Effective emission reduction system for hydrogen combustion engines

Michal Puškár [1]
Pavol Tarbajovský [2]

[1] Technical University of Košice, Faculty of Mechanical Engineering; Letná 9, Košice, Slovensko; email: michal.puskar@tuke.sk
[2] Technical University of Košice, Faculty of Mechanical Engineering; Letná 9, Košice, Slovensko; email: pavol.tarbajovsky@tuke.sk

Grant: APVV-23-0266
Grant name: Research and development of effective technical innovations for application of hydrogen technologies in vehicles according to the European Green Deal.
Field specialization: JR - Other machinery industry

Grant: VEGA 1/0495/25
Grant name: Research and implementation of low-emission technologies for sustainable drive systems in transport.
Field specialization: JR - Other machinery industry

Grant: KEGA 007TUKE-4/2023
Grant name: Transfer of innovations and advanced technologies, determined for more ecological and more efficient vehicle drive systems, into the educational process.
Field specialization: JR - Other machinery industry

Abstract As global efforts to reduce greenhouse gas emissions intensify, there is growing interest in alternative propulsion systems that support sustainable transport. Among these, hydrogen-fueled internal combustion engines have emerged as a promising option due to their potential to significantly lower carbon-based emissions. Despite emitting primarily water vapor, hydrogen combustion at elevated temperatures leads to the production of nitrogen oxides, which remain a critical environmental concern. This paper introduces a novel concept for an emission reduction system tailored to the specific challenges of hydrogen-fueled internal combustion engine operation addressing factors such as elevated water vapor concentrations, the necessity for effective NO_x control, and the demand for corrosion-resistant system components. The proposed exhaust system represents a technological advancement aimed at minimizing pollutant output while improving the environmental and functional performance of hydrogen combustion engines.

Keywords hydrogen, combustion engine, emission

1. INTRODUCTION

With the growing emphasis on reducing greenhouse gas emissions and transitioning towards sustainable mobility, increasing attention is being devoted to alternative propulsion technologies. One promising pathway is the utilisation of hydrogen as a fuel in internal combustion engines, which offers the potential for decarbonising the transport sector while retaining the established operational principles of conventional powertrains.

Although the primary component of hydrogen combustion exhaust is water vapour, nitrogen oxides (NO_x) are also formed due to the high combustion temperatures, posing potential risks to air quality and human health [1]. The literature indicates that NO_x formation in hydrogen-fuelled engines is significantly influenced by the combustion strategy, combustion chamber geometry, and ignition control parameters [2,3]. In order to mitigate these emissions, technologies such as exhaust gas recirculation (EGR), selective catalytic reduction (SCR), and advanced catalytic systems based on zeolites and metal oxides are commonly employed [3–5].

Another specific feature of the exhaust system in hydrogen internal combustion engines is the elevated water vapour content, which may condense and lead to corrosion of exhaust components. According to [4], the application of corrosion-resistant materials and thermally stable alloys is essential to withstand the combined effects of high humidity, elevated temperatures, and pressure fluctuations. Consequently, the design of the exhaust manifold must account for both mechanical and chemical stresses on the system [6].

Some studies have also explored the potential for waste heat recovery from exhaust gases through energy recovery systems, which may enhance the overall efficiency of the vehicle [5,7]. However, such approaches require tailored solutions due to the distinct physical properties of hydrogen exhaust, particularly its high temperature and humidity [8].

Overall, it is evident that the exhaust system for a hydrogen internal combustion engine necessitates a fundamentally different design approach compared to fossil-fuel-based systems. The design must ensure efficient expulsion of exhaust gases, minimise NO_x formation, and simultaneously address the challenges of condensation and material corrosion [9].

2. EXHAUST SYSTEM FOR A HYDROGEN INTERNAL COMBUSTION ENGINE

The development of an exhaust system for a hydrogen internal combustion engine requires the implementation of specific technical solutions that take into account the physico-chemical properties of the exhaust gases, emission control requirements, and operational conditions [10]. The key design aspects of the exhaust system, as summarised in Table 1, can be categorised into several areas: material selection, NO_x mitigation, water vapour handling, and thermal flow management.

Parameter	Conventional engine	Hydrogen engine
Regulated emissions	CO_2, CO, HC, NO_x, particulate matter	H_2O, NO_x
Corrosion risk	Low to moderate	High
Catalyst requirement	Three-way catalyst or SCR	NO_x catalyst
Condensate accumulation	Minimal	Substantial
Material requirements	Standard-grade steels	Stainless steel, ceramics, aluminium alloys
Exhaust energy potential	Low to moderate	Moderate to high

Table 1 Comparison of the exhaust system of a hydrogen engine and a conventional internal combustion engine

Due to the high proportion of water vapour in the exhaust, condensation and the resulting corrosion pose a significant threat to the service life of the exhaust system. For this reason, stainless steels and ceramic coatings resistant to acidic condensate are preferred. In certain applications, titanium alloys or composite materials are also considered, offering a combination of low weight and high resistance to chemical degradation.

Although hydrogen contains no carbon, its combustion at elevated temperatures leads to the formation of thermally induced NO_x. Technologies such as NO_x adsorbers and zeolite-based catalysts may be applied to reduce these emissions, particularly in engines operating under transient load conditions [4].

The large volume of water vapour creates a risk of condensation within the exhaust piping, especially during cold starts and low engine loads. This issue can be addressed by specific muffler designs. Thermal flow management is also critical for ensuring the durability of exhaust components and the safe operation of the vehicle. Based on these considerations, a dedicated exhaust system design for hydrogen internal combustion engines was developed.

3. EXHAUST SYSTEM FOR HYDROGEN COMBUSTION APPLICATIONS

The exhaust system designed for hydrogen combustion applications, illustrated in Figure 1, forms an integral part of the hydrogen combustion engine concept. Its primary objectives are to optimise exhaust gas expulsion, minimise NO_x formation, and ensure resistance to the high humidity present in hydrogen exhaust gases. Note: the figure depicts the system without the catalyst insert.

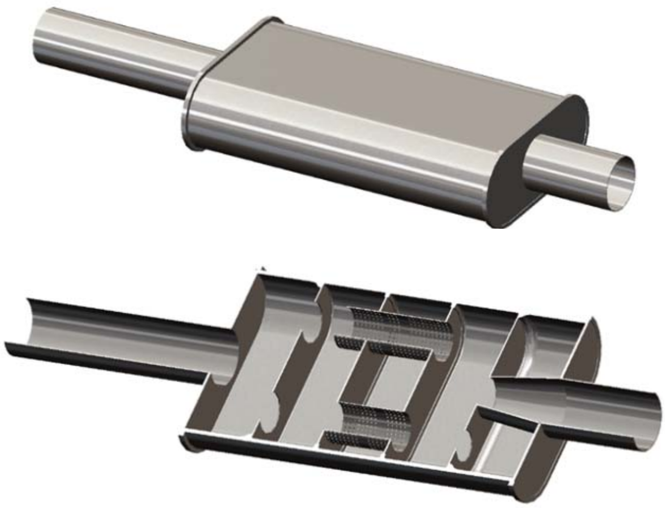

Figure 1 Exhaust system designed for hydrogen combustion applications

This exhaust system comprises an inlet pipe connected to a dual-chamber resonator featuring a symmetrical baffle to ensure uniform gas flow. The exhaust gases subsequently pass through a compression perforated tube and an expansion perforated tube situated within the absorption section. This section aids in reducing acoustic noise and in capturing condensate droplets. The exhaust gases are then directed to a catalyst specifically engineered for nitrogen oxide reduction, optimised for high water vapour content (Figure 2).

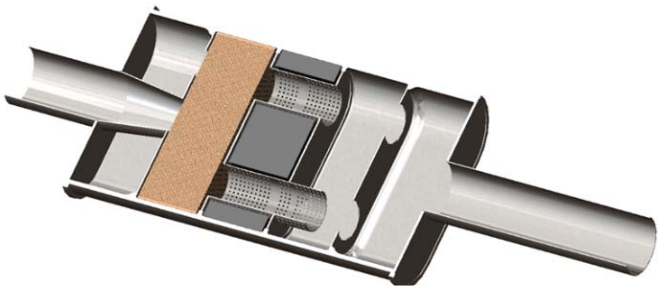

Figure 2 Comprehensive architecture of the designed exhaust systém

The outlet pipe is connected to the catalyst through an asymmetrical baffle, which separates the expansion chamber from the catalyst and serves to regulate backpressure wave propagation. At the transition area, a reverse cone is installed. Its narrowest diameter matches that of the perforated pipes, thereby ensuring balanced exhaust flow and preventing condensation (Figure 3).

Figure 3 Concept of the reverse cone and perforated tubes

The system concept delivers the following functional advantages:

- Reduction of NO_x emissions through a specialised catalytic system,
- Minimisation of water vapour condensation via controlled thermal flow and corrosion-resistant materials,
- Noise attenuation through the integrated resonator and absorber sections,
- Improved combustion efficiency by favourable redistribution of backpressure waves that support stable and homogeneous hydrogen combustion.

The proposed exhaust system for hydrogen combustion engines represents an innovative solution that specifically addresses the characteristics of hydrogen exhaust gases - particularly their high water vapour content, absence of carbonaceous compounds, and tendency to produce nitrogen oxides (NO_x) at elevated temperatures. The system's design prioritises a multi-functional approach: ensuring efficient exhaust flow, reducing harmful emissions, suppressing acoustic noise, and mitigating condensation and corrosion of system components.

This system is particularly applicable to light- and medium-duty automotive transport, where it offers an attractive compromise between the retention of conventional engine architecture and the requirements of carbon-neutral propulsion. With the anticipated expansion of hydrogen combustion engine technologies during the transitional phase of transport sector decarbonisation, this exhaust solution provides a practical and technologically feasible alternative for reducing environmental impact.

4. CONCLUSIONS

This study presents an exhaust system optimised for the specific requirements of hydrogen internal combustion engines. The system concept integrates multiple functional components, including a resonator chamber, an absorption section, a specialised NO_x catalyst, and an expansion chamber with a reverse cone. These elements collectively contribute to the reduction of nitrogen oxide formation through controlled temperature management and an efficient catalytic process. Simultaneously, the system mitigates water vapour condensation by means of thermal flow regulation and the use of corrosion-resistant materials.

Additional benefits include improved acoustic properties and support for stable and efficient hydrogen combustion. The findings suggest that a well-designed exhaust system can significantly contribute to the safe, reliable, and environmentally friendly operation of hydrogen-fuelled combustion engines.

Future research will be focused on the numerical optimisation of individual components and experimental validation under real-world operating conditions.

References

1. Choudhary V., Ghosh A., Banerjee R. : Design Considerations for Exhaust Systems in Hydrogen-Fueled Internal Combustion Engines, International Journal of Hydrogen Energy, Volume 45, Issue 55, 2020, Pages 30572–30583.
2. Kumar A., Singh D., Sinha S. : A Review on NO_x Emissions from Hydrogen Fueled Internal Combustion Engines and Their Control Strategies, Renewable and Sustainable Energy Reviews, Volume 143, 2021, Article No. 110911.
3. Tarkowski R. : Hydrogen-Driven Transport Systems: Environmental and Technical Challenges, Energies, Volume 15, Issue 4, 2022, Article No. 1120.
4. Tian H., Li J., Gao Y. : Thermal Management and Waste Heat Recovery Technologies for Hydrogen Internal Combustion Engines, Energy Reports, Volume 6, 2020, Pages 3278–3289.
5. Verhelst S., Wallner T. : Hydrogen-Fueled Internal Combustion Engines, Progress in Energy and Combustion Science, Volume 35, Issue 6, 2009, Pages 490–527.
6. Hiroyuki Yamada, Rumiko Hayashi, Kenichi Tonokura : Simultaneous measurements of on-road/in-vehicle nanoparticles and NOx while driving: Actual situations, passenger exposure and secondary formations, Science of The Total Environment, Volumes 563–564, 1 September 2016, Pages 944-955
7. W.A. Simmons, P.W. Seakins : Estimations of primary nitrogen dioxide exhaust emissions from chemiluminescence NOx measurements in a UK road tunnel, Science of The Total Environment, Volume 438, 1 November 2012, Pages 248-259
8. K.M. Fameli, V.D. Assimakopoulos: Development of a road transport emission inventory for Greece and the Greater Athens Area: Effects of important parameters, Science of The Total Environment, Volume 505, 1 February 2015, Pages 770-786
9. Xiangyu Feng, Yunshan Ge, Chaochen Ma, Jianwei Tan, Xin Wang : Experimental study on the nitrogen dioxide and particulate matter emissions from diesel engine retrofitted with particulate oxidation catalyst, Science of The Total Environment, Volume 472, 15 February 2014, Pages 56-62
10. Bendu H, Murugan S. Homogeneous charge compression ignition (HCCI) combustion: mixture preparation and control strategies in diesele ngines. Renew Sustain Energy Rev 2014; 38: 732–46.