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Turbulent Combustion of zero-carbon fuels

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Combustion is the process of controlled burning of a fuel to produce heat and energy. It is widely used in industries such as power generation, transport, manufacturing and construction. For example, it powers engines in road vehicles and aircraft, produces electricity in power stations, and generates heat for industrial processes such as producing steel or cement. Because it plays such a central role in modern life, it is important to understand and improve how combustion works. In addition, sound is an unwanted but inevitable by-product of combustion and can lead to detrimental effects on engine hardware, even resulting in complete engine disintegration. By computationally modelling combustion, engineers can test ideas virtually, improve fuel efficiency, reduce pollution, and design cleaner, more effective and safer systems without relying on costly or risky real-world experiments.

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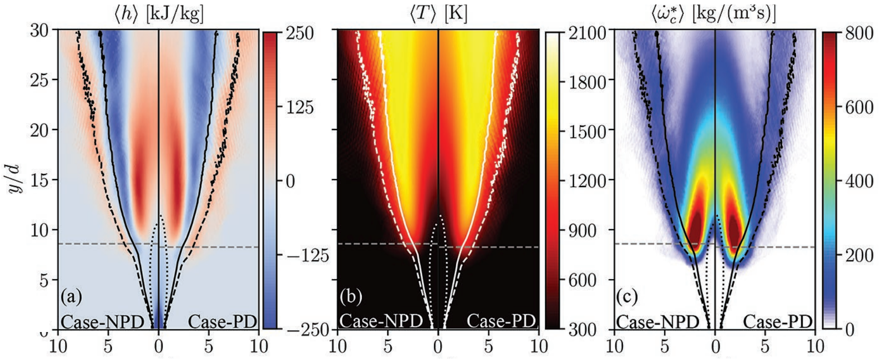
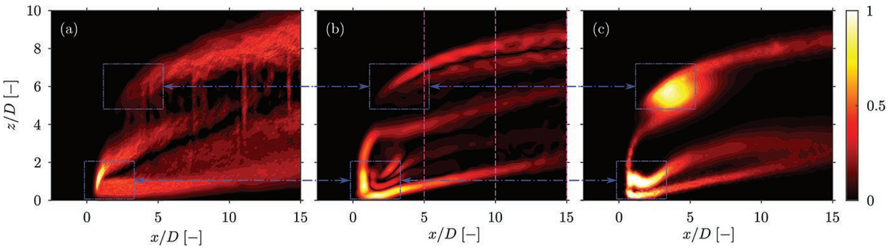


Since hydrogen is lighter than oxygen and nitrogen in air, it can diffuse faster, creating additional challenges for modelling of hydrogen combustion with differential diffusion (DD) effects. However, the figure on the left demonstrates that these challenges can be ignored while computing combustion in practical systems as DD effects are small. Further details can be found in the paper published in the Combustion and Flame journal paper (ref. 4). Avoiding the use of additional models for DD effects for practical systems can yield substantial savings in computation cost as discussed in the International Journal of Hydrogen Energy paper currently under review (ref. 14).



A comparison of computed and measured (using laser diagnostics) hydrogen flames in a jet-in-cross flow configuration. A very good comparison is seen and further details are in the papers published in the International Journal of Hydrogen Energy (ref. 10) and Journal of Fluid Mechanics (ref. 8 & 9).

Researchers from the Department of Engineering at the University of Cambridge, led by Prof. Swaminathan, were awarded an ARCHER2 Pioneer Project grant to advance research on hydrogen as a low-carbon fuel, and explore the use of machine learning for combustion modelling. Hydrogen is increasingly recognised as a critical component of future energy systems aiming to reduce carbon emissions. However, safely and efficiently using hydrogen in engines and turbines remains challenging due to its high reactivity and distinct combustion characteristics compared to traditional fuels.

This research investigates the potentials of blending hydrogen with small amounts of methane to address these challenges. It examines fuel behaviour when injected into a fast-moving air stream, a condition relevant to modern gas turbines and advanced and modern combustion systems. In addition, it explores the use of machine learning to accelerate high-fidelity simulations to inform modern combustor design.

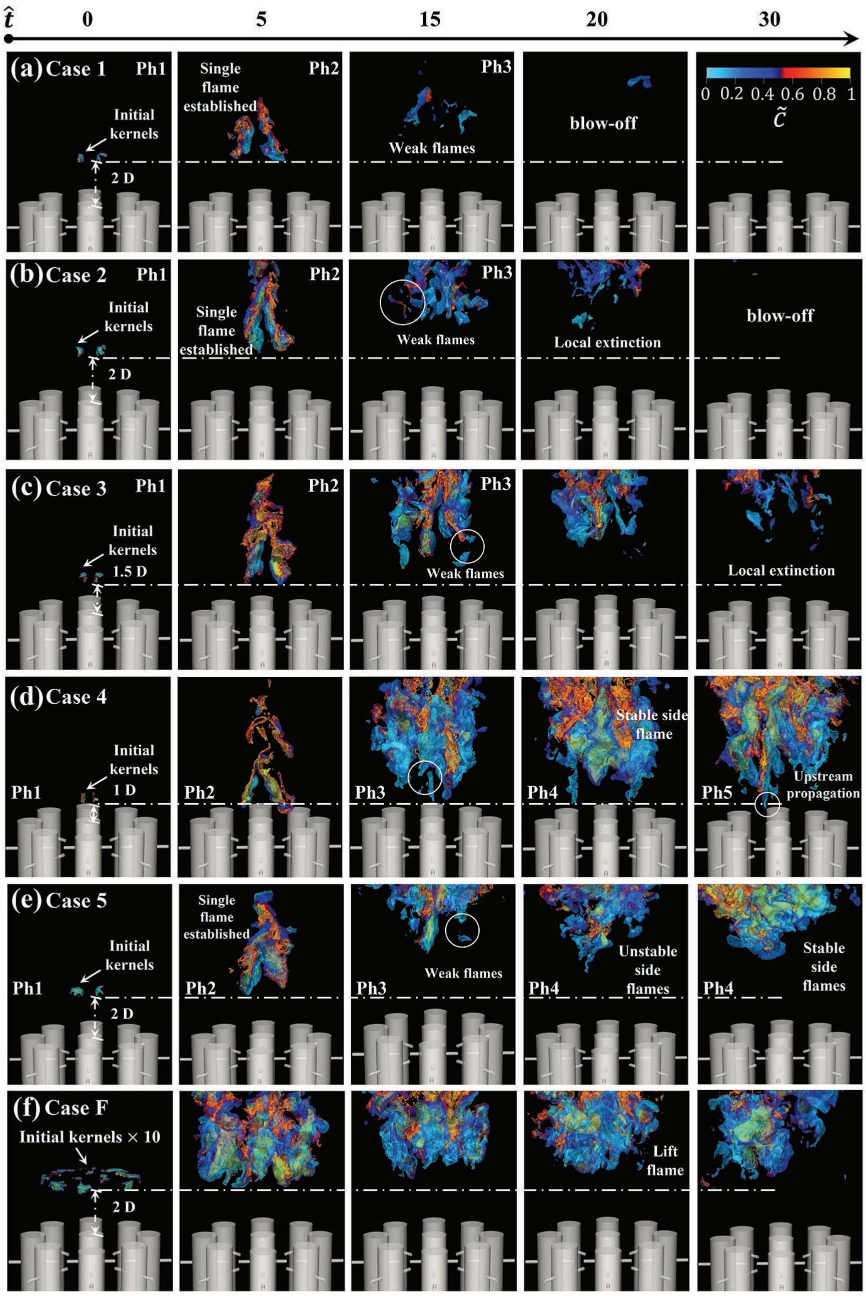
The findings of this study enhance understanding of how such blended fuels burn and how flames respond under varying conditions. This knowledge will inform the design of next-generation engines that deliver low emissions and can accommodate changing fuel compositions. As efforts towards net zero intensify, these insights play key roles in developing cleaner and more adaptable hydrogen-based energy technologies.

In addition, the project has generated open-access datasets (referenced in the publications listed on page 4) that are used by researchers internationally. Open access publishing enhances the visibility and dissemination of research by removing paywalls, leading to higher usage. It also facilitates educational reuse and promotes public engagement, allowing professionals outside academia to benefit from the latest findings.[1]

Overall, the project aimed to provide computationally efficient, robust and accurate combustion models, specifically for future low- and zero-carbon fuels, and to support the development of lower-emission gas turbines for power generation and aviation. These models can also be leveraged to develop future engines for road and marine transport. Combustion-induced noise is going to be an important differentiator for future aero engines since noise levies by airports are on the horizon. Simulations using the high-fidelity models can be used to estimate these noise levels, which can then inform the design of quieter engines.

The models developed and tested in this project are used by gas turbine manufacturers in the UK and overseas to inform and support their design decisions. In one case, an overseas company reported savings of approximately two million pounds, and a year in engine development resources, by using these tools. The simulations help industry users identify performance issues before engines are built, which can reduce the need for physical prototypes, and lead to substantial cost savings. Helping airlines to limit noise and emissions brings significant benefits. These simulations aim to design engines which run more smoothly and quietly, reducing the social and environmental impacts, and helping airline companies that are taxed according to the noise and emissions from their aeroplanes.

1. Cambridge University Press (n.d.). Benefits of open access. Retrieved June 17, 2025, from **https://www.cambridge.org/core/open-research/open-access/benefits-of-open-access**



This figure shows the success or failure of ignition leading to complete light-around resulting in a successful flame inside the combustion chamber with 9 burners. This is a flagship simulation from this project, and the results are under review for publication in Combustion and Flame (ref.11, 13), and Proceedings of the Combustion Institute Journals (ref.12).

Acknowledgement:

- ARCHER2 Pioneer Project e808: Investigations of zero-carbon fuels turbulent combustion
- Mitsubishi Heavy Industries, Ltd., Takasago, Japan

Journal articles:

The research carried out in this project has already led to 14 papers and many conference papers.

1. Y. Liu, J. C. Massey, F. Faldella, Y. Tanaka and N. Swaminathan (2026). Large eddy simulation of lean premixed hydrogen/methane Bunsen flames: effects of hydrogen content and pressure. Flow Turbul. Combust. 116, 33, 24 pages (**https://doi.org/10.1007/s10494-026-00730-6**).

2. A. D. Kumar, P. R. Soundararajan, C. J. Li, J. C. Massey, N. Swaminathan (2026). Characteristics of heat release rate spectra in turbulent flames with different fuels. Fuel, 415, 138409 (**https://doi.org/10.1016/j.fuel.2026.138409**).

3. A. B. Murugavel, J. C. Massey, N. Swaminathan. Effects of pressure and hydrogen enrichment with methane in a reacting jet in crossflow. Accepted Combust. Sci. Technol., 09/Sep/2025 (**https://doi.org/10.1080/00102202.2025.2560428**).

4. C. D. K. Schumann, J. C. Massey, Y. Liu, C. J. Li, Y. Tanaka, N. Swaminathan (2026). A priori and a posteriori analysis of differential and preferential diffusion in large eddy simulations of partially premixed hydrogen-air flames. Combust. Flame., 283, 114537 (**https://doi.org/10.1016/j.combustflame.2025.114537**).

5. C. Li, C. D. K. Schumann, R. Dere, J. C. Massey, C. Ezenwajiaku, N. Rocha, M. Talibi, R. Balachandran, Y. Tanaka, N. Swaminathan (2025). Influences of momentum flux ratio and fuel injection on flame stabilisation in a lean direct injection burner. Proc. Combust. Inst., 41, 105956 (**https://doi.org/10.1016/j.proci.2025.105956**).

6. C. D. K. Schumann, J. C. Massey, C. J. Li, N. Swaminathan (2025). Large eddy simulation of transient leading edge propagation in a turbulent lifted hydrogen jet flame. Proc. Combust. Inst. 41, 105827 (**https://doi.org/10.1016/j.proci.2025.105827**).

7. H. Yang, J. C. Massey, N. Swaminathan (2025). Large eddy simulation of turbulent premixed combustion with a data-driven filtered density function model. App. Energy Combust. Sci. 24, 100393 (**https://doi.org/10.1016/j.jaecs.2025.100393**).

8. A. B. Murugavel, J. C. Massey, N. Swaminathan (2025). Pressure effect on mixing and combustion mode of a hydrogen/helium jet in crossflow. J. Fluid Mech, 1017, A3, 29 pages (**https://doi.org/10.1017/jfm.2025.10416**).

9. A. D. Kumar, J. C. Massey, A. B. Murugavel, Z. X. Chen, N. Swaminathan (2025). Spectral characteristics of the heat release rate in turbulent flames. J. Fluid Mech. 1007, A29, 31 pages (**https://doi.org/10.1017/jfm.2025.56**).

10. A. B. Murugavel, J. C. Massey, Y. Tanaka, N. Swaminathan (2024). The effect of methane addition on reacting hydrogen jets in crossflow. Int. J. Hydrogen Energy, 80, 57-67 (**https://doi.org/10.1016/j.ijhydene.2024.07.014**).

11. C. J. Li, R. Dere, J. C. Massey, B. Cosway, C. Ezenwajiaku, C. D. K. Schumann, M. Talibi, R. Balachandran, Y. Tanaka, N. Swaminathan. Flame blow-off correlation for lean direct injection hydrogen burners. Submitted to Combust. Flame 27/Jan/2026.

12. C. J. Li, C. D. K. Schumann, J. C. Massey, Y. Tanaka, N. Swaminathan. Flame propagation and lighting sequence in a cluster of hydrogen LDI burners. Submitted to Proc. Combust. Inst. (41st Symp), 11/Nov/2025 (accepted for ISOC2026).

13. H. Yang, J. C. Massey, N. Swaminathan. JPResUnet: A Joint Probability Density Function Translation Model in Partially Premixed Flames. Submitted to Combust. Flame 23/Feb/2026.

14. C. D. K. Schumann, Ca. J. Li, Y. Tanaka, N. Swaminathan, J. C. Massey. Differential and preferential diffusion effects in LES of a hydrogen LDI burner. Submitted to Int. J. Hydrogen Energy, 24/Feb/2026.

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About ARCHER2

ARCHER2 is the UK's National Supercomputing Service, a world class advanced computing resource for UK researchers. ARCHER2 is provided by UKRI, EPCC, HPE and the University of Edinburgh. ARCHER2 is the latest in a series of National Supercomputing Services provided to UK researchers.

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https://www.archer2.ac.uk/research/case-studies/

This project was an **ARCHER2 Pioneer Project**, awarded by UKRI to conduct computationally intensive modelling, simulation and calculations to deliver ambitious and pioneering projects.