flow structures [8]. These methods reveal that injector positioning, nozzle design, and in-cylinder motion must be considered jointly to achieve optimal fuel-air distribution.

Therefore, proper control of injection parameters and combustion chamber dynamics is decisive in determining engine performance, NO_x emissions, and operational stability.

In addition to stratification, hydrogen engines are especially prone to abnormal combustion events such as backfire and pre-ignition. These issues are caused by hydrogen's low ignition energy and high flame speed and are often triggered by hot residual gases, improper injection timing, or elevated wall temperatures [17, 41]. Controlling these phenomena is essential for ensuring safe and stable operation.

Furthermore, hydrogen combustion at high temperatures promotes NO_x formation. While ultra-lean mixtures can suppress NO_x, they may also reduce power output and increase cycle-to-cycle variability [1, 20]. Thus, effective mitigation strategies – such as water injection, cooled EGR, optimized injection, and valve timing – are needed to balance performance and emissions [12, 39].

Computational Fluid Dynamics has become a crucial tool for analyzing hydrogen combustion due to the complexity of flame propagation, pollutant formation, and flow interactions. CFD models, ranging from Reynolds-Averaged Navier–Stokes (RANS) to Large Eddy Simulations (LES), have been validated against experimental data and allow for detailed investigation of in-cylinder processes [15, 37]. These simulations are beneficial for assessing the effects of geometry, injection strategies, and turbulent mixing in hydrogen-fueled engines.

3D-CFD simulations, in particular, provide superior accuracy in predicting heat release rates and flame development compared to simplified 2D or 0D models [16, 36].

This study uses computational fluid dynamics (CFD) simulations to investigate the behavior of air–hydrogen mixtures flowing through the intake valve system and interacting with various piston crown geometries. The primary objective is to assess how piston design influences turbulence intensity, mixing quality, and combustion efficiency – factors critical for stable, efficient hydrogen combustion [29, 43].

Previous studies have emphasized the importance of optimizing charge motion – particularly swirl and tumble flows – for enhancing combustion in engines fueled with alternative gases such as sewage gas or hydrogen-enriched blends [3]. Modifications to intake and combustion chamber geometry have proven effective in improving swirl characteristics and reducing NO_x emissions.

For instance, [25] demonstrated that geometric adjustments near the inlet valve seats can enhance charge motion and combustion quality while meeting emission constraints. Similarly, swirl-stabilized flame studies indicate that adding hydrogen increases NO_x formation, but this can be mitigated by raising excess air levels or swirl intensity, thereby improving mixture homogeneity and reducing peak temperatures [22].

These findings underscore the necessity of carefully designing the intake system and piston geometry to optimize in-cylinder flow and minimize emissions in hydrogen-fueled internal combustion engines.

The role of intake geometry – including plenum volume, port shape, and runner length – cannot be overstated in this context. Optimized intake configurations can improve air-fuel mixing, reduce dead zones, and enhance tumble or swirl motion, leading to better combustion efficiency and lower emissions [2, 23]. Variable intake systems offer flexibility across engine speeds, further optimizing torque and fuel economy. Injection strategy – including timing, duration, and split/single injection schemes – strongly influences mixture formation and combustion characteristics. Delayed injection in DI engines improves efficiency and reduces pre-ignition risk, while split injection may enhance mixing but requires careful calibration to avoid NO_x spikes [28, 30].

Injection strategies must also be tailored to engine type. For example, rotary engines benefit from early injection, while dual-fuel setups require precise pilot injection control [14, 44]. These parameters are key to leveraging hydrogen's combustion potential across diverse engine architectures.

Additionally, the intake design affects engine response and thermal behavior, making it a critical factor in performance and durability [6, 40].

2. Related work

2.1. Hydrogen combustion characteristics in ICEs

Hydrogen's broad flammability limits, minimal ignition energy, and rapid diffusion support lean-burn combustion. Yet, these same traits heighten the risk of backfire, pre-ignition, and elevated NO_x levels due to increased combustion temperatures [46]. Huang et al. [2] pointed out that consistent mixture formation and effective control of in-cylinder air motion are key to mitigating these issues.

Thanks to its combustion properties – such as fast flame speed and low ignition threshold – hydrogen enables efficient lean-burn operation. Nevertheless, these characteristics also introduce challenges like knock, spontaneous ignition, and greater NO_x emissions under high-temperature conditions. Research [13, 35] indicates that quick combustion enhances thermal efficiency, though it can reduce power output under stoichiometric conditions. To stabilize combustion and curb NO_x formation, strategies like direct injection and targeted mixture preparation near the ignition site are essential [30, 48].

2.2. Importance of in-cylinder flow and swirl motion

Proper in-cylinder airflow plays a key role in ensuring thorough air-fuel mixing and maintaining stable combustion. Swirl and tumble flows, induced by the design of intake ports and valve geometry, enhance turbulence and speed up flame development [18, 21]. Increased swirl in hydrogen-fueled engines enables lower emissions while maintaining high volumetric efficiency, as shown, among others, in studies using Particle Image Velocimetry (PIV) and CFD simulations [26, 38].

Studies by [25] on alternative fuel engines showed that optimizing the intake system—especially the regions near the inlet valves – can significantly improve swirl intensity. Their results, validated through flow-bench and combustion tests, revealed that geometric changes could yield better combustion characteristics and lower NO_x emissions.

Swirl and tumble motions are fundamental in direct-injection hydrogen engines to avoid stratification and ensure reliable ignition. Through CFD, Liu et al. [29] demonstrated that piston crown shape directly influences large-scale vortex formation, affecting mixing efficiency and flame propagation dynamics.

2.3. CFD simulation as a tool for flow characterization

CFD methods are vital for examining the unsteady and intricate flow behavior within combustion chambers. Traversari et al. [43] employed high-fidelity CFD simulations to analyze turbulence generated by interactions between valves and the piston. Their research underlined the significance of fine mesh resolution and the selection of appropriate turbulence models, such as k–ε or LES, for accurate prediction of in-cylinder processes.

In hydrogen-air mixture studies, CFD modelling – using approaches like k–ε or LES – enables simulation of vortex structures and the influence of moving components such as valves and pistons [19, 23]. Furthermore, CFD tools are valuable beyond engine analysis. For example, Czyż et al. [11] used them to assess the aerodynamic influence of individual vehicle elements, quantifying drag contributions in an ultra-efficient electric vehicle. Their analysis highlighted how body shape affects flow detachment and turbulence formation – insights that are also critical in optimizing intake system performance.

Combining CFD with machine learning methods allows for optimization of injection parameters and significantly accelerates the design of H_2 fuel systems [23].

Mattarelli et al. [31] further validated that advanced piston profiles could enhance turbulence, speed up flame propagation, and reduce cycle-to-cycle variability. This supports the view that piston geometry is not merely a mechanical component but a functional element in combustion optimization.

2.4. Hydrogen-methane blends and swirl stabilization

Recent research on swirl-stabilized combustion in hydrogen-enriched methane flames [25] has revealed a trade-off between enhanced mixing and increased NO_x emissions. Their results suggest that increasing swirl can homogenize the mixture and lower peak flame temperatures, thus reducing NO_x emissions. However, excessive swirl may lead to incomplete combustion or flame quenching.

These studies underline the necessity for a balanced intake strategy, where geometric configurations of valves, intake ducts, and piston crowns work synergistically to manage in-cylinder dynamics without incurring performance penalties.

3. Methods

3.1. Research object

The combustion engine on which the geometry of the intake and crank-piston system was based was the Yamaha EH65 engine. It is an industrial, two-cylinder, V-shaped, air-cooled engine with a capacity of 653 cm^3. The basic technical data of the unit are presented in Table 1.

Table 1. Technical data of the Yamaha EH65

Parameter	Unit	Value
Engine type	–	Air-cooled, OHV, V2, with horizontal shaft
Cylinder bore × stroke	mm	80 × 65
Displacement	cm^3	653
Maximum power	kW	15 at 3600 rpm
Maximum torque	Nm	45.6 at 2600 rpm
Compression ratio	–	8.3
Fuel	–	Unleaded petrol
Ignition system	–	TCI ignition
Service weight	kg	49.5
Dimensions (length × width × height)	mm	463 × 499 × 476

Figure 1 shows the Yamaha EH65 internal combustion engine.

Fig. 1. Yamaha EH65 internal combustion engine

The combustion engine has an indirect injection system with two injectors, one for each cylinder. This forced the modification of the intake system to install additional injectors supporting LPG, CNG, and hydrogen HANA H2001 Gold. Figure 2 shows the model of the intake manifold with additional sockets for gas injectors.

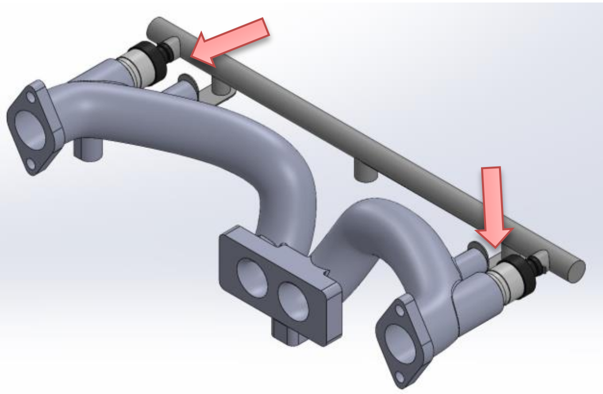

Fig. 2. Yamaha EH65 engine modified intake system model. Arrows indicate the location of the additional gas injector ports

3.2. Simulation parameters

The conducted research is preliminary in nature. It aims to understand the behavior of injected hydrogen in the intake manifold of an internal combustion engine. Additionally, it aims to determine the optimal injector nozzle position relative to the intake valve stem diameter. Furthermore, the authors attempted to modify the hydrogen injection length characteristics. For this reason, many elements of the simulation model were simplified. The model does not simulate the combustion process, focusing solely on the process of filling the combustion chamber with hydrogen. The CFD flow analysis was performed in SolidWorks Flow Simulation. The engine geometry was mapped using reverse engineering techniques. The software uses the k–ε (k–epsilon) turbulent model – or more precisely, a modified version of the k–ε model adapted to CFD engineering applications. Similar simplifications in CFD setup were employed in external aerodynamics studies of UAVs, where mesh density and CAD model fidelity were adjusted to balance computational cost and simulation accuracy [42]. The mesh was based on cubes and consisted of 8037 cells and 4585 fluid cells that bordered the solid material. The basic mesh had the size Nx = 10, Ny = 14, Nz = 12. The critical locations of the mesh were automatically densified to increase the accuracy of the calculations. The authors are aware of the small number of cells, but this is a preliminary study aimed at investigating the problem. In the future, simulation studies will be conducted with a much more refined mesh, and the results will be compared. Figure 3 shows a basic mesh model of the Yamaha EH65 engine.

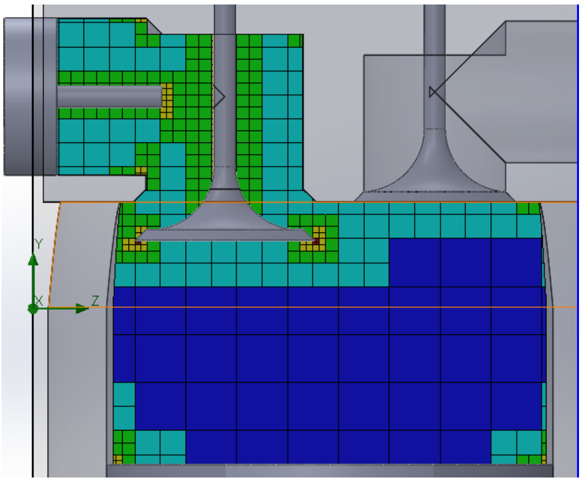

Fig. 3. Yamaha EH65 engine basic mesh model

The initial/boundary conditions of the working medium parameters in the intake manifold were assumed in accordance with the measurements of the actual engine running on standard Pb 95 gasoline. The test scenario assumed two different locations for mounting the injector tip. The first is 8 mm from the intake valve stem axis, and the second is 12 mm from the exact location. The location of the injector tip in the intake manifold lumen is consistent with the location of the additional gas injector sockets shown in Fig. 2. The injector nozzle distance depends on the factory HANA H2001 Gold injector fuel channel extensions. Two lengths are available to approximate the dimensions specified. Figure 4 shows the location of the injection tip at a distance of 8 mm from the valve stem axis.

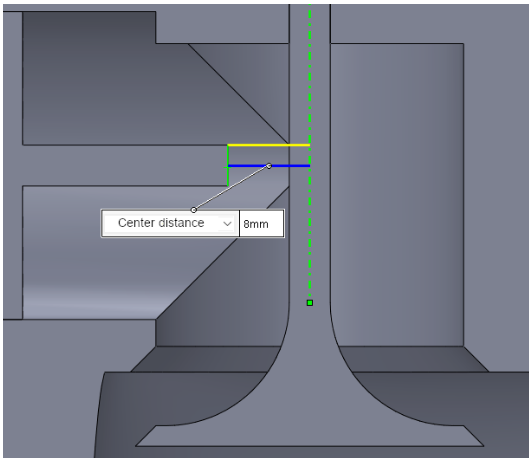

Fig. 4. The location of the injection tip at a distance of 8 mm from the valve stem axis

Another parameter that was changed during the tests was the hydrogen injection profile. The calculated hydrogen injection of 0.15 kg/s for one work cycle completely replaces the energy dose of gasoline necessary to operate the engine at a rotational speed of 3000 rpm. The injection dose and rotational speed parameters were selected in accordance with the actual operating parameters of the engine, which is the driving element of the mobile generator. Injection profile A, shown in Fig. 5, introduces a dose of hydrogen at one peak at 4 milliseconds.

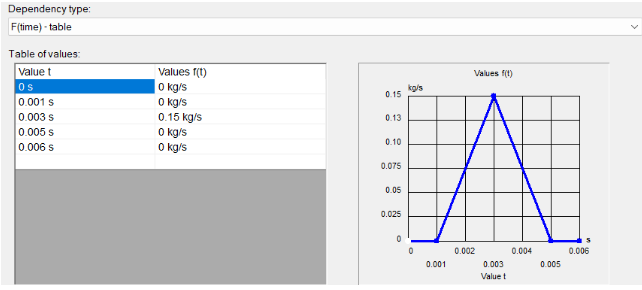

Fig. 5. Injection profile A

Injection profile B, shown in Fig. 6, on the other hand, spreads the fuel dose, reducing the dose peak by half while maintaining the injection time.

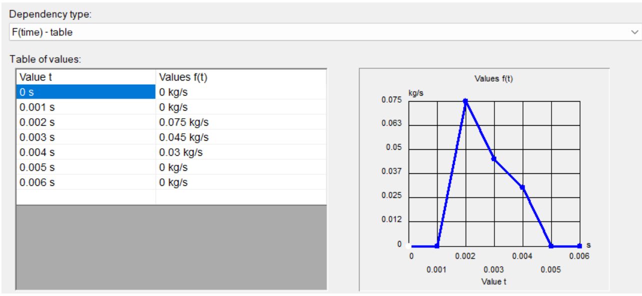

Fig. 6. Injection profile B

The results were presented in time windows, which were chosen to show the hydrogen injection process optimally. The selected windows are 0.001, 0.0011, 0.0012, 0.0014, 0.0016, 0.0018, 0.002, 0.0022, 0.0028, 0.004, 0.005 seconds.

3.3. Justification for the selection of parameters and simulation methods

The main assumptions of the CFD model result from the need to analyze the mechanisms of hydrogen mixing with air in the intake valve area and the initial phase of cylinder filling. The literature [2, 27] emphasizes that intake geometry, injection timing, and H_2 stream parameters significantly impact the homogeneity of the mixture and the formation of depleted or enriched zones. The selection of two injection profiles (pulsed – A and distributed – B) and two injector tip locations (8 mm and 12 mm from the valve stem axis) reflects typical strategies used in experiments and CFD analyses [47]. Studies [34] have shown that a shorter injector tip distance promotes vorticity intensification and improves mixing. In turn, the B-profile, extended in time, limits local excess hydrogen concentration, reducing the risk of pre-ignition or knocking [8, 13].

The simulations were performed without considering the combustion reaction, allowing the focus to be only on the mixing and flow phases. This approach is commonly used in preliminary work on H2-ICE engines and is confirmed in the literature [16, 47].

Additionally, the adopted mesh size and local densities in critical regions (e.g., injector area) ensure adequate accuracy of the flow analysis without excessive increases in computational costs.

4. Results

4.1. Effect of injector location

The simulation results include a spatial-temporal analysis of hydrogen distribution in the intake system for different injector location variants (8 mm and 12 mm) and two injection time profiles (A and B). The simulations were performed in the time range from 0.001 s to 0.005 s.

The numerical simulations detailed the hydrogen flow patterns under varying injector positions and injection profiles. Figures 3–5 and the accompanying data snapshots illustrate transient behavior in the intake manifold at critical time frames (0.001 s to 0.005 s).

When the injector was positioned closer to the intake valve stem (8 mm), the resulting hydrogen jet exhibited higher penetration velocity and more direct alignment with intake airflow. This configuration enhanced local turbulence intensity, promoting better initial mixing with ambient air.

In contrast, positioning the injector further away (12 mm) led to a wider dispersion pattern but slower penetration, suggesting increased residence time for mixture formation but potentially less directional control.

For the configuration with the injector placed 8 mm from the intake valve, faster spray penetration, and a more dispersed hydrogen distribution are observed in the initial injection phases (t = 0.001–0.002 s). In the 12 mm configuration, the spray has a more directed character, and the high-concentration region remains longer near the injector. These differences are apparent in the isosurfaces shown in Fig. 7 (columns 1 and 3). For t = 0.005 s, hydrogen spreads towards the intake valve in both cases, but the 8 mm configuration shows a more uniform distribution.

4.2. Effect of injection profile

Injection Profile A (sharp 4 ms pulse) caused a strong, concentrated fuel jet. While this led to rapid mixture generation, it also increased the risk of localized stratification.

Injection Profile B, which delivered hydrogen over the same period with lower peak flow, produced a more homogeneous distribution and better integration with the in-cylinder swirl.

Profile A (shorter pulse) generates a more focused stream with a transparent hydrogen concentration gradient along the injection axis. Profile B (extended injection time) results in a broader gas distribution in the manifold space. For the same injector position (e.g., 8 mm), Fig. 7 (columns 1 and 2) simultaneously shows apparent differences in the stream geometry and isosurface range. For profile B, the stream reaches a greater lateral range, which may affect the mixing conditions at the intake valve.

4.3. Combined effects

The best mixing performance – assessed visually by spatial uniformity and flow symmetry – is observed for the 8 mm injector distance using Injection Profile B. This configuration showed early-stage uniform fuel-air mixing with minimal backflow or stagnation zones.

The most uniform hydrogen distribution in the collector volume was obtained for the configuration with the injector placed 8 mm from the intake valve and time profile B. In this configuration, the hydrogen concentration isosurfaces show the most excellent coverage of space, which may indicate favorable conditions for mixture homogeneity. The distribution details are shown in Fig. 7 in the bottom row.

5. Discussion

The simulations demonstrate that piston crown geometry and intake conditions must be designed with an injection strategy to optimize hydrogen fuel delivery in ICEs.

The closer injector location (8 mm) benefits from the kinetic energy of the intake stream, enabling better entrainment and momentum coupling. Although less aggressive, Profile B avoids sharp flow transitions, reducing swirl destabilization.

These results align with findings from [4] and [5], emphasizing the critical interplay between injection dynamics and in-cylinder turbulence for hydrogen engines.

5.1. Implications for combustion

Optimized mixture formation not only supports more complete combustion but also addresses typical issues in hydrogen-fueled ICEs:

- Backfire and pre-ignition mitigation via smoother concentration gradients.
- NO_x control through stratification avoidance and lower local temperatures.

The studies [13] showed that the homogeneity of the mixture directly affects the reduction of knock combustion zones and local overheating, which correlates with the efficiency of the B injection profile observed in this work. Therefore, the 8 mm + B configuration can reduce cycle variability and improve ignition stability, which is crucial in ignition systems with many starts [20].

5.2. Simulation limitations

The simulations use simplified geometry and mesh resolution, which may not fully capture fine-scale turbulence or heat exchange effects.

The lack of combustion phase modeling restricts conclusions to pre-ignition flow behavior.

The limitation of the flow phase, without modeling of chemical reactions, is typical for preliminary analyses in H2-ICE projects [16]. Failure to consider thermal losses and material properties (e.g., thermal conductivity of the piston crown) may lead to an underestimation of the influence of local temperature gradients on spontaneous ignition. In the following steps, it is worth considering including combustion submodels (e.g., Zeldovich for NO_x) and validation using optical methods (e.g., TLIF) [8]. According to Vasudev et al. [45], a validated integration of mixing models with thermo-kinetic combustion submodels enables accurate ignition timing and pollutant formation prediction.

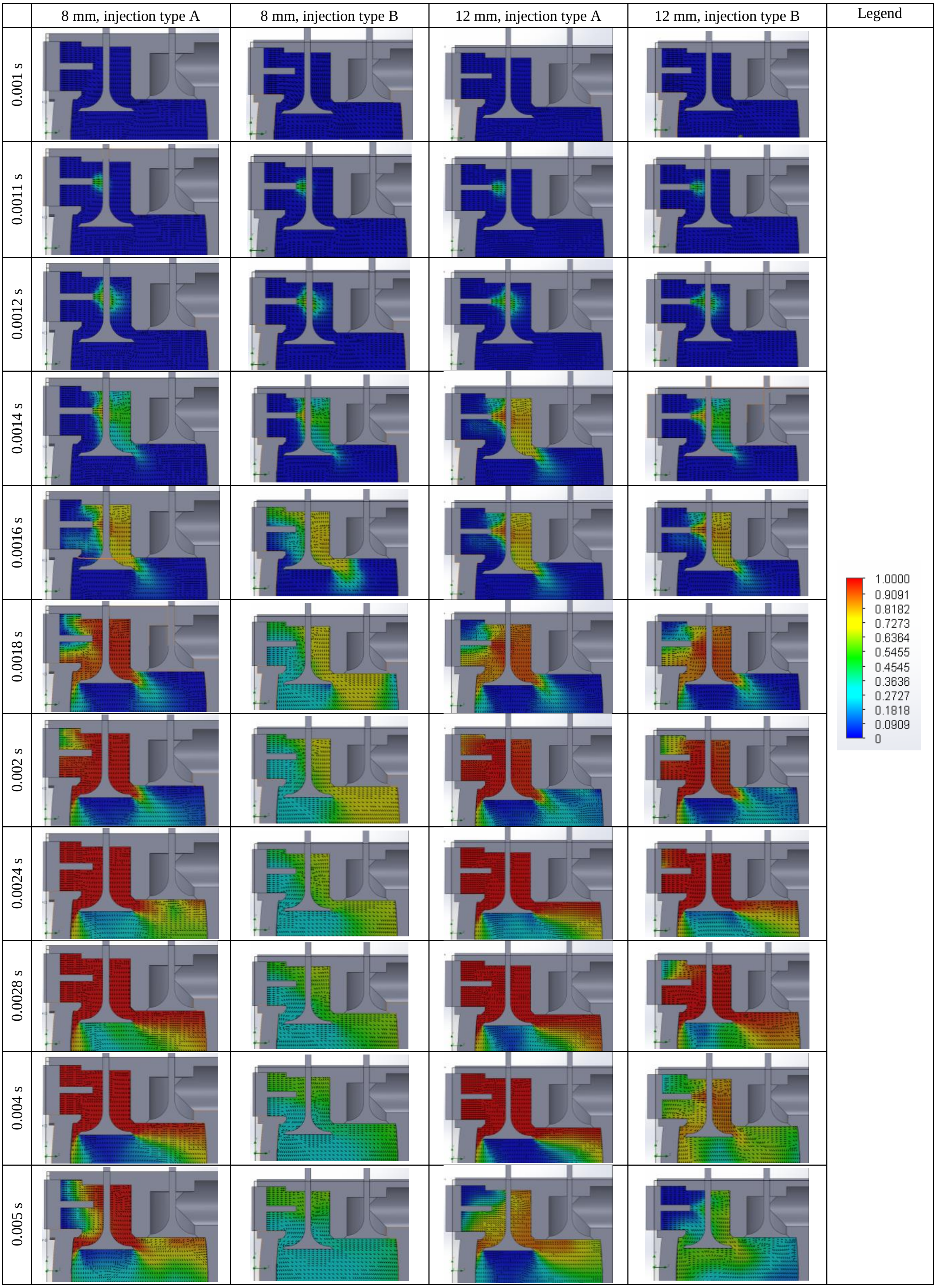

Fig. 7. The data snapshots illustrate transient behaviour in the intake manifold at critical time frames (0.001 s to 0.005 s)

This highlights the importance of extending CFD simulations beyond the intake phase in future work.

Despite these constraints, the study provides a valuable parametric baseline for future experimental validation and full-cycle combustion modeling.

6. Conclusion

The conducted CFD simulations have confirmed that the hydrogen injection strategy – specifically injector location and temporal profile – has a decisive impact on mixture homogeneity and spatial fuel distribution within the intake manifold.

Key conclusions are as follows:

– Injector placement 8 mm from the intake valve results in higher flow penetration velocity and better mixing due to the synergy with intake air momentum
– With a temporally extended hydrogen dose, Injection Profile B reduces concentration gradients and mitigates local stratification zones
– Combining 8 mm positioning with Profile B yields the most favorable conditions for air–hydrogen mixing, suggesting benefits in terms of combustion stability and NO_x mitigation.

Despite being combustion-free, the simulation approach offers valuable insights into pre-ignition mixture dynamics and supports further experimental work.

These findings reinforce the importance of coordinated optimization of the intake geometry, injector configuration, and injection parameters in developing hydrogen-powered ICEs.

In the next stage of the work, the following is planned:

– Implement full-cycle simulations that take into account the modeling of the combustion process, including the mechanisms of nitrogen oxide formation (e.g., Zeldowicz model)
– Experimental validation of results using advanced optical diagnostics, such as laser-induced fluorescence (TLIF) or Schlieren imaging
– Extension of analyses to multi-cylinder configurations and assessment of the impact of variable load conditions on mixing efficiency and engine stability.

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