

October 23 & 24

COMBURA



NVV  2023

Book of Abstracts

NVV 
Nederlandse Vereniging
voor Vlamonderzoek



Combura 2023

October 23 & 24, 2023

Domusdela, Eindhoven, The Netherlands

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A. GENERAL INFORMATION

The COMBURA symposium stands as a pivotal annual event fostering the exchange of insights within combustion research and its tangible applications in the Netherlands. It is an initiative of the Nederlandse Vereniging voor Vlamonderzoek NVV (Netherlands Association for Flame Research).

This year the general theme is ***Impact of open research on industrial combustion***. Participants from universities, research institutes, and industrial companies in the Netherlands and surrounding countries are invited.

The COMBURA event starts in the late afternoon of October 23rd with the NVV Members Meeting followed by the COMBURA conference dinner.

On October 24th, a symposium is held with various type of lectures and workshops. The COMBURA theme is addressed in different ways: by plenary lectures on combustion technologies with high industrial relevance, by contributions of industrial researchers on problems they want to bring in focus, and by a workshop offering joint discussion and hands-on experience with the industrial problems solving.

Program Committee

- Francesca De Domenico, Delft University of Technology
- Domenico Lahaye, Delft University of Technology
- Jeroen van Oijen, Eindhoven University of Technology
- Dirk Roekaerts, Delft University of Technology

Organizing Committee

- Domenico Lahaye, Delft University of Technology
- Marjan Beekmans, Eindhoven University of Technology

CONTACT

For any question regarding the Symposium: contact Marjan Beekmans at m.beekmans@tue.nl

B. PROGRAM

(Version available one week before the meeting was held)

Plenary session

- 8:45 WELCOME
9:00-9:40 KEYNOTE LECTURE by **Anh Khoa Doan**
MILD Combustion: overview of current research and challenges
9:40-10:20 KEYNOTE LECTURE by **Christine Rousselle**
Ammonia, the other hydrogen for clean thermal applications
10:20-10:40 *Break (Coffee, tea, soft drinks, snacks)*

10:40-11:40 INDUSTRIAL COMBUSTION PROBLEMS, part I

The session on industrial combustion problems wishes to promote the dialogue between industry and academia. In the first part, challenges in the operation and design of industrial furnaces are explained by three industrial partners:

Christine Bertrand (Origen Carbon Solutions): Vertical shaft convertor for the calcination of lime.

Sethu Ramalingan (Danieli-Corus): Furnaces for the production of hot blast used as preheated oxidizer for hot blast stoves used in the production of steel.

Dmitry Gyrontsev (CelSian): Furnaces for the production of glass.

11:40-13:00 Poster session

13:00-13:45 *Lunch*

Parallel sessions

14:00-15:00 Oral presentations and workshop in parallel sessions

15:00-15:20 *Break (Coffee, tea, soft drinks)*

15:20-16:20 Oral presentations and workshop in parallel sessions

In the workshop on INDUSTRIAL COMBUSTION PROBLEMS Combura participants can learn and join the discussion on how to best address the challenges of industrial combustion.

More information can be found at: <https://tinyurl.com/Combura-2023-workshop-updates>

Plenary session

16:30-17:00

The results and recommendations of the industrial combustion workshop will be reported. Then, the winner of the NVV Combustion Award 2023 will be announced. This award is given to the young expert with the best Master Thesis in the field of combustion technology. Finally, the three best posters presented at the symposium will receive an award from the Dutch Section of the Combustion Institute (DSCI).

ORAL PRESENTATIONS AND WORKSHOP

	SESSION I	SESSION II	SESSION III
14:00-14:20	Gabriela Sanchez	Claudia-Francisca Lopez-Camara	WORKSHOP ON INDUSTRIAL COMBUSTION PROBLEMS
14:20-14:40	Victor Vloeberghs	Kaushal Dave	
14:40-15:00	Diego Quan	Stijn van Rijn	
15:00-15:20	BREAK	BREAK	BREAK
15:20-15:40	Maria Rosaria Acquaviva	Jesse Hameete	WORKSHOP ON INDUSTRIAL COMBUSTION PROBLEMS
15:40-16:00	Patrick Hemmen	Mark Hulsbos	
16:00-16:20	Jesse Hofsteenge	Shyam Sundar Hemamalini	

C. ABSTRACTS OF KEYNOTE LECTURES

Keynote lecture 1

By **Anh Khoa Doan**, Assistant Professor in AI for Fluid Mechanics, Aerospace Engineering, Delft University of Technology.

MILD Combustion: overview of current research and challenges

Moderate or Intense Low-oxygen Dilution (MILD) combustion (also called flameless combustion) has been a topic of research for the last few decades thanks to its potential in reducing pollutant emissions such as NO_x. Such combustion regime is achieved by a combination of preheated reactants and low O₂ concentrations and is then generally characterized by lower peak temperatures and distributed reaction zones, thereby decreasing temperature gradients, acoustic oscillations, and NO_x emissions. Despite the more than 25 years since the first description of this combustion regime, several aspects of MILD combustion remain to be fully understood preventing the wider application of such combustion regime to, for example, gas turbines.

In this talk, the fundamental aspects of MILD combustion will be first introduced. Then an overview of recent research will be presented focusing on: (i) works that attempted to provide a rigorous definition of what constitutes the MILD combustion regime, (ii) experimental configurations which achieved MILD combustion conditions and (iii) efforts in the development of accurate numerical model for the simulation of MILD combustion.

Keynote lecture 2

Christine Rousselle, University of Orléans

Ammonia, the other hydrogen for clean thermal applications

The objective to reach neutral carbon footprint in 2050 accelerates the energy transition. Industries and scientists collaborate for developing zero CO₂ emission solutions for all energy sectors: power, transport and industry. Hydrogen and hydrogen derived fuels, 'e-fuels' will play an important role. Ammonia, one of the simplest electro fuels, is a promising candidate as energy and hydrogen carrier, but it can also be used directly as a zero-carbon fuel, pure or mixed with hydrogen or biofuels. However, the combustion properties of ammonia are far from those of conventional fuels and are not well known. During this talk, the state of art of ammonia combustion will be presented with focus on the remaining challenges. Both fundamental aspects and application issues will be addressed.

D. LIST OF ORAL PRESENTATIONS

(Alphabetical order according first author's name)

Effect of high strain on hydrogen ultra-lean premixed flamelet

Maria Rosaria **Acquaviva**, Ivan Langella
Delft University of Technology

Investigation of size-informed droplet transport using Mie-scattered imaging and Interferometric particle imaging

Kaushal **Dave**, Francesca De Domenico, Fulvio Scarano, Arvind Gangoli Rao
Delft University of Technology

Particle resolved hyperspectral pyrometry measurements of burning iron particles

Jesse **Hameete**, Muhammed Abdallah, Leon Thijs, Tess Homan, XiaoCheng Mi, Nico Dam, Philip de Goey
Eindhoven University of Technology

Modelling the interaction of burning iron particles and turbulence

Shyam Sundar **Hemamalini**, Jeroen van Oijen, Benedicte Cuenot, XiaoCheng Mi
Eindhoven University of Technology

Flame Flashback Behavior when Subjected to Pressure Peak at Ignition Conditions - Comparison Between Hydrogen and Metha

Patrick **Hemmen**
Bosch Thermotechniek B.V.

Numerical Analysis of Sensitivity of Cyclone Burner FTF to Swirl Intensity Variation

Jesse **Hofsteenge**, Jim Kok
University of Twente

Burning velocity measurements for flat hybrid iron-methane-air flames

Mark **Hulsbos**, R.T.E. Hermanns, R.J.M Bastiaans, L.P.H. de Goey
Eindhoven University of Technology

Gas-phase synthesis of iron oxide nanoparticles produced via diffusion flames

Claudia-Francisca **Lopez-Camara**, Juliana Davoglio Estradioto, Sabrina Schleich, Paolo Fortugno, Hartmut Wiggers
University of Duisburg-Essen; Northwestern University

DNS and LES of temporal mixing layers of hydrogen combustion for the Argon Power Cycle

Diego **Quan**, Alessandro Ballatore, Jeroen van Oijen
Eindhoven University of Technology

The effect of hydrogen addition on the wavelength depending absorption of combustion generated nanoparticles from premixed ethylene flames

Stijn **van Rijn**, Merel van Helten, Martijn Goudberg, Anatoli Mokhov, Ulrike Dusek
University of Groningen

Effect of temperature and pressure on lean turbulent hydrogen flames

Gabriela **Sanchez**, Jeroen van Oijen
Eindhoven University of Technology

LES of lifted hydrogen flame through transported PDF method

Victor **Vloeberghs**, Gioele Ferrante, Ivan Langella, Dirk Roekaerts
Delft University of Technology

E. LIST OF POSTER PRESENTATIONS

(Alphabetical order according first author's name)

Large Eddy Simulation of a Lean Premixed Swirl-Stabilized Combustor

Giacomo Abbasciano, Gioele Ferrante, Ivan Langella, Arvind Gangoli Rao
Delft University of Technology

Investigation of dual fuel (methanol/diesel) setup for industrial diesel engine

Frank Ahout, Edward Goossens, Bahram Nourani
HAN University of Applied Sciences

FGM modelling of H₂-Ar-O₂ turbulent reacting mixing layers

Alessandro Ballatore, Jeroen van Oijen
Eindhoven University of Technology

Reactor Modeling of Hydrogen Flash Reduction of Magnetite particles

Bharat Bhatia, Benedicte Cuenot, Jeroen van Oijen, XiaoCheng Mi
Eindhoven University of Technology

Combined effect of strain and water injection in lean premixed hydrogen flamelets

Biagio Cassese, Alessandro Porcarelli, Ivan Langella
Delft University of Technology

Numerical characterization of high-pressure hydrogen injections for compression-ignition engines

Nick Diepstraten, Bart Somers, Jeroen van Oijen
Eindhoven University of Technology

1D Acoustic Network Modelling of a Cyclone Burner with Different Swirl Numbers Using taX Software

Berksu Erkal, Jim Kok
University of Twente

A high fidelity simulation framework for intensified biomass gasification

Anna Felden, Wiebren De Jong
Delft University of Technology

Iron particles ignition in hot coflow

Giulia Finotello, Yuri Shoshin, Philip De Goey, Muhammed Abdallah
Eindhoven University of Technology

BALANS: Renewable Heat And Power From Non-Woody Biomass

Jing Fu, Artur Pozarlik, Amir Mahmoudi, Huub Ratering
University of Twente; HoST

Reconstruction of downstream acoustics from two separate SISO measurements of flame

Hamed F. Ganji, Viktor Kornilov, Jeroen van Oijen, Ines Lopez Arteaga
Eindhoven University of Technology

Analysis of combusted iron powder using X-ray computed tomography

Conrad Hessels, Giulia Finotello, Xiaocheng Mi, Roy Hermanns, Philip de Goey
Eindhoven University of Technology

Experimental and Numerical Investigation of a diffusion burner with CO₂ Dilute Oxy-Combustion of Natural Gas and Hydrogen

Nicolas Jouret
KU Leuven

Effect of ammonia blending in strained lean premixed hydrogen flamelets

Ribhav Khanduja, Alessandro Porcarelli, Ivan Langella
Delft University of Technology

AmmoniaDrive: Ignition Delay Time and Burning Velocity of Ammonia/Anode-Off-Gas mixtures

MohammadReza Kohansal, Rob Bastiaans, Anatoli Mokhov
University of Groningen; Eindhoven University of Technology

Non-catalytic methane steam reforming

Yang Li, Aravind Purushothaman Vellayani, Anatoli V. Mokhov
University of Groningen

Modeling on the flame propagation characteristics of ammonia/hydrogen/air mixtures

Xin Liu, Rob Bastiaans
Eindhoven University of Technology

Super (critical) Combustion

Sylwia Oles
University of Twente

Mixing characterization of high-pressure H₂ jets using LIF and Rayleigh scattering

Max Peters, Noud Maes, Nico Dam, Hugo Quintens, Michele Bardi, Jeroen van Oijen
Eindhoven University of Technology; IFPEN

Reduce Carbon and NO_x Emissions while Increasing Heater Profitability with New Technology

Erwin Platvoet
XRG Technologies LLC, USA

Characterising the Burning Velocity of Iron Powder using a V-shaped Burner

Helen Prime, Yuriy Shoshyn, Roy Hermanns, Philip de Goey
Eindhoven University of Technology

Characterization of iron particle temperatures in a 200kW boiler system

Niek van Rooij, Yuriy Shoshyn, Philip de Goey
Eindhoven University of Technology

Lean Blow-off behavior of flames with different Lewis numbers

Tong Su, Nicolas Worth, Boyan Xu, Rob Bastiaans
Eindhoven University of Technology

Design of Experiments optimized combustion and emissions for OME-diesel blends

Zhongcheng Sun, Harold van Beers, Michel Cuijpers, Bart Somers, Noud Maes
Eindhoven University of Technology

To probe the internal structure and composition of burning iron particles via interceptive quenching

Wenjiang Tian, Muhammed Abdallah, Jesse Hameete, Yuriy Shoshin, XiaoCheng Mi
Eindhoven University of Technology

An experimental study on fire propagation characteristics of lithium iron phosphate batteries

Wang Qinzheng, Huaibin Wang, Chengshan Xu, Changyong Jin, Xuning Feng
Beijing Institute of Technology; Tsinghua University; Chinese People's Police University; University of Shanghai for Science and Technology

CFD studies of ammonia/hydrogen flames in gas turbines

Shuzhan Wang, Krtin Kala, Xin Liu, Rob Bastiaans
Eindhoven University of Technology

F. ABSTRACTS

(Alphabetical order according first author's name)

Acquaviva
Cassese
Dave
Erkal
Ganji
Hameete
Hemamalini
Hemmen
Hofsteenge
Hulsbos
Khanduja
Lopez-Camara
Quan
van Rijn
Sanchez
Vloeberghs
Wang Q.

EFFECT OF HIGH STRAIN ON HYDROGEN ULTRA-LEAN PREMIXED FLAMELET

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Abstract

The current interest in hydrogen as a clean fuel as well as hydrogen blends has revealed an important feature of hydrogen flames, namely its behaviour under intensive strain [1]. Indeed, hydrogen addition has been shown to delay the extinction strain rate and to widen the flammability limits [2], indicating that hydrogen is able to sustain very high strain rates, which is a result of the peak of heat release rate increasing with strain. Moreover, for syngas fuels, it has been found that hydrogen percentage influences the lean flame response with strain in terms of NO_x emissions and consumption speed [3]. In particular, in lean conditions the consumption speed is shown to increase with strain, which is the opposite behaviour observed for hydrocarbon flames. Nevertheless, it is still unclear how strain affects hydrogen flame and NO_x emissions especially at very ultra-lean condition. This motivates the present work which aims at numerically investigating the behaviour of lean premixed laminar hydrogen flames under high level of strain, and its effect on NO_x emissions.

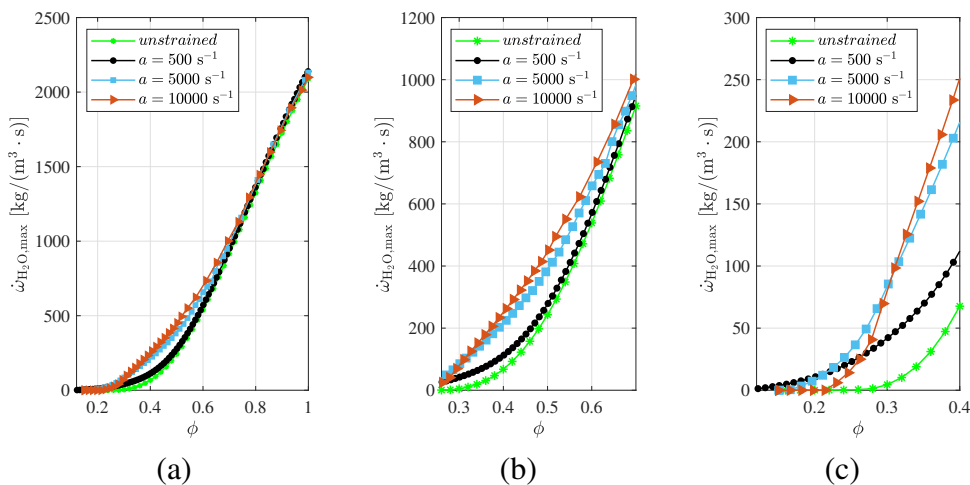


Figure 1. (a) Peak of water vapour reaction rate $\dot{\omega}_{\text{H}_2\text{O}}$ as a function of equivalence ratio ϕ for unstrained and three different values of applied strain rates a . (b) Zoom around the ultra-lean zone and the extinction zone (c).

The reactant-to-product configuration is used for this purpose. The one-dimensional simulations are performed with the code CHEM1D where the reaction kinetics is modeled with the UCSD mechanism modified with the mechanism from Capurso *et al.* [4] for NO_x prediction. Computation are performed for three different values of the applied strain rate a , namely 500 s^{-1} , 5000 s^{-1} , 10000 s^{-1} for a range of lean equivalence ratios ϕ . Figure 1 indicates the lean flammability limit in terms of peak of H_2O reaction rate $\dot{\omega}_{\text{H}_2\text{O}}$. Depending on the value of the equivalence ratio, three different behaviours can be noticed. At values of the equivalence ratio within the range $0.7 \leq \phi \leq 1$ (Figure 1-(a)),

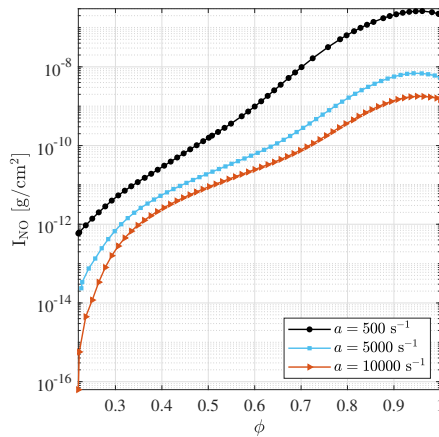


Figure 2. Density-weighted NO integral I_{NO} as a function of the equivalence ratio ϕ for different applied strain rates a .

the peak reaction rate is weakly affected by the strain. On the contrary, for intermediate values of equivalence ratio (Figure 1-(b)), the peak reaction rate significantly increases as the strain rate increases as has observed in [1]. One would then expect that the effect of strain would be to lower the lean flammability limit. Nevertheless, an inversion of trend is observed (Figure 1-(c)) which is related to the different behaviour of radicals under the strain near the extinction.

Next, NO_x emissions are quantified in terms of density-weighted NO integral across the flamelet, for different applied strain rates (Figure 2). As can be noted, the ultra-lean condition combined with high strain strongly pushes down NO_x level. For a fixed strain rate, lower NO values are observed for leaner conditions, which is consequence of the lower adiabatic flame temperature, as one would expect. On the other hand, the reduction of NO with strain rate is still observed as found in [1]. Such reduction appears to be stronger around the ultra-lean side, where the slope of the curve become steeper as strain increases due to the approaching extinction. These observations suggest that strain affect the hydrogen flame differently depending on the equivalence ratio and these behaviours are further studied in this work.

Reference

- [1] A. Porcarelli, B. Kruljević, and I. Langella, "Suppression of NOx emissions by intensive strain in lean premixed hydrogen flamelets," *International Journal of Hydrogen Energy*, 2023.
- [2] G. S. Jackson, R. Sai, J. M. Plaia, C. M. Boggs, and K. T. Kiger, "Influence of H2 on the response of lean premixed CH4 flames to high strained flows," *Combustion and Flame*, vol. 132, no. 3, pp. 503–511, 2003.
- [3] D. Ning, A. Fan, and H. Yao, "Effects of fuel composition and strain rate on NO emission of premixed counter-flow H2/CO/air flames," *International Journal of Hydrogen Energy*, vol. 42, no. 15, pp. 10 466–10 474, 2017.
- [4] T. Capurso, D. Laera, E. Riber, and B. Cuenot, "NOx pathways in lean partially premixed swirling H2-air turbulent flame," *Combustion and Flame*, vol. 248, p. 112 581, 2023.

COMBINED EFFECT OF STRAIN AND WATER INJECTION IN LEAN PREMIXED HYDROGEN FLAMELETS

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Abstract

Lean and strained premixed hydrogen-air flamelets are investigated numerically at lean conditions in a reactants to products counterflow configuration for increasing levels of strain rate and water injected. The amount of water injected is representative of a pre-evaporated stream of droplets. The study shows that, unlike common water injection systems where NO_x suppression is associated to a decrease of flame performance and thermal efficiency, the combination with relatively high strain levels can prevent or limit the performance decrease without incurring in a re-increase of NO_x , particularly in leaner conditions.

Introduction

Burning hydrogen at lean premixed condition, where the adiabatic flame temperature is lower, allows to reduce NO_x emissions, but technological challenges exist. One possibility to stabilise hydrogen in this regimes is to exploit its peculiar response to strain. Hydrogen addition has been shown to delay extinction to higher strain rates [1]. Furthermore, unlike hydrocarbon flames, the consumption speed shows an increasing trend with strain in hydrogen flames [2]. Strain has also proven to be effective in suppressing NO emission [3]. Injection of water steam or droplets is also known to effectively further suppress NO_x [4]. On the other hand, the temperature reduction also implies a decrease of combustion performances. In a previous study by the authors [4], it was shown for one lean burning regime that this efficiency loss can be partially limited exploiting the strengthening property of premixed hydrogen flames under intensive strain. In this study, the analysis is expanded to a leaner hydrogen burning regime, where the more negative Markstein length is expected to further exacerbate the efficiency gain with increasing strain rate.

Model and Setup

Detailed-chemistry one dimensional numerical simulations are performed for pure hydrogen lean and strained flamelets on a reactants-to-products counterflow configuration in CHEM1D. Lean conditions are established for two equivalence ratios of $\phi = 0.5$ and 0.7 . Strain rates range from $a = 100 \text{ s}^{-1}$ to $a = 10000 \text{ s}^{-1}$, while water molar fractions range from 1% to 4% in the "wet" cases. Water is injected as a steam of pre-evaporated droplet into the reactants boundary. The reactants temperature in the "dry" case is fixed at 400K and decreases with water molar fraction in the "wet" cases [4]. GRI3.0 mechanism is used for the kinetic data with a mixture-averaged diffusion model.

Results

As shown in previous works and reported in figure 1, NO_x emissions display a decreasing trend with strain [3] and water molar fractions [4] for the $\phi = 0.7$ case in terms of density-weighted NO integral, which is defined as $\int_{-L/2}^{L/2} \rho Y_{\text{NO}} dx$. Even if the decrease with strain is less steep, Figure 2 shows that for the $\phi = 0.5$ case a similar trend is observed.

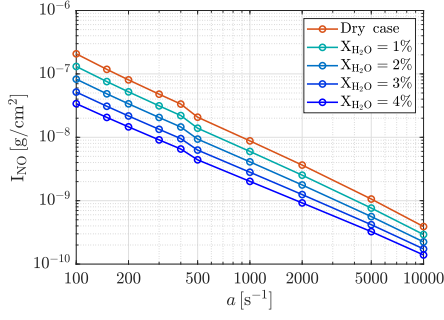


Figure 1. I_{NO} for $\phi = 0.7$

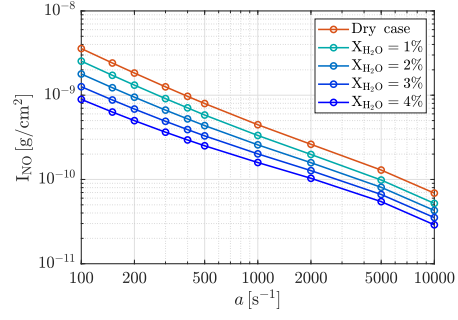


Figure 2. I_{NO} for $\phi = 0.5$

While steam injection is beneficial for NO_x emissions mitigation, it also leads to lower peak reaction rates, here analysed considering a water based progress variable $c = Y_{\text{H}_2\text{O}}/(Y_{\text{H}_2\text{O}})_{\text{max}}$. This occurrence can be observed at a fixed strain rate in figures 3 and 4 for both the regimes investigated. On the other hand, the contour plots also show that strain can be used to re-increase the peak reaction rates of the wet cases to the one of the dry unstrained case. However, as already discussed in previous studies [4], for the $\phi = 0.7$ case this is possible only for a limited amount of steam injected, i.e. up to $X_{\text{H}_2\text{O}} = 1\%$. In contrast, the reaction rate re-increase is stronger for the $\phi = 0.5$ case (figure 4), and thus it is possible to achieve and possibly surpass the performance of the unstretched dry case with a higher water injected (up to $X_{\text{H}_2\text{O}} = 4\%$). Similar considerations hold for the consumption speed (not shown). Hence, the combination of intensive strain and water injection in hydrogen flames can be potentially exploited to achieve low emissions while preserving the combustion efficiency.

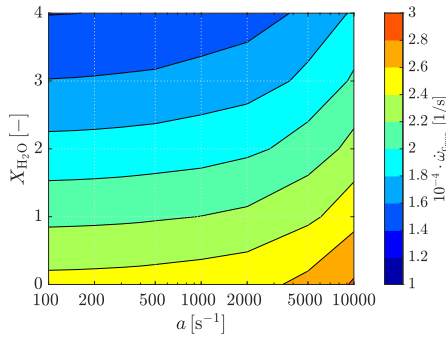


Figure 3. Peak reaction rate at $\phi = 0.7$

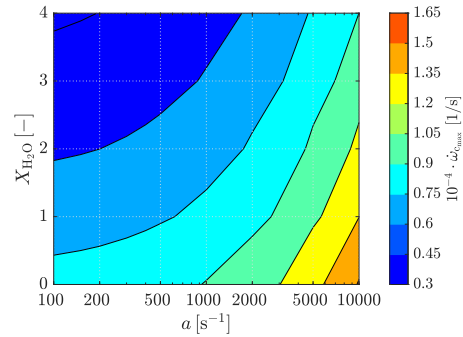


Figure 4. Peak reaction rates at $\phi = 0.5$

References

- [1] G. S. Jackson, R. Sai, J. M. Plaia, C. M. Boggs, and K. T. Kiger, “Influence of h2 on the response of lean premixed ch4 flames to high strained flows,” *Combust Flame*, vol. 132, no. 3, pp. 503–511, 2003.
- [2] J. Van Oijen, A. Donini, R. Bastiaans, J. ten Thije Boonkamp, and L. De Goeij, “State-of-the-art in premixed combustion modeling using flamelet generated manifolds,” *Prog Energy and Combust Sci*, vol. 57, pp. 30–74, 2016.
- [3] A. Porcarelli, B. Kruljević, and I. Langella, “Suppression of nox emissions by intensive strain in lean premixed hydrogen flamelets,” *Int J Hydrogen Energy*, 2023.
- [4] B. Cassese, A. Porcarelli, and I. Langella, “Combined effect of strain and water injection in premixed hydrogen flamelets,” *Submitted to ERCOFTAC Bulletin*, 2023.

INVESTIGATION OF SIZE-INFORMED DROPLET TRANSPORT USING MIE-SCATTERED IMAGING AND INTERFEROMETRIC PARTICLE IMAGING

K.A. Dave, F. De Domenico, F. Scarano and A. Gangoli Rao

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FPT department, Faculty of Aerospace Engineering, Delft University of Technology

Abstract

The aviation industry is seeking the development of H₂-based propulsion systems to align with global net-zero emissions goals by 2050. To be viable in the near future, these systems must exhibit fuel flexibility, accommodating both low-carbon alternative fuels and conventional jet fuels. Our ongoing research at TU Delft focuses on developing a versatile low-NO_x multi-fuel combustor, designed for H₂, kerosene, and their blends. Emissions from spray combustors are intricately tied to fuel atomization quality, necessitating the control of fuel atomization. While qualitative analysis can be conducted through planar imaging, quantitative data, such as droplet size distribution, often requires specialized (expensive) techniques like Phase Doppler interferometry (PDI) and Planar drop-sizing (PSD). This paper introduces an alternative approach that combines simple planar imaging techniques based on Mie-scattering. This method simultaneously measures droplet size and transport, providing an intensity-based relative droplet sizing from Mie-scattered images. This relative sizing is calibrated with actual droplet size distribution obtained from Interferometric Particle Imaging (IPI). To conclude, this work proposes a novel straightforward measurement setup which simplifies spray diagnostics.

Introduction

Amidst the global push to achieve net-zero emissions by 2050, there is an industry-wide effort to develop innovative H₂-based propulsion systems for aviation. To ensure widespread adoption in the short-to-medium term, these new aero-engine technologies must exhibit fuel flexibility, capable of using low-carbon H₂ when available and conventional jet fuels when not. The work discussed here is part of TU Delft's ongoing research focused on developing a low-NO_x multi-fuel combustor. The goal is to design a fuel-agnostic combustor that can efficiently operate with H₂, kerosene, or a combination of both fuels.

While transitioning to H₂ inherently eliminates most emissions associated with combustion, emissions from kerosene combustion are closely linked to the quality of fuel atomization. Therefore, studying and controlling fuel spray properties are crucial for designing and improving the performance of a multi-fuel combustor. Qualitative analysis of fuel sprays can be conducted using planar imaging, but obtaining exact quantitative data, such as droplet size distribution, often requires specialized and costly measurement techniques like Phase Doppler interferometry (PDI) and Planar drop-sizing (PSD) [1].

As an alternative, we propose using a combination of simple planar imaging techniques based on Mie-scattering to simultaneously measure droplet size and study spray transport. This approach extracts droplet transport details (position, velocity, droplet density) and provides intensity-based relative droplet sizing from Mie-scattered images of the spray plume, which are captured with a small magnification and a large field of view. This relative droplet sizing is then correlated with the actual droplet size distribution obtained from Interferometric Particle Imaging (IPI), utilizing images captured with a large magnification and a very small field of view.

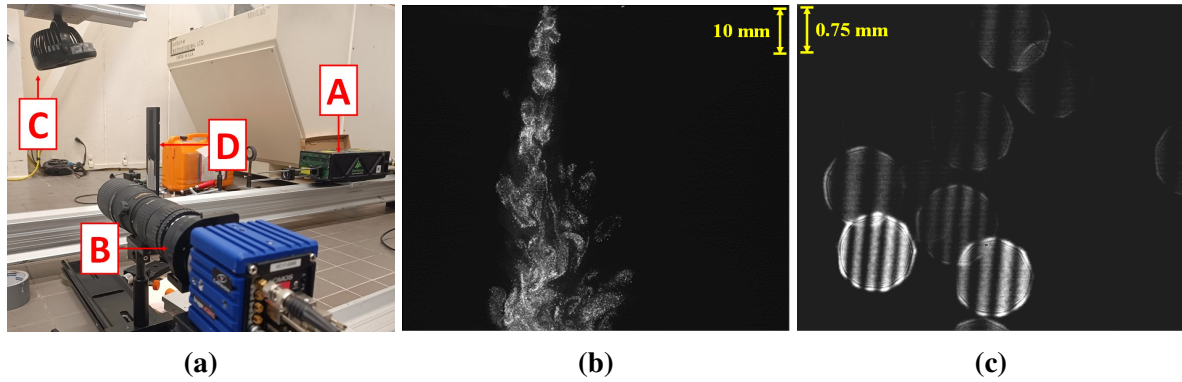


Figure 1. The setup used during the spray measurement campaign including A: Qunatel Nd:YAG 532nm laser mounted with sheet optics, B: sCMOS camera with imaging lenses, C: fan spray and D: knife-edge used to obtain a top-hat laser sheet is shown in **Figure 1a**. **Figure 1b** shows a sample of the Mie-scattered image of the spray plume with fan OFF while **Figure 1c** shows the interference fringe pattern produced by the droplets in case of IPI.

Methodology

The setup used in our spray measurement method is shown in **Figure 1a**. In the Mie-scattered image (see **Figure 1b**), the recorded intensity of scattered light depends on the intensity of the incident light sheet, collection angle, signal attenuation before collection, and the scattering cross-section. Assuming the first three factors are uniformly applied to all the signals collected by the sensor, the peak intensity variation observed in the image can be linked to the scattering cross-section and, consequently, to the droplet diameter. Thus, analyzing the Mie-scattered images with this assumption would yield a relative size distribution of the droplets in the spray being measured. Converting this relative size distribution to the actual droplet diameter requires a calibration measurement, which is made using the IPI technique.

IPI, also known as Interferometric Laser Imaging for Droplet Sizing (ILIDS) in literature, was first proposed by Glover et al. [2]. It also relies on the Mie-scattered signal from the droplets illuminated by a laser sheet and detects the interference patterns between the light reflected from the surface and the light refracted through an individual droplet. The droplet diameter can then be assessed based on the number of fringes recorded in the IPI image (refer **Figure 1c**). This technique has since been used by several researchers, for in-situ measurements in engine environments [3], and for measuring evaporating droplets [4]. Numerical simulators/models for predicting expected fringe patterns as a function of the optical setup and spray characteristics have also been proposed in the literature [5, 6]. The model proposed by Yao et al. [6] will be used for estimating the range of droplet sizes in the fan spray.

Results

The initial processing of the Mie-scattered images showed a dynamic range capability of $8 \cdot D$, where 'D' represents the diameter of smallest individual droplets. The IPI images will provide the actual range of droplet diameters present in the fan spray investigated in this experiment and can be used for calibrating the full spray plume. The combined approach of Mie-scattered imaging and IPI appears promising and is considered superior to either of the techniques applied individually, as it provides a rather simple methodology for in-situ analysis of size-informed droplet transport in a swirl-stabilized combustor.

References

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1D Acoustic Network Modelling of a Cyclone Burner with Different Swirl Numbers Using taX Software

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Abstract

This article addresses the importance of developing early-stage thermoacoustic design capabilities for large furnaces and boilers fueled by gas. As the industry shifts from natural gas to hydrogen, predicting the combustion behavior of these systems becomes challenging, especially when using blends of CH₄ and H₂, which can lead to hard-to-control low-frequency oscillations. Self-sustained oscillations in combustion systems can significantly harm performance, efficiency, emissions, and mechanical components. To predict instabilities in combustion systems effectively, one-dimensional acoustic network modeling based on linear wave equations is proposed. The article explores the application of the taX software to perform one-dimensional acoustic network modeling for a 100 kW cyclone burner, replicating three benchmark cases and simulating three additional models. Additionally, the article investigates the combustion performance of a 60% hydrogen and 40% methane blend in the real test rig, DYNAF, using taX simulations with flame transfer functions derived from CFD simulations for the cyclone burner. This article provides a comprehensive discussion of the results obtained from these simulations.

Introduction

This study investigates the challenges faced by furnaces and boilers using fuel gases, especially as the industry moves from natural gas to hydrogen. When these systems use a blend of CH₄ and H₂, they can experience troublesome vibrations that are hard to control. This is a significant issue because these vibrations can negatively impact system performance, efficiency, and environmental emissions, while also potentially causing damage to system components. To address these challenges, there's a growing need for improved early-stage design techniques for these systems. One promising approach is one-dimensional acoustic network modeling. This modeling method simplifies the understanding of these systems, making it easier to predict and control their behavior. In this study, we utilize the taX software to perform one-dimensional acoustic network modeling on a 100 kW cyclone burner, allowing us to explore its performance [3,4]. Additionally, we examine how a blend of 60% hydrogen and 40% methane behaves in a real testing setup called DYNAF, employing this modeling approach. 1D modelling is performed with n-τ model within the context of network modeling. It explores the concept of a flame transfer function (FTF), which mathematically represents the connection between acoustic disturbances in the combustion chamber and corresponding fluctuations in heat release from the flame. The FTF, described by Eqn.1, where n is amplification factor and time delay is τ. They are determined through CFD simulations.

$$H_f = \frac{Q'}{\phi'} = n \cdot e^{-i\omega\tau} \quad (1)$$

Results and Discussion

the taX software is employed to predict the eigenfrequencies of the Dynaf combustor, using the n- τ model with values obtained from CFD simulations [1]. The experiment involves varying the upstream tube length and swirl numbers, with a focus on understanding their impact on the Flame Transfer Function (FTF). Results show that while increasing tube length tends to slightly lower eigenfrequencies for higher frequencies (>400Hz), the relationship between length and eigenfrequency remains challenging to discern. Additionally, higher swirl numbers do not consistently increase the imaginary part of eigenfrequencies, with variations observed. Notably, the shortest upstream tube exhibits no unstable modes within the studied frequency range (Figure 1, Figure 2).

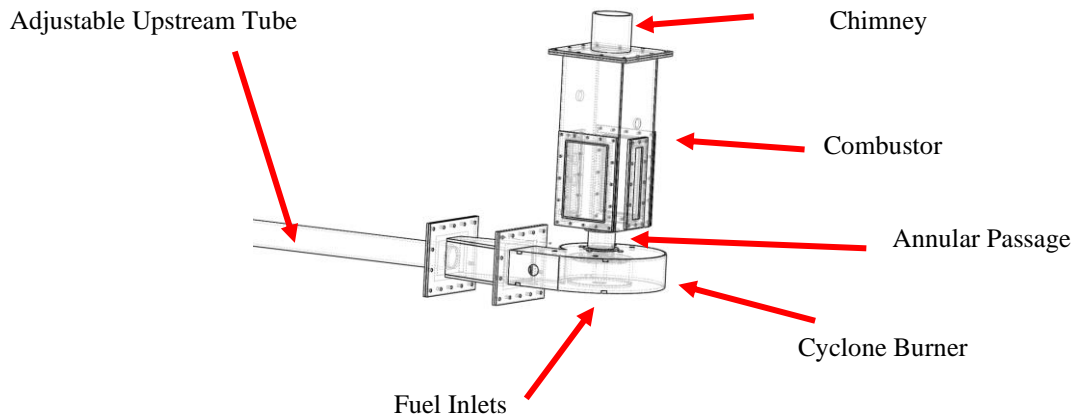


Figure 1. Cyclone Burner

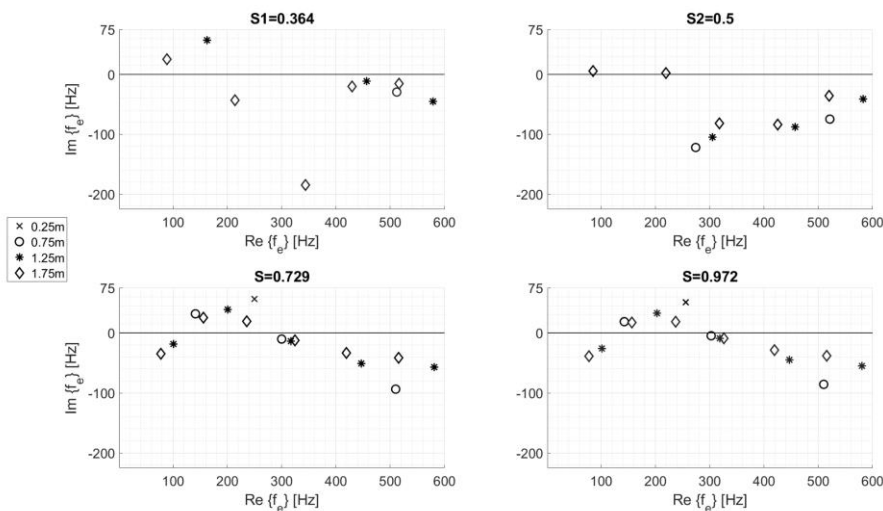


Figure 2 Comparison of Eigenfrequencies for Different Swirl Numbers

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RECONSTRUCTION OF DOWNSTREAM ACOUSTICS FROM TWO SEPARATE SISO MEASUREMENTS OF FLAME

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Abstract

This study presents a prospective method for evaluating the thermoacoustic properties of components downstream of a flame, utilizing two separate Single-Input-Single-Output (SISO) acoustic measurements of the flame. Traditional direct assessment of the downstream reflection coefficient often encounters practical challenges due to the necessity of measurements or modeling in the high-temperature downstream region of the system.

Methodology

First SISO measurement: Impedance tube technique[1] The main purpose of the impedance tube setup is to evaluate the acoustic field in the tube to subsequently calculate the reflection coefficient R_{in} , and it works based on the multi-microphone approach.

Second SISO measurement: flame TF technique[2] The TF technique is a commonly used method for measuring the response of stabilized flames to acoustic disturbances. By definition, the flame TF is the ratio of the relative heat release perturbation (Q'/\bar{Q}) to the upstream periodic velocity perturbations (v'/\bar{v}):

$$F(\omega) = \frac{\hat{Q}' \bar{v}}{\hat{v}' \bar{Q}}. \quad (1)$$

Reconstruction technique As already noted, reflection coefficient of active subsystem (R_{in}) can be directly measured from the multi-microphone method and using impedance tube setup. This SISO function based on the definition can be written as:

$$R_{in} = \frac{R_{dn} T_{11} - T_{21}}{T_{22} - R_{dn} T_{12}}, \quad (2)$$

where in the limit of zero Mach number, $T_{11} = T_{22} = \frac{1}{2}(\epsilon + 1 + \theta F)$ and $T_{12} = T_{21} = \frac{1}{2}(\epsilon - 1 - \theta F)$ [2]. Here, $\theta = \frac{T_2}{T_1} - 1$ is the temperature jump, $\epsilon = \frac{\rho_1 c_1}{\rho_2 c_2}$ the specific impedance jump across the flame and F represents the flame transfer function.

By examining the definition of the input reflection coefficient R_{in} , it is possible to rewrite the equation and obtain R_{dn} :

$$R_{dn} = \frac{R_{in} T_{22} + T_{21}}{T_{11} + R_{in} T_{12}} \quad (3)$$

Eq. (3) is the theoretical base of the measurement technique proposed and studied in this contribution. Namely, by using an impedance tube measurement to obtain the input reflection coefficient R_{in} and a flame transfer function (TF) technique to characterize F we are aiming to reconstruct the downstream acoustics.

Results & Discussion

To test the concept introduced in the previous section, we examine three distinct perforated burner decks, constructed using silicon-carbide SiC fibers, silicon-dioxide SiO₂ fibers, and brass disk. Refer to Figure 1 for a visual representation. Following the burners and their associated flames, a quartz tube spanning a length of 10 cm has been positioned. Our objective revolves around reconstructing a reflection coefficient

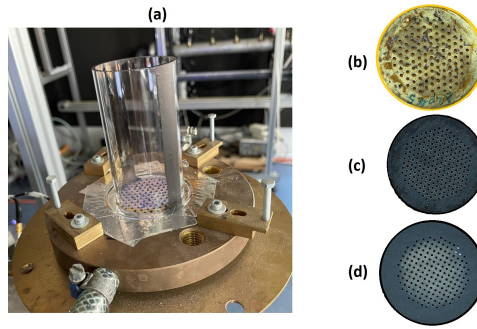


Figure 1. (a) The case of study. (b) A perforated burner made from brass plate; (c) and (d) are two other perforated burners, namely SiC and SiO₂ burners, respectively.

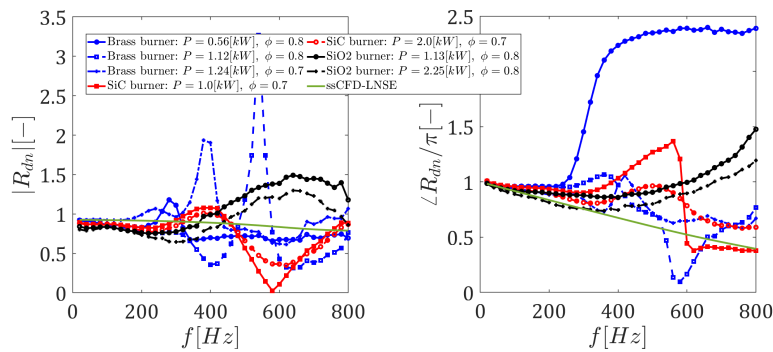


Figure 2. Reconstruction of downstream acoustics in the presence of flame.

of a uniform quartz tube with an open end. With the obtained F and R_{in} , we can reconstruct the R_{dn} using Eq. (3), as shown in Figure 2. It is anticipated that the reconstructed reflection coefficients will exhibit uniformity across different burners and operating conditions. This expectation arises from the insensitivity of downstream acoustics to variations in inflow velocity and minor temperature fluctuations in the flame, attributed to slight changes in the combustible flow mixture. To enable an accurate comparison among the constructed downstream reflection coefficients (R_{dn}), we also consider CFD results obtained from the ssCFD-LNSE solver. Upon comparison, it becomes apparent that while there is a satisfactory agreement at low frequencies, substantial discrepancies emerge at mid and high frequencies. These discrepancies manifest in both the absolute values and phase of the reflection coefficients. Our sensitivity analysis shows that this process is highly sensitive to the presence of noise in the measured data.

Recapitulation

Directly characterizing the thermoacoustic properties of the downstream segment of a flame presents a serious challenge. Consequently, the prospect of reconstructing downstream acoustics from two distinct measurements has been explored. Specifically, our study involves an active subsystem consisting of a perforated burner with accompanying flames and a uniform tube with open end. As a result, we observed that the derived downstream reflection coefficients exhibit notable responsiveness to the presence of noise and uncertainty in both the measured flame TF and the input reflection coefficient. Hence, the extension of our study aims to broaden the applicability and robustness of the reconstruction technique in the full frequency range.

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PARTICLE RESOLVED HYPERSPECTRAL PYROMETRY MEASUREMENTS OF BURNING IRON PARTICLES

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Combustion of solid particles has been a subject of significant interest for many years, owing its importance to applications such as power generation in coal-fired power plants. Metallic particles of aluminum, boron, and magnesium have also been utilized for decades in propulsion systems for rockets and ramjets. Lately, there has been a spike in interest with the rise of the new field of metal dust combustion, potentially replacing the need for carbon-based fuels like coal. The scientific community for metal fuels have been growing for quite some time. As the research into metal fuels expands, the need for accurate diagnostic techniques will also grow. Out of all the flame parameters, temperature might be the most important one. In typical gas flames, the flame temperature is an important indicator for Soot and NO_x . In iron flames, soot is not an issue, but evaporation of iron, and the subsequent formation of nano-particles, could be a problem. Multiple experimental studies have been conducted using dual color and three color pyrometry, but these studies do not agree in their results [1, 2]

In this study, a method is presented which enables the measurement of the temperature of burning metal particles using hyperspectral pyrometry. A simple setup was built using a spectrograph and an intensified CCD camera and used for single iron particle combustion in air with the use of an electric preheater. This setup is shown in figure 1(a). We present temperature histories of individual combusting metal particles using hyperspectral pyrometry. This method gives an increase in accuracy over traditionally used two- or three-color pyrometry, while maintaining temporal and spatial resolution. Temperatures can be determined between 1800 to >3000 K with a precision of typically $<1\%$. It is shown that the maximum temperature of the burning iron particles increases from 2760 K to 2840 K with an increasing mean particle size from 32 to 54 μm in air with 21 % oxygen. The relatively high temperatures and its dependence on particle size are possibly related to flow field properties of the current experimental setup. Opportunities for this method, as well as future work, are discussed.

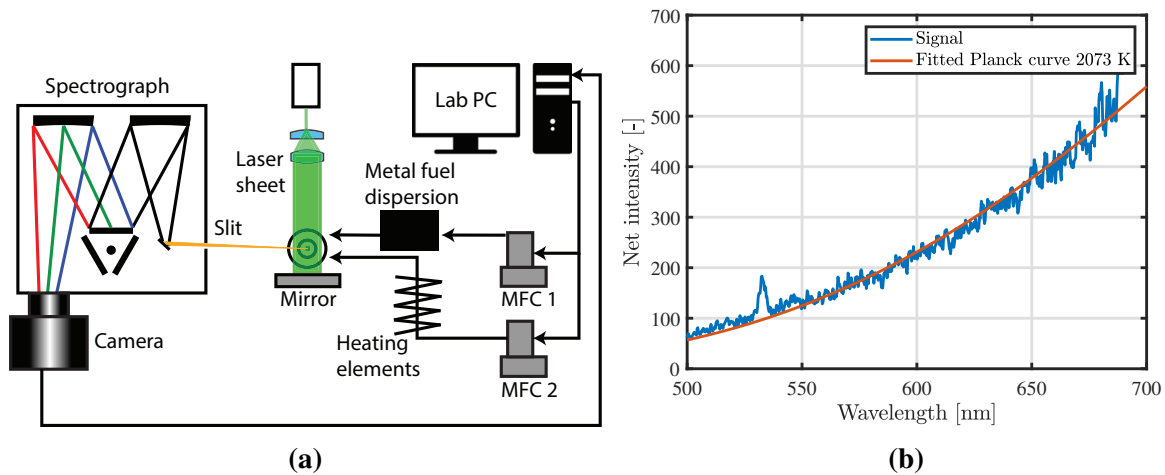


Figure 1. (a) Schematic overview (top-view) of the experimental setup. Particles are dispersed by means of electrostatic dispersion. The feed rate depends on the current that is being fed to the dispersion system, as explained by Shoshin & Dreizin [3]. After dispersion, the particles enter a hot coflow that is electrically preheated up to 1015K. The particles experience auto ignition and the luminescence of the particle is captured by an imaging system consisting of a spectrograph and an intensified CCD camera. (b) an example of a spectral intensity profile at a given HAB, integrated over the (vertical) width of the corresponding trace in (b). The temperature at each HAB can be determined from such a profile by means of non-linear least squares fitting to a Planck distribution. The peak at 532 nm is due to the green laser, as described in section 3.1, and is masked in the fitting procedure. The good fit indicates that there is no reason to doubt the graybody assumption.

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MODELLING THE INTERACTION OF BURNING IRON PARTICLES AND TURBULENCE

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Abstract

Over the past few years, the iron power cycle has seen rapid development to the point where there are effective operational iron powder combustors in use today. Turbulent iron flames lie at the heart of such combustors, and understanding the complex interplay of burning iron particles and turbulence is essential in improving the efficiency of such combustors and also explain and mitigate some unique problems facing modern iron combustors – agglomeration of particles, incomplete combustion and formation of nanoparticles[1]. This work is the first attempt in modelling turbulent iron particle combustion, fully resolving the turbulent length scales and also the interparticle gradients in temperature and oxidizer concentration.

Preferential Concentration in Particle-laden Turbulent Flows

Preferential concentration is a unique physical phenomenon specific to turbulent flows with particles. Eaton and Fessler [2] described this phenomenon to be correlated to the Stokes number St . This phenomenon is of interest as the inhomogenization of Fe particles through preferential concentration can explain the aforementioned problems seen in modern combustors.

An *a priori* analysis using typical iron particle properties in modern iron combustors [3] and flow properties typically seen in coal combustors [4] (assuming similar flow profiles) predicts the Stokes number for Fe particles to be $St \approx 2$, which indicates the certainty of occurrence of preferential concentration. The primary objective of this work is the observation of preferential concentration of burning Fe particles in a turbulent flow. This is achieved in the present work using DNS simulations of turbulent Fe combustion.

Simulation Setup & Results

An Euler-Lagrange framework is used to model the particle-laden flow. Gas-phase equations are solved using the DNS solver NTMIX-CHEMKIN [5], and the particle reaction kinetics are modelled based on Mi et al.[6]. A mixing layer is chosen as a canonical flow scenario to establish an initial reference case. DNS simulations of coal dust combustion in a turbulent mixing layer are used as the reference for geometry and flow setup [7]. Detailed case setup information will be presented at the symposium.

In the current work, the results of a case with parameters presented in Table 1 is discussed. With the heat release from the burning particles, turbulence onset is seen which gives rise to preferential concentration of the particles, as seen in Figure 1. Preferential concentration is qualitatively described from the mean minimum spacing of the particles.

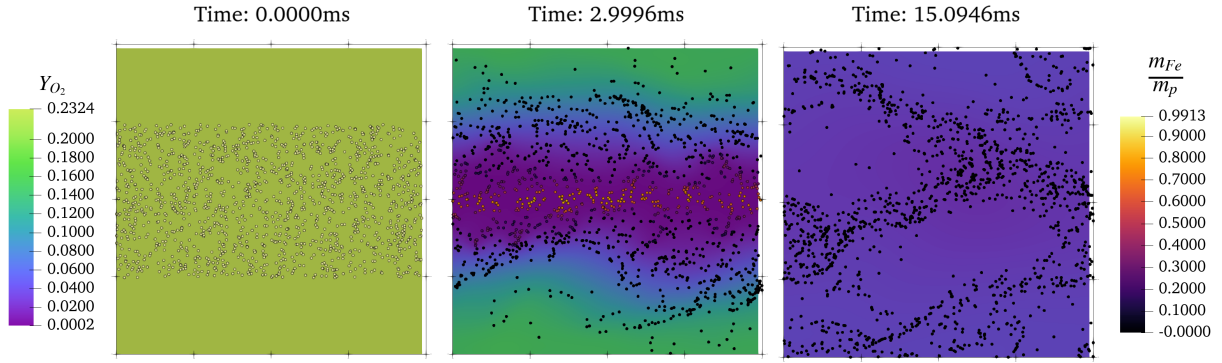


Figure 1. Visualization of gas oxygen concentration and particle Fe mass fraction at $t = 0, 3, 15$ ms in a Fe -particle filled mixing layer; Particle distribution at $t = 15$ ms shows preferential concentration; Particles are not to scale with the domain.

Preferential concentration is quantified through different methods in literature. An immediate follow-up is to review these methods and quantify the preferential concentration seen in Figure 1 using a single quantitative parameter. This will enable comparison of preferential concentration across different cases. The influence of multiple sensitive parameters on the flow, the particle, and the reaction behaviours, resulting in different regimes are also identified. Hence, a rigorous parametric analysis to categorize the different regimes from the parameters is required.

Parameter	Value
Domain size	8×8 mm
Hot stream temperature	2500K
Cold stream temperature	900K
Relative flow velocity	50m/s
Particle diameter	$5 \mu\text{m}$

Table 1. Geometry, flow and particle parameters simulated in present work

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FLAME FLASHBACK BEHAVIOR WHEN SUBJECTED TO PRESSURE PEAK AT IGNITION CONDITIONS – COMPARISON BETWEEN HYDROGEN AND METHANE

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Abstract

When developing a new hydrogen boiler for carbon emission-free domestic heating, safety is paramount. Therefore, it is relevant to evaluate the safety concerns associated to using hydrogen as a novel fuel as opposed to well-known methane. One of such concerns is the risk of flame flashback at ignition conditions. Where the desired behavior is that a flame stabilizes on the burner after ignition, it could happen that a flame cannot stabilize on the burner, but can instead unintentionally propagate through the burner, thereby initiating flame flashback.

The purpose of this work was to compare flame behavior of a typical hydrogen and methane burner in response to a pressure peak at ignition conditions, by means of computational fluid dynamics simulations. The scenario investigated in this work is that a pressure peak arising from ignition forces a flame into the burner. Depending on the boundary conditions, there are three possible outcomes: the flame could keep burning, the flame could quench, or the flame could ignite the upstream mixture, which is an undesirable flashback event.

Despite the focus on ignition conditions, it was not desired to model ignition itself. Rather, ignition was assumed to cause a pressure peak, which in turn affects the flame. Since only the effect on the flame is of interest, prescribing a pressure peak directly while ignoring ignition is sufficient for this analysis. Some properties of the pressure peak had to be assumed, because its source—ignition—was not modeled. For simplicity, the pressure peak was assumed to be a single square wave. Its time duration was 1 ms. The amplitude of the pressure peak was varied in a range up to typical ignition pressures observed in laboratory measurements.

The simulation setup comprised a two-dimensional axisymmetric burner plate with typical dimensions for a hydrogen and methane burner. The burner thickness was identical for both fuels, but the hole diameter was smaller for the hydrogen burner. Starting from a laminar, burner-stabilized flame at ignition operating conditions, the flame was subjected to the pressure peak in time-dependent simulations. While the global operating conditions were identical for hydrogen and methane (heat input 12 kW with air-fuel equivalence ratio 1.3), the hydrogen burner had a higher flow rate per burner hole. The detailed chemistry solver from Ansys® Fluent 2023 R1 was used. The hydrogen simulations used Stanford H₂/O₂ Mechanism version 1.2 [1] and the methane simulations used GRI-Mech 3.0 [2].

Given the higher flow rate per burner hole for hydrogen, the nominal pressure drop across the hydrogen burner is higher than the methane burner. This implies that the hydrogen burner should be less affected by a pressure peak of equal amplitude than the methane burner. From this perspective, a higher nominal pressure drop may make a burner less susceptible to flame flashback induced by pressure peaks.

However, a fairer comparison may be to consider the net pressure difference across the burner during a pressure peak, when the pressure peak opposes the nominal pressure drop across the burner. Considering the three possible outcomes after the pressure peak (burning, quenching, flashback), it was found that the crossover from one outcome to the next occurs at similar

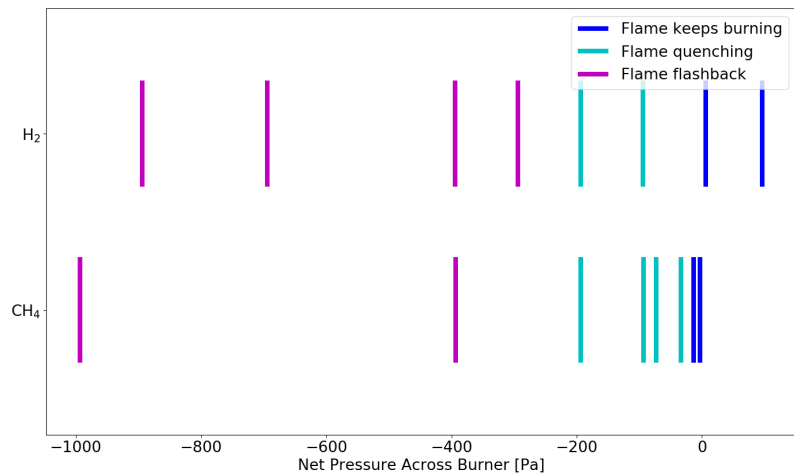


Figure 1. Flame behavior in response to pressure peak, expressed in terms of net pressure difference across burner during pressure peak

net pressure differences for both the hydrogen and methane burner (Figure 1), for the specific geometries and conditions considered in this work. Specifically, if the net pressure difference across the burner remains positive in the nominal flow direction during the pressure peak, or gets slightly negative ($\sim 10^1$ Pa), the flame can keep burning in response to the pressure peak. Alternatively, if the net pressure difference across the burner is moderately negative ($\sim 10^2$ Pa), the flame goes through the burner hole but does not ignite the upstream mixture and ultimately quenches. Finally, if the net pressure difference across the burner is strongly negative (approaching $\sim 10^3$ Pa), the flame goes through the burner hole without quenching and thus ignites the upstream mixture, which represents flame flashback.

Differences between hydrogen and methane were most noticeable at lower pressure peak amplitudes. At these conditions, a methane flame was found to respond more slowly to the pressure signal than a hydrogen flame. In contrast, at higher pressure peak amplitudes, flame propagation was dominated by the pressure level, with little difference between fuels.

Recommendations for future work are twofold. First, visualizations of the flame suggest that the simulation domain may have been too short to capture the full flashback phenomenon, especially for methane, so it is recommended to increase the domain size. Second, it is recommended to investigate the effect of burner thickness, as increasing burner thickness is expected to decrease the risk of flame flashback.

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NUMERICAL ANALYSIS OF SENSITIVITY OF CYCLONE BURNER FTF TO SWIRL INTENSITY

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Abstract

The effect of swirl variations on the forced response of a lab-scale cyclone burner is studied. This burner, fuelled by a blend of 40 vol% methane and 60 vol% hydrogen, was designed to emulate the combustion dynamics of a large industrial furnace. A great portion of industrial combustion systems are swirl-stabilized. Therefore, it is interesting to study the effect of swirl intensity on the thermoacoustic stability of the system. For this, simulations are performed in Fluent using SAS-SST URANS turbulence modelling and an FGM model for combustion. The incoming air-fuel mixture is pulsed at specific frequencies. To reduce the required amount of resources, each simulation is forced with a superposition of sine waves at distinct frequencies. It is shown that, as the swirl level increases, the combustion time delay decreases, due to a more compact flame. The flame is most responsive at lower swirl levels, with the maximum gain observed around frequencies of 400-600 Hz, after which it rolls off. At higher swirl levels, the flame behaves like a low-pass filter, as the compact flames are less responsive to low-frequency forcing. An increase in gain was observed in these cases at the very highest forcing frequencies. It is believed this is due to a coupling between the forcing frequency and the vortex shedding frequency.

Method

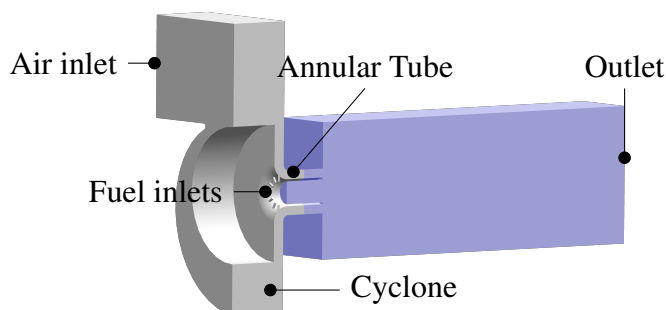


Figure 1. Complete fluid domain of burner with cyclone and simulated fluid domain in blue.

Figure 2. Forcing frequencies applied in the simulations, yielding a computational speed-up factor of four over single-harmonic.

Simulation	f_1	f_2	f_3	f_4
B1	50	90	132	176
B2	222	270	320	372
B3	426	482	540	600

A cut-out view of the cyclone burner is shown in Fig. 1. In blue the computational domain is shown. The axial velocity is forced at the domain inlet according to:

$$\tilde{u}_x(\vec{x}, t) = \bar{u}_x(\vec{x}) \left(1 + \frac{A}{N} \sum_i^N \sin(2\pi f_i t) \right). \quad (1)$$

In Table 2, the N forcing frequencies of each simulation are shown. The swirl number is varied by multiplying the tangential velocity component from the inlet profile. The resulting swirl number range is [$S1 = 0.36, S2 = 0.50, S25 = 0.61, S4 = 0.96$]. Turbulence is modelled using the Scale Adaptive Simulation (SAS) method of the $k - \omega$ SST model [1]. For combustion, the FGM combustion model, developed by Gövert and Kok is used [2].

Results highlights

In Fig. 3, results of the mean heat release rate are shown. Largely different flame shapes are observed in the investigated swirl number range. A sudden change in flame shape is found for case S2.5, due to the formation of an inner recirculation zone (IRZ). The swirl number threshold for the IRZ is in accordance with literature [3]. The Flame Transfer Function (FTF) (view Fig. 4) reflects the different flame shapes throughout the swirl number range. Especially, between the cases with and without an IRZ the difference in FTF behaviour is clear. The phase lag reduces as the swirl number increases as a result of the more compact flame. Furthermore, it reduces more or less linearly, indicating a constant time delay. For the high-swirl cases, the flame acts a low-pass filter, with values not exceeding unity. An exception to this happens at higher frequencies, where the gain increases due to a coupling between the forcing frequency and the vortex shedding frequency. In the low-swirl cases, the absence of an IRZ makes the flame much more sensitive to the forcing at lower frequencies, with the gain growing up to 3.8.

Further work is ongoing to include the effects of heat loss, equivalence ratio fluctuations and to validate the numerical results by experimental data.

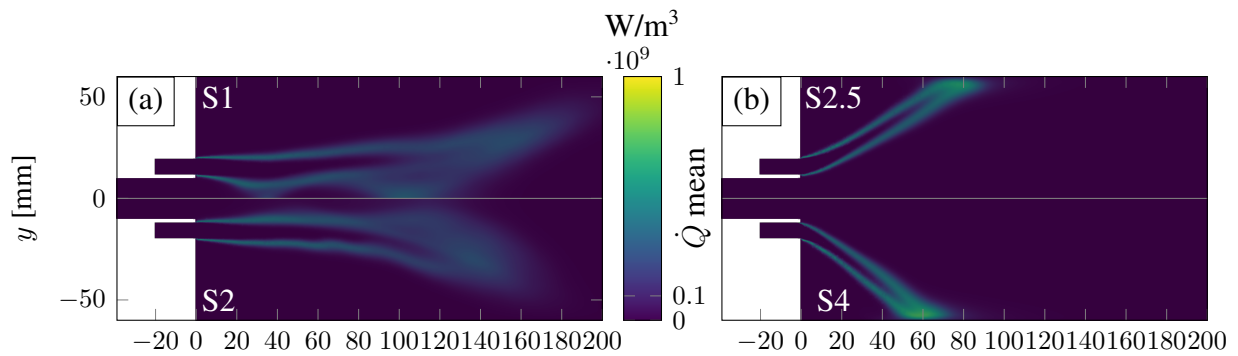


Figure 3. Contours of the time-averaged heat release rate \dot{Q} of the unforced simulations. The plots are generated at a cross-section in the middle of the burner. Only half of the domain is shown for each case, as the flow is symmetric.

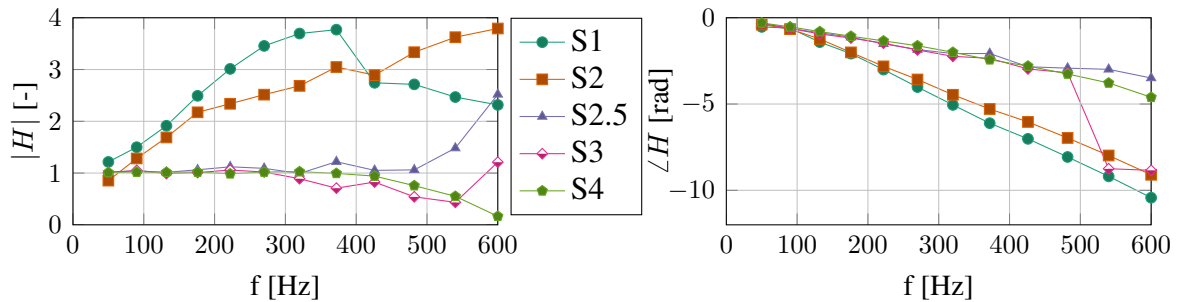


Figure 4. Gain and phase lag of the FTF for different swirl numbers.

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BURNING VELOCITY MEASUREMENTS FOR FLAT HYBRID IRON-METHANE-AIR FLAMES

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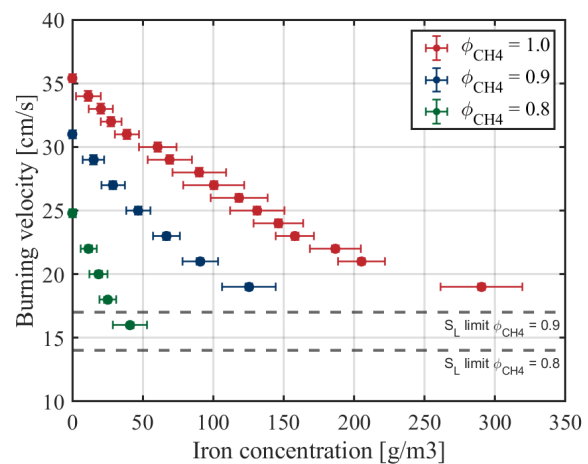
Abstract

Recently, a cyclic energy storage concept was proposed involving the use of metal powder as CO₂-free energy carrier, known as the metal fuel cycle. In this cycle, the burning of iron powder is considered as the discharge agent of the energy carrier. However, for this cycle to be an efficient one, better understanding of the laminar burning velocity of iron powder is required. Earlier findings regarding the burning velocities of iron flames in literature are not easily compared since the powders and experimental equipment vary widely from Bunsen flames [1, 2] to counterflow [3] and spherical expanding flames [4, 5]. In gaseous flames, these methods of measuring the laminar burning velocity are all subjected to stretch, and extrapolation to non-stretched flames is needed for proper comparison. However, for iron loaded flames, the effects of stretch are still unknown. Furthermore, measurements are in many cases also subjected to scatter from which the source is in many cases only partially quantified.

This study presents a newly developed burner based on the Heat Flux Method (HFM) [6] which can measure the burning velocities of flat hybrid iron-methane-air flames, as illustrated in Figure 1a. Since laminar iron flames are particularly difficult to stabilize and have - even for micron-sized particles - burning velocities in close proximity to their terminal velocity, methane is used as stabilizing agent. Due to the different properties of the hybrid flames and corresponding unburned mixture, the Heat Flux Burner (HFB) was redesigned to create a flat particle-laden flow profile, which was validated using PIV. For the seeding of iron to the gaseous mixture, an in-house developed dispersion system is used, which employs a loadcell to meter the iron mass flow to the burner.



(a) A flat hybrid iron-methane-air flame stabilized on the perforated plate of the adapted HFB.



(b) Burning velocities of hybrid iron-methane-air flames for different iron concentrations and methane-air equivalence ratios.

The results - given in Figure 1b - demonstrate a steady decrease in burning velocity when iron is added to a stoichiometric or lean methane-air-flame. The iron acts as heat sink within these flames, consequently reducing the flame temperature and laminar burning velocity. This effect is stronger in lean flames since the total heat release from the methane is less compared to the stoichiometric case. A limit in burning velocity is found for hybrid flames with a lean methane-air composition. Here it is hypothesized that the burning velocity is reduced enough to allow the iron to contribute to the burning velocity of the hybrid flame, thus stabilizing the burning velocity.

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EFFECT OF AMMONIA BLENDING IN STRAINED LEAN PREMIXED HYDROGEN FLAMELETS

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Abstract

Lean premixed and highly strained ammonia/hydrogen-air counterflow flamelets are investigated numerically. The influence of varying fuel mixture ratio on NO_x emissions and consumption speed is assessed. The contribution of thermal NO_x route is kept fixed for all mixtures by adjusting the equivalence ratio (ER) such that the same peak flame temperature is achieved. Results show that NO_x is still suppressed by strain for all fuel mixtures investigated. Furthermore, the increasing trend of consumption speed with strain rate for pure hydrogen fuel is retained up to relatively large amounts of ammonia in the fuel blend, indicating that strain can be used as a mean to decrease NO_x without suppressing the flame in ammonia/hydrogen blends.

Introduction

In the pursuit of greener fuels to mitigate greenhouse gas emissions, research is focused on carbon-free fuels like hydrogen. Hydrogen flames exhibit unique properties, including resistance to extinction at high strain rates [1], resistance to lean blow-off in ultra-lean conditions due to its high reactivity and lower heating value and, unlike hydrocarbon fuels, increase in consumption speed with strain rate due to the negative Markstein length at lean ERs [2]. Recently, it was shown that NO_x formation via the thermal pathway is suppressed by increasing strain rate in lean premixed conditions [3]. Latest research studies further discussed the possibility to blend hydrogen with ammonia in order to tackle the controlling challenges of lean pure hydrogen flames [4]. However, it is still unclear if the burning characteristics observed in pure hydrogen flames, including the strain induced suppression of NO_x emissions, also apply to blends of hydrogen and ammonia. This study investigates counter-flow premixed hydrogen/ammonia flames numerically, focusing on their behavior under intensive strain conditions, specifically on its impact on the consumption speed and NO_x emissions.

Model and Setup

Detailed-chemistry one-dimensional simulations are conducted on lean premixed flamelets in a counter-flow reactants-to-products configuration in CHEM1D. Strained conditions are established in a range from $a = 100\text{s}^{-1}$ to $a = 10000\text{s}^{-1}$. Fuel blends are obtained by incrementally increasing the ammonia content in volume by 25%. GRI3.0 mechanism is used for kinetic data along with a multicomponent diffusion model. The reactants temperature is fixed at 300K. To ensure a fixed thermal NO_x formation, the products temperature is also kept constant by adjusting the ER for each blend (see Table 1). The starting condition is established for pure hydrogen fuel at equivalence ratio $\phi = 0.7$, resulting in a products temperature of 2021K.

Table 1. Equivalence ratios of varying ammonia/hydrogen fuel mixtures.

X_{NH_3}	ϕ
0 %	0.7
25 %	0.79
50 %	0.85
75 %	0.904
100 %	0.957

Results

In Fig. 1 left, the fuel consumption speed, S_c , normalised by the unstretched displacement speed is reported as a function of strain rate for different ammonia/hydrogen blends. As expected, an increasing trend is displayed for pure hydrogen fuel due to its negative Markstein length. In contrast, a decreasing trend is shown for pure ammonia due to its low reactivity, where the applied strain leads to flame weakening and ultimately extinction. When hydrogen/ammonia blends of 25% up to 50% ammonia are used, the strain rate at which S_c starts to decrease occurs at lower values as one would expect, suggesting an earlier extinction limit. On the other hand, it is interesting to note that the initial increase of S_c is steeper for the cases where ammonia is added as compared to pure hydrogen mixture. For higher ammonia content (75%), the low reactivity of ammonia dominates and the flame is weakened already at values of applied strain rate as low as $a = 200 \text{ s}^{-1}$. A drawback of introducing ammonia in the fuel mixture is that, even in low fraction, it exacerbates NO_x emissions. This is shown in Fig. 1 right, where the density-weighted NO_x integral, defined as $I_{\text{NO}_x} = \int_x \rho(Y_{\text{NO}} + Y_{\text{NO}_2})dx$, is plotted as a function of strain rate for different fuel blends. Nevertheless, the highest emissions are observed when low quantities of ammonia are present. This is because, while ammonia combustion triggers a strong increase of nitrogen free radicals, the high hydrogen content still ensures a highly-reactive mixture. Nevertheless, a decreasing trend is promisingly observed with strain rate for all the mixtures. Overall, these results suggest that strain can be potentially used to re-increase the burning rate of blend ammonia/hydrogen flames with low ammonia content, achieving a stable but still highly-reactive burning mixture, simultaneously limiting NO_x emissions.

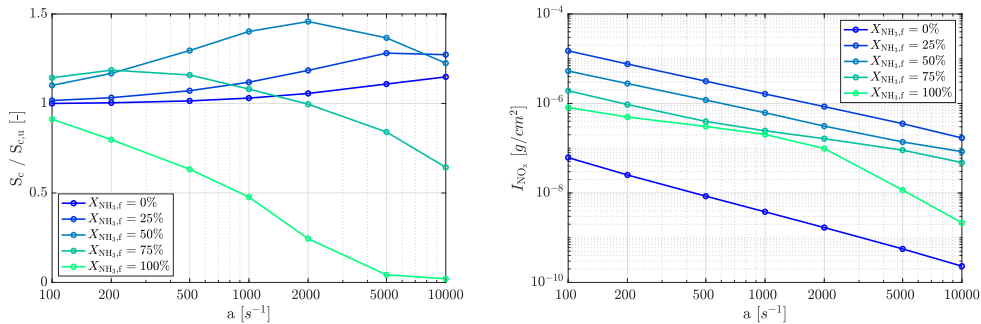


Figure 1. Normalised consumption speed (left) and density weighted NO_x integral (right) as a function of strain rate for different hydrogen/ammonia fuel blends.

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GAS-PHASE SYNTHESIS OF IRON OXIDE NANOPARTICLES PRODUCED VIA DIFFUSION FLAMES

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Abstract

Iron oxide nanoparticles (IONPs) present superparamagnetic properties, leading to interesting applications in e.g., catalysis [1] and cancer therapy [2]. Gas-phase synthesis methods for the production of IONPs have shown to be able to operate in continuous and to be highly reproducible and scalable [3]. Therefore, it is appealing to produce IONPs using this procedure as it has potential for industrial scale production.

The present work explores the capability to synthesize and stabilize oxidation-sensitive phases of IONPs. The gas-phase reactor used accounts for a 1D matrix burner, capable to operate under premixed and diffusion flame conditions. On this work, only the diffusion flame mode has been explored, having the inlet gas-phase reactant (iron pentacarbonyl, $\text{Fe}(\text{CO})_5$) injected together with the fuel (methane, CH_4) through separated channels respect the oxidizer (oxygen, O_2). Once the reactant reaches the flame, it decomposes into iron atoms and $\text{Fe}_x\text{O}_y\text{H}_z$ molecular species, which nucleate, condensate and grow to form the resultant nanoparticles. Additionally, an inline quench nozzle was added downstream to avoid nanoparticle agglomeration. The synthesized IONPs were harvested at a filter, and characterized using Transmission Electron Microscopy (TEM), X-ray Diffraction (XRD), Raman Spectroscopy, X-ray Photoelectron Spectroscopy (XPS), and Brunauer-Emmett-Teller (BET) analysis.

The results show that the synthesized nanoparticles present a mixture of different oxidation states (mainly the magnetic phases magnetite, Fe_3O_4 , and maghemite, $\gamma\text{-Fe}_2\text{O}_3$) and a narrow size distribution. These insights bring us to conclude that IONPs can be successfully produced through a scalable and cost-effective process such as the gas-phase synthesis using a flame reactor. In the near future, inline IONPs coating will be explored to prevent IONPs from further oxidation and improve long-term stability.

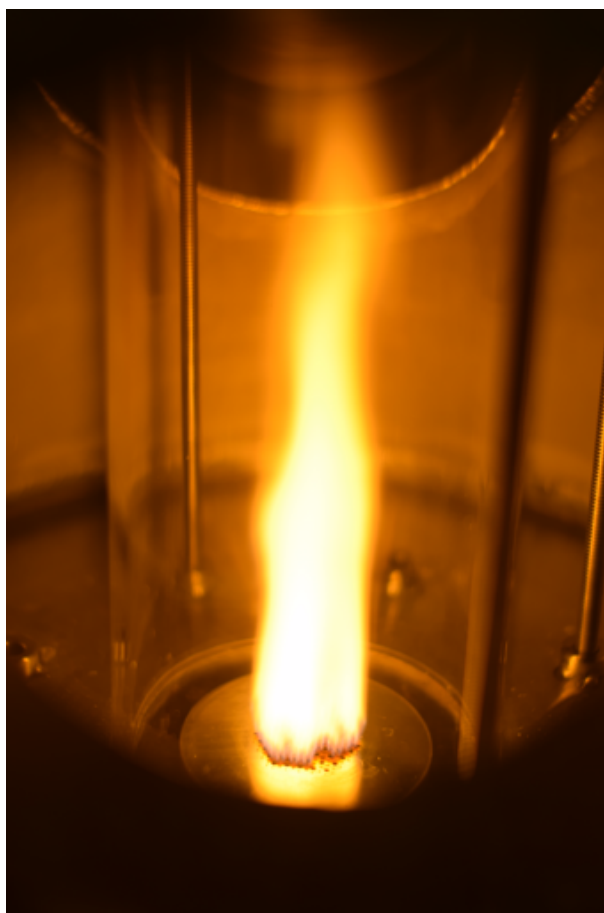


Figure 1. Inner of the reactor showing the matrix burner and the flame when IONPs are being produced

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DNS AND LES OF TEMPORAL MIXING LAYERS OF HYDROGEN COMBUSTION FOR THE ARGON POWER CYCLE

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Abstract

The Argon Power Cycle (APC) is a promising energy conversion system that uses argon as a working fluid instead of nitrogen, which could increase the efficiency due to the low specific heat capacity of argon. Here we investigate the combustion of pure hydrogen in a mixture of oxygen and argon by means of Direct Numerical Simulations -DNS- with detailed chemistry and Large Eddy Simulations -LES- with tabulated chemistry (FGM). The main findings in turbulent and combustion quantities are reported, and recommendations for accurate large scale modeling are given.

The Argon Power Cycle

The Argon Power Cycle (APC) which could increase the efficiency by approximately 25% due to the low specific heat capacity of argon. One advantage of the APC is the absence of NO_x formation during the combustion process, thanks to the lack of nitrogen. Moreover, when hydrogen is employed as fuel, there will be no carbonaceous emissions either. In the case of stoichiometric and complete combustion, the exhaust only contains argon and water. When water is removed from the system by condensation, the argon can be led back to the intake to be reused. This could be done by a closed-loop configuration, also understood as 100% exhaust gas re-circulation, as illustrated in figure 1.

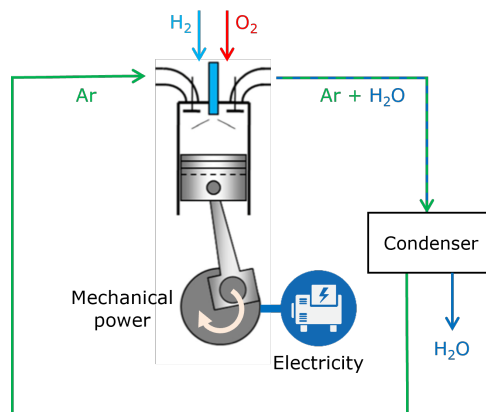


Figure 1. Schematic overview of the Argon Power Cycle

Direct Numerical Simulations -DNS- are performed using a fully compressible, in-house code with sixth order accuracy in space and third order in time. The DNS is used to unravel the intricacies of the turbulence-chemistry interaction of $\text{H}_2 + \text{O}_2 + \text{AR}$ combustion. The configuration consists of an igniting temporal planar mixing layer of pure H_2 surrounded by a hot mixture of $\text{O}_2 + \text{AR}$ as depicted in Figure 2. The initial pressure is 1bar and the Reynolds number is 10,000. Statistical convergence and sufficient resolution are ensured. Accurate sub-models for

viscosity [1] and transport based on non-unity Lewis number are employed. Figure 3 shows three middle z -plane cuts of an ignited DNS case.

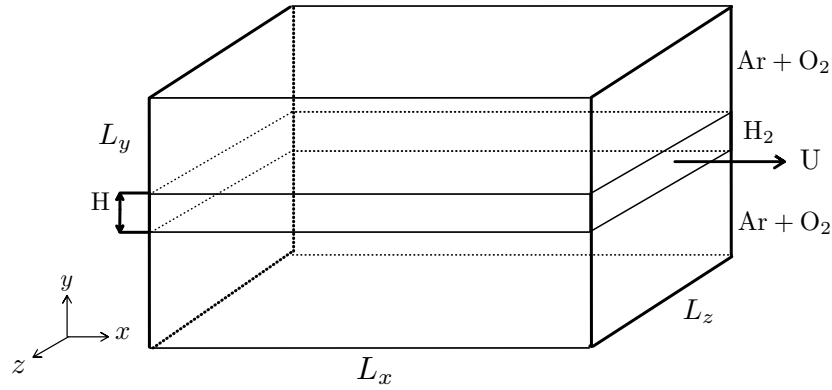


Figure 2. Schematic of a temporal planar mixing layer

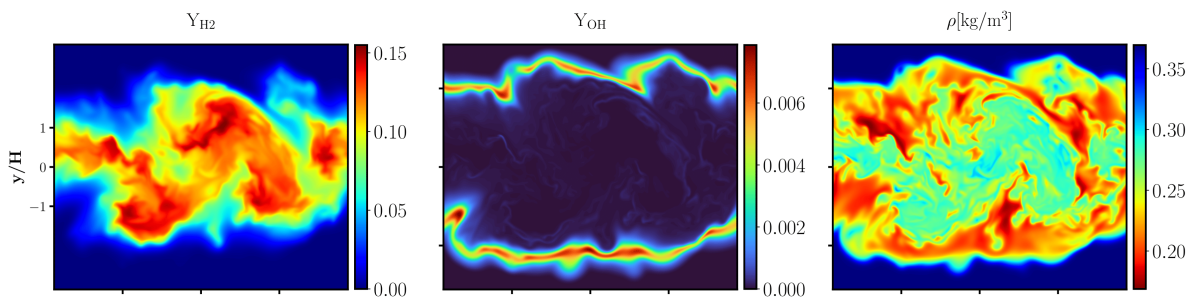


Figure 3. H_2 mass fraction, OH mass fraction, and density after 0.2ms

The initial fields of the DNS are filtered with two different filter sizes, which are then used for Large Eddy Simulations -LES-, using tabulated chemistry based on the Flamelet-Generated Manifold method [2]. The results of both methods are assessed, statistically, for turbulence and combustion quantities of interest.

The LES-FGM shows satisfactory agreement with the DNS for parameters of interest like ignition delay, maximum temperature and burning rate. Recommendations are given for future DNS studies, as well as for larger types of simulations based on LES-FGM.

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The effect of hydrogen addition on the wavelength depending absorption of combustion generated nanoparticles from premixed ethylene flames

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Abstract

It is well known that soot, or black carbon (BC), has a large warming effect on the climate due to the absorption in a wide range of wavelengths [1]. The effects of coloured organic carbon (also known as brown carbon (BrC)) are also significant, as in some studies they account for 10% to 20% of the near atmospheric UV absorption [2]. A study is done to examine the optical and thermo-chemical properties of combustion generated carbonaceous aerosols. Various premixed burner-stabilized 1-D flat flames of mixtures of ethylene (C₂H₄) and hydrogen (H₂) are analysed by varying H₂/C₂H₄ ratio and exit velocity. The equivalence ratio is kept constant at 2.3. The exit velocities range from 6 cm/s to 10 cm/s, while the hydrogen fraction in the fuel ranges from 0% to 50%.

Methods

An AE43 aethalometer is used to measure the absorption of the combustion generated nanoparticles at 7 different wavelengths ranging from 370 nm to 950 nm. The wavelength depending absorption is calculated using the Angstrom Absorption Exponent (AAE), defined by:

$$AAE_{\lambda_1/\lambda_2} = - \frac{\ln\left(\frac{b_{abs,1}}{b_{abs,2}}\right)}{\ln\left(\frac{\lambda_1}{\lambda_2}\right)} \quad (1)$$

Where $b_{abs,1}$ is the absorption coefficient at wavelength λ_1 and so on.

Additionally, a selection of the flame conditions is used to sample the combustion generated particles on an aerosol filter in order to measure the Organic Carbon (OC) to Elemental Carbon (EC) ratio, using a thermo-optical analyzer (Sunset). The goal is to find the effect of hydrogen addition and exit velocity on the OC/EC ratio. Preliminary results suggest a much higher organic fraction for high hydrogen content and low exit velocity.

For the same selection of flame conditions the aerosol size distribution is measured using a Scanning Mobility Particle Sizer (SMPS), to find whether the hydrogen addition and exit velocity influence the size distribution of the aerosol.

The flame temperature has been determined by solving 1D species and energy conservation equations using San Diego mechanisms [3].

Results

The AAE with respect to the whole measured spectrum, also denoted as $AAE_{370-950}$, is plotted on the y-axis versus the mol fraction of hydrogen in the flat ethylene flame (Figure 1). A pure ethylene flame produces aerosol with a AAE of around 1.3, with some higher values for the lower exit velocities compared to the high exit velocity. The AAE of the generated particles however drastically increase for lower exit velocities combined with high hydrogen content in

the fuel. A higher AAE suggests the presence of more organic material, as BC is known to absorb a very broad spectrum while the organic material like BrC is known to absorb mainly the near-UV part of the spectrum.

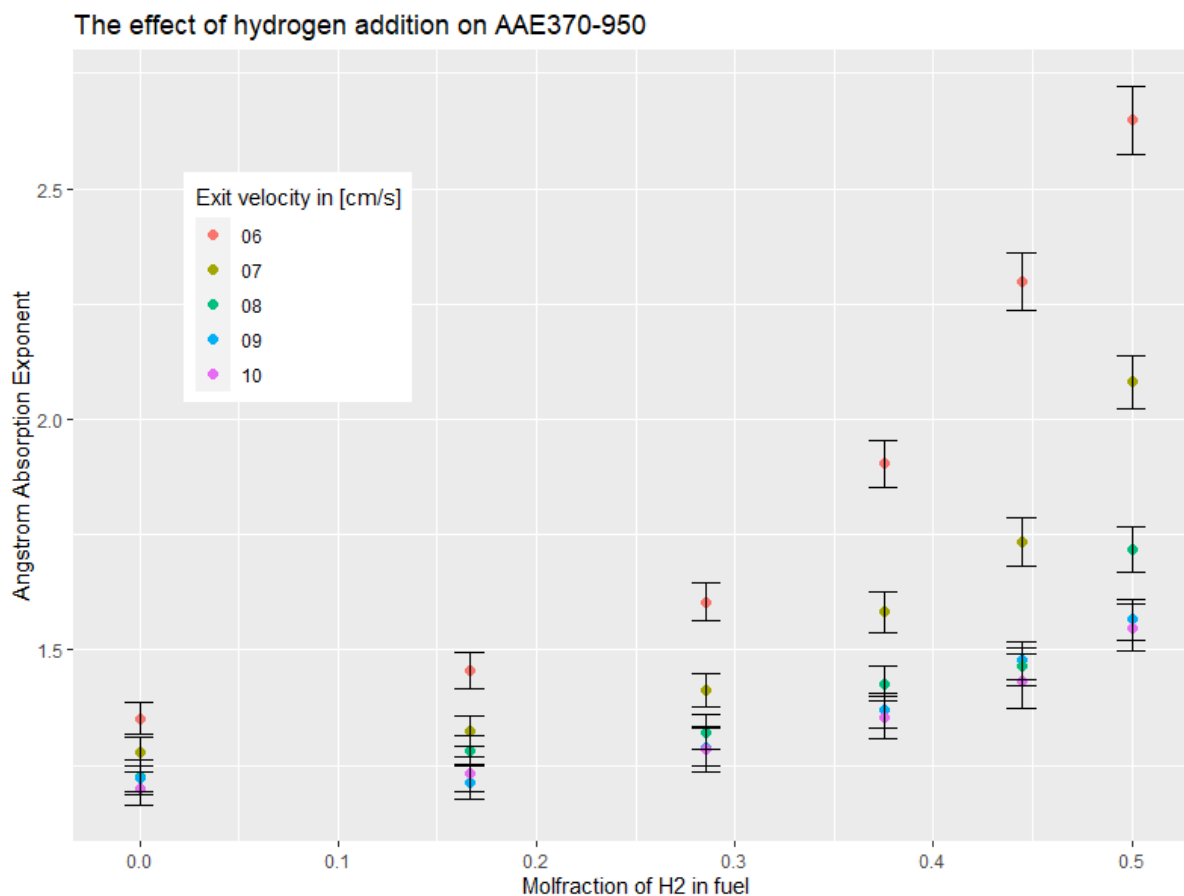


Figure 1. Increasing either the mol fraction of hydrogen or decreasing the exit velocity, the AAE increases slightly. If done both, the AAE increases drastically.

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EFFECT OF TEMPERATURE AND PRESSURE ON LEAN TURBULENT HYDROGEN FLAMES

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Abstract

Hydrogen is a simple fuel to produce from renewable electricity, a clean energy carrier and a carbon-free alternative fuel. However, its combustion characteristics present a challenge, since it has different chemical and transport properties compared to traditional fossil fuels [1]. For example, the burning velocity of hydrogen-air mixtures is much higher than that of methane-air flames and it is more sensitive to the fuel-air ratio, which may lead to flame stabilization problems. Additionally, hydrogen has a higher diffusivity, which gives rise to preferential diffusion effects, equivalence ratio fluctuations, even higher burning velocities and significantly different flame dynamics on premixed flames [2].

The intrinsic instabilities of laminar hydrogen flames have been studied before, e.g. by Berger et al. [3]. In this study, lean premixed turbulent hydrogen-air mixtures are investigated with Direct Numerical Simulations (DNS) in order to move forward in understanding its combustion characteristics. A parametric study was done to analyze the effect of initial conditions on the flame structure, dynamics and preferential diffusion behavior. Specifically, the effect of varying the fresh gas temperature (T_u) and pressure (p) was studied.

Numerical setup

Three-dimensional Direct Numerical Simulations (DNS) were performed using the in-house developed code DISCO. The simulations were initialized with two flame fronts that propagate towards each other as shown in Fig. 1. The flame fronts are separated by a planar turbulent jet that consists of a lean ($\phi = 0.7$) hydrogen-air mixture, similar to the configuration proposed by Hawkes et al. [1]. The separation between the flame fronts was set larger than the jet width to allow turbulence to develop before the flames touch the jet. The velocity (U_{jet}), jet width (H) and flame front separation (W) were modified such that the jet Reynolds number remained the same for all cases ($Re_{jet} = 10206$).

Results and discussion

Figure 2 shows the effect of T_u and p on the instabilities of turbulent hydrogen flames. At 300 K, there is wrinkling along the flame front and fluctuations of the source term of H_2O (ω_{H_2O}) due to preferential diffusion. As T_u increases, less small structures and more large-scale structures can be observed. The integral reaction rate is enhanced at higher temperatures, due to the temperature increase itself, but also due to the increase of surface area. Additionally, the source term of H_2O is more equally distributed along the flame front, due to the reduced preferential diffusion effects. At 2 atm, the enhanced preferential diffusion effects lead to more wrinkling and formation of both small and large-scale structures, there are fluctuations of ω_{H_2O} and the integral reaction rate increases due to the increased surface area. This tendency corresponds to the results obtained by Berger et al. [3] in laminar flames.

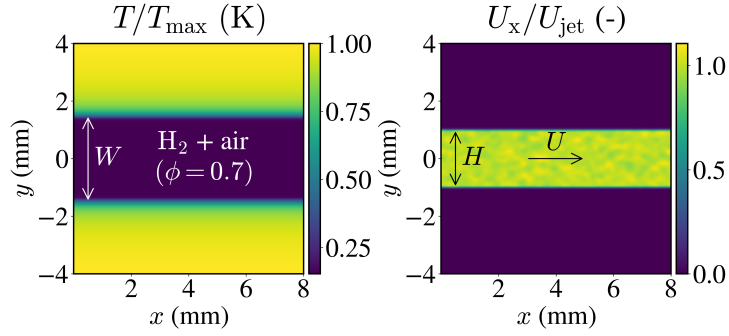


Figure 1. Initial setup of direct numerical simulations.

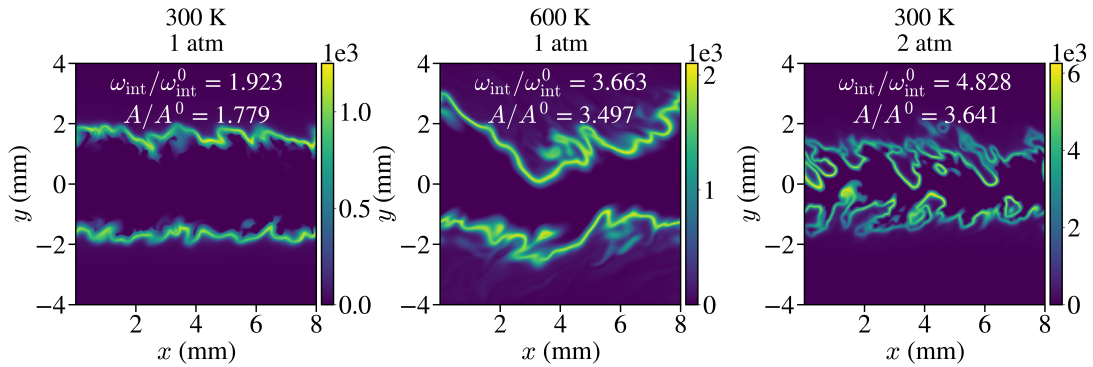


Figure 2. Contour plots of $\omega_{\text{H}_2\text{O}}$ ($\text{kg}/\text{m}^3\text{s}$) at position $z = 0$, showing the corresponding normalized integrated source term and surface area, with increasing T_u and p

Conclusions

The behaviour of premixed turbulent hydrogen flames was studied. When hydrogen is used as fuel, preferential diffusion effects become important, leading to regions with enhanced burning rates. At higher initial temperatures, the integral reaction rate is enhanced and the effect of thermodiffusive instabilities is lowered, leading to a more even distribution of source terms along the flame front. On the other hand, at higher pressures, the thermodiffusive instabilities are stronger, leading to more wrinkling.

Acknowledgements

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LES OF LIFTED HYDROGEN FLAME THROUGH TRANSPORTED PDF METHOD

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Introduction

Hydrogen is often presented as a carbon-free alternative fuel for power generation systems, due to its high specific energy and the possibility of producing it through renewable energy. Its wide flammability range allows for flame stabilization at ultra-lean conditions, achieving control over its elevated flame temperature and nitric oxide emissions. Moreover, with respect to hydrocarbons, hydrogen has a higher diffusivity compared to heat and the other species involved, introducing the so-called differential diffusion effects.

Large eddy simulations (LES) are a powerful tool for the analysis of complex reacting flows in practical flame holders. Among the many turbulent combustion models proposed in the literature, Eulerian stochastic fields (ESF) approaches provide a closure of the reaction rate terms within the transported probability density function (TPDF) methodology. They can be used in combination with detailed or tabulated chemistry. ESF models have been developed for hydrocarbons under the assumption of equal species diffusivities, therefore they cannot capture differential diffusion effects. In this study, LES with ESF closure is used to simulate a turbulent partially premixed hydrogen flame, following two approaches: detailed chemistry with full transport of species and Flamelet Generated Manifold (FGM) tabulation to lower computation costs. A comparison is made for the San Diego and Ó Conaire chemistry mechanisms with experiments from the literature. The aim is to extend the FGM/ESF approach for hydrogen combustion, including differential diffusion modelling strategies.

Case and Methodology

The turbulent lifted hydrogen flame in vitiated coflow, studied by Cabra et al. [1], is simulated through LES. The flame stabilization in this set-up is controlled by fuel jet and hot coflow (oxidizer) mixing, and it occurs where the equilibrium between convective transport and reaction rate is reached. Therefore the lift-off height is a very sensitive parameter. A preliminary analysis is carried out using the ESF closure in conjunction with detailed chemistry, solving a transport equation for every species with the model implemented by Breda et al. [2]. Two kinetic mechanisms, Ó Conaire and San Diego, are compared. A wall-adapting local eddy-viscosity model (WALE) is used for the subgrid stress closure in both simulations. The same test case will be simulated to evaluate the performance of the *ESF/FGM* model, as an adaption of the solver by Breda et al. based on (REDIM) tabulation. A database of 300 freely propagating 1D flamelets is generated in *CHEMID* with the San Diego mechanism and parametrized on a progress variable and a mixture fraction, for which transport equations are solved. The reactants mixture through the database spans a range of H₂, O₂, H₂O and N₂ composition at different temperatures according to the jet/coflow mixture fraction. The *ESF/FGM* will be further extended to include differential diffusion effects adapting the model proposed by Mukundakumar et al. [3], and the sensitivity of the results will be addressed.

Results

The lift-off height in the Cabra flame has been shown to be sensitive to turbulence specification in the jet and coflow temperature. The two kinetic mechanisms are compared here at fixed

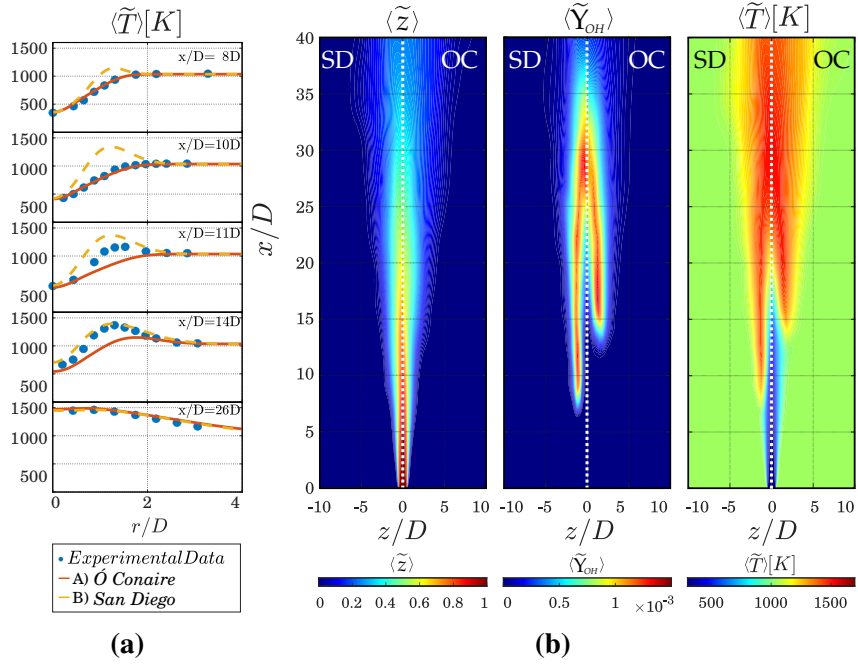


Figure 1. a) Radial temperature profiles for different axial locations. b) Mid-plane contours of average mixture fraction, OH mass fraction and temperature: San Diego mechanism (left), Ó Conaire mechanism (right)

inlet turbulence conditions. The full transport solver predicts a stable flame for both kinetic mechanisms. However, there is a high sensitivity of the lift-off height to the chosen mechanism. Figure 1a shows the radial temperature profiles for different axial locations. The presence of a combustion reaction is characterised by a peak in temperature on the jet shear layer, around $1.3 r/D$. San Diego predicts a lift-off height of around $9D$, close to the experimental observation of $10D$. For Ó Conaire, a lift-off height of around $14D$ is observed, which is significantly higher.

The mid-plane contours in Figure 1b further strengthen this observation. The OH radical, which is an intermediate species in the oxidation reaction, has higher concentrations upstream for San Diego. Higher reaction rates for radicals in this mechanism, due to differences in kinetic parameters, facilitate the oxidation reaction. This in turn allows the flame to stabilise earlier in the jet. The San Diego mechanism, therefore, presents itself as the preferred choice for the ESF/FGM version of the solver, which is still under development.

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An experimental study on fire propagation characteristics of lithium iron phosphate batteries

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Abstract

The lithium iron phosphate (LiFePO₄) battery exhibits excellent thermal stability, making it a promising candidate for energy storage applications. However, in the event of thermal runaway, the release of flammable gases can lead to a dangerous situation. Typically, the thermal runaway process involves two stages of gas injection, with the first stage dominated by electrolyte vapor and the second stage dominated by a mixture of combustible gases such as CH₄, H₂, C₂H₄, C₃H₆, CO, and CO₂. Under the combined effects of solid heat transfer and convective heat transfer of vent gas, the lateral propagation of thermal runaway in LiFePO₄ battery modules is not easily triggered. However, if the released gases are ignited by an external source, such as an electric spark, the thermal runaway of a cluster of LiFePO₄ batteries can propagate longitudinally, aided by flame and thermal radiation. This phenomenon is referred to as the "fire propagation" of LiFePO₄ battery clusters.

Keywords: Lithium iron phosphate battery, Energy storage, Thermal runaway propagation, Fire propagation

Figure 1 depicts the temperature and voltage profiles of vertically arranged batteries during a thermal runaway and fire propagation event. The lower layer battery was heated using a heater, and when it experienced thermal runaway, the combustible gas was ignited using a spark. The jet flame continuously heated the bottom of the upper layer battery until a location on the jelly roll reached the trigger temperature for thermal runaway, causing the upper layer battery to also trigger thermal runaway. The voltage curve indicates that when the lower layer battery jet flame heating continued until 376 s, the battery separator at the bottom ruptured, causing massive internal short-circuiting of the battery with various exothermic and gas-producing reactions occurring inside the battery. The released gas was ignited and produced sustained jet flames.

After the lower layer battery jet flame heating continued for 47 s and heated the upper layer battery, the pressure relief valve of the upper layer battery opened and released combustible gas, which ignited when exposed to a flame. At 431 s, the upper layer battery entered the main eruption phase of thermal runaway, with the pressurized combustible gas mixture undergoing violent combustion under the influence of fire propagation.

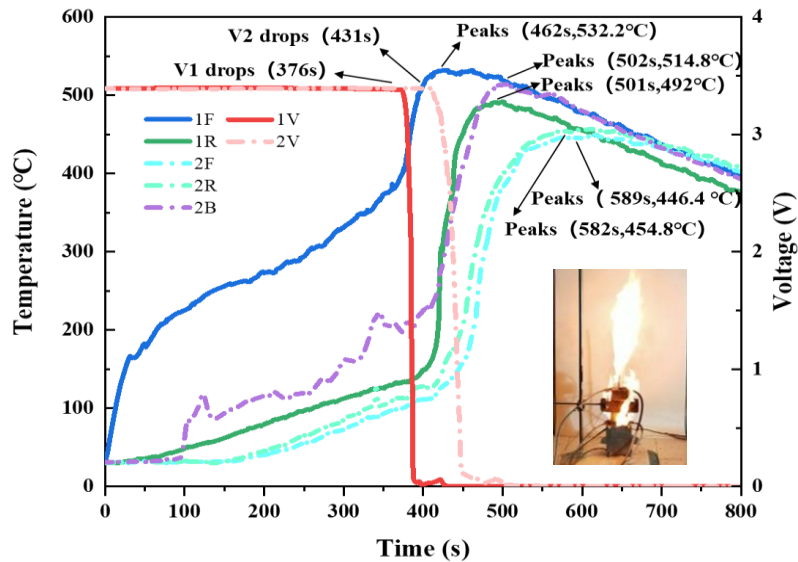


Fig. 1 The fire propagation behavior of lithium iron phosphate battery

In the thermal runaway process of LiFePO_4 battery cells used for energy storage, the flame has little effect on the surface temperature of the battery. When there is no flame, the LiFePO_4 batteries for energy storage will only trigger lateral thermal propagation. When there is a flame, the LiFePO_4 batteries for energy storage can trigger both lateral and longitudinal thermal propagation. The energy flow display of an LiFePO_4 battery module for energy storage indicates that 25.5% of the combustion energy can trigger longitudinal fire propagation.

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