Flame Self-Interactions in Turbulent Boundary Layer Flashback of Hydrogen-Rich Combustion

David Stewart
Department of Mechanical Engineering
University of Newcastle Upon Tyne
Supervisor: Dr Umair Ahmed

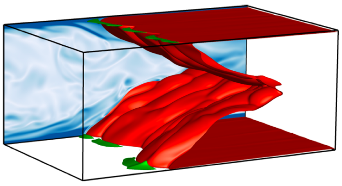
Abstract

A three-dimensional Direct Numerical Simulation (DNS) database of a premixed hydrogen-rich flame in turbulent boundary layer flashback has been interrogated to investigate the distribution of flame topologies associated with flame self-interaction (FSI) events for the first time. The analysis has been carried out at different axial locations within the turbulent channel flow to demonstrate the boundary walls influence on the statistics of FSIs. It has been found that the presence of the boundary wall has significant influence on the geometry of the tubulent flames surface, and consequently the burning rate, providing valuable information in terms of modelling.

Introduction

Climate change is becoming an increasing issue globally, with power generation industries striving to gain control over pollutent emmisions. Hydrogen-rich syngas fuels are being considered as a clean and efficient fuel for emission free power generation. Hydrogen has the cleanest combustion pollutants, an infinite hydrogen water cycle and high energy effiency. However the properties of hydrogen that allow for these great benefits increase the risk of flame flashback, which is the uncontrolled upstream propagation of a flame. This phenomena leads to the development of hydrogen combustors much more challenging. It is essential to achieve improvements of the predictive capabilities in the modelling of boundary layer flashback for hydrogen-rich combustion if we are to develope future combustors to harness this pioneering energy source for a cleaner and more sustainable future.

Figure 1. Iso-surface of temperature at 1700K with regions of negative flow (flashback) shown as green iso-surfaces.



Methodology

Turbulent premixed flames comprise of a thin and highly wrinkled layer of reacting gas that forms an interface between unburned reactants and hot products. When a flame sheet wrinkles and interacts with itself, local FSI topologies are produced and they effect the burning characteristics of the flame significantly. The four main FSI topologies investigated are Burnt Gas Pockets (BGP), Unburnt Gas Pockets (UBGP), Tunnel Closures (TC) and Tunnel Formations (TF). These FSI topologies must be fully understood if we are to formulate accurate models for hydrogen combustion.

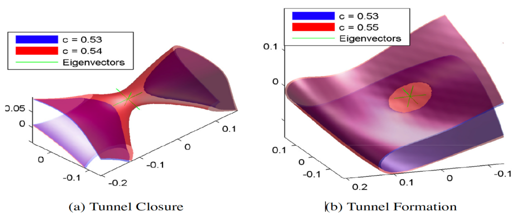


Figure 2. Example of two FSI

For an explaination on the mathematics on how these topologies are identified within the DNS database you are directed to reference [1]. My project focused on investigating the nature and distribution these FSI topologies within the channel flow at different wall distances to provide an understanding of the boundary walls influence on turbulent premixed hydrogen-rich flames for the purpose of improving surface-based modelling methods. These models will be used in the design of future industrial combustion equiptment.

Project Aims

To interrogate a DNS dataset corresponding to a premixed hydrogen-air flame in turbulent boundary layer flashback at different distances from the boundary layer to identify the walls influence on the nature and distribution of FSI topologies.

Results and Discussion

The findings of this analysis shared agreements on the flames behaviour with similar DNS studies of turbulent premixed flames but new inconsistencies were also observed suggesting the boundary layer significantly influences the geometry of the flames surface.

Results in Agreement with Previous Studies

Figure 3.

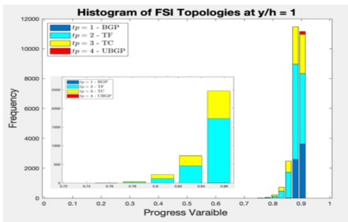


Figure 3. shows the frequency of FSI topologies at the channel half height. It shows that the FSI events exisisted in a very confined region at the trailing edge of the flame towards the burnt products. It also shows the rarity of UBGPs (red bar) explained by the transient nature of such an event. These obervations are in agreement with ref. [2] and [3] respectively.

Results in Disagreement with Previous Studies

Figure 4.

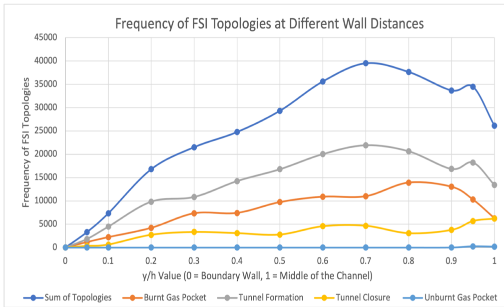


Figure 4. shows the frequency of each FSI event and the overall frequency at different differences from the boundary wall. We can see the overall frequency of FSI events increases with distance from the boundary wall, then decreases towards the region of the channel half height. This behaviour has never been observed before for turbulent premixed flames at boundary layer flashback.

From fig 4. the frequency hierarchy of FSI events is seen to be TF > BGP > TC > UBGP which is inconsistent with three previous studies [2][3][4] of freely propagating turbulent premixed flames. This suggest the boundary wall has a significant effect on the flames local topologies and thus surface area, and consequently the overall turbulent burning rate. By analysing the mean and Gaussian curvatures of the FSI topologies we can derive and catagorise their surface geometries. It was found that at the vicinity of the wall, all the FSI topologies were of a convex cup surface geometry. The predominant surface geometries for UBGP, BGP, TF and TC events were saddle concave, cup convex, cup convex and saddle concave respectively. This is in disagreement with ref. [2] and [4] were they describe the geometries to be cup concave, cup convex, saddle and saddle respectively.

Conclusion

It is evident from the finding within this analysis that the presence of the boundary layer wall has a significant effect on the geometry of the flames surface and consequently the overall turbulnt burning rate. Understanding the statistical behaviours and frequencies of these FSI events is of fundamental importance to formulate accurate models on turbulent premixed combustion at boundary layer flashback, aiding the design of modern industrial combustion equiptment. The findings of this analysis may need to be accounted for when formulating surface-based models around the aforementioned flow conditions.

References and Acknowledgement

I am grateful for Dr Umair Ahmeds' continued support throughout this project and for ROCKET-HPC.

[1] R. Griffiths, J. Chen, H. Kolla, R. Cant and W. Kollmann, "Three-dimensional topology of turbulent premixed flameinteraction", Proceedings of the Combustion Institute, vol. 35, no. 2, pp. 1341-1348, 2015.
[2] G. Ozel-Erol, U. Ahmed, and N. Chakraborty, “Flame self-interactions in globally stoichiometric spherically expanding flames propagating into fuel droplet-mists,” Proc. Combust. Inst.
[3]S. Trivedi, G. V. Nivarti, and R. S. Cant, “Flame self-interactions with increasing turbulence intensity,” Proc. Combust. Inst. 37, 2443–2449 (2019).
[4] S. Malkeson, U. Ahmed, A. Pillai, N. Chakraborty and R. Kurose, "Flame self-interactions in an open turbulent jet spray flame", *Physics of Fluids*, vol. 33, no. 3, p. 035114, 2021.