

Turbulent premixed hydrogen flames at high Karlovitz number: A DNS study

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1 Introduction

There has been increasing interest recently in applying hydrogen or hydrogen-rich fuel to combustors due to the potential for near-zero carbon dioxide emissions. The turbulent velocity fluctuation in realistic combustion devices is reported to be 150 times higher than the lean hydrogen laminar flame speed [1]. However, direct numerical simulation (DNS) of hydrogen flames under such high turbulence intensities is rare as the high hydrogen flame speed requires high resolution to achieve the turbulent Reynolds number for realistic turbulent flames.

The aim of this work is to gain detailed understanding of the structure and statistical quantities of premixed turbulent hydrogen/air flames in an unconfined three dimensional domain in the presence of homogenous, high speed turbulence using DNS with detailed chemical mechanisms.

Turbulent flames simulated in this work (Flame A, B and C) are shown in the regime diagrams [2]. Flame A and B are characterised to be thin reaction flames, while Flame C lies in the broken reaction zone in the diagram.

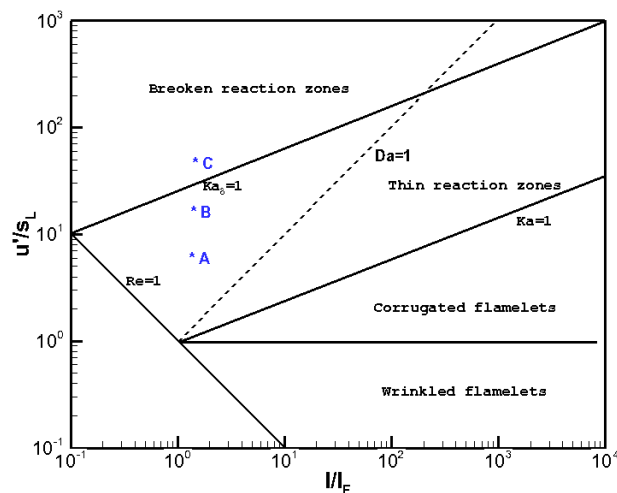


Fig 1. Simulated cases in the regime diagrams

The important non-dimensional characterisation numbers are Karlovitz and turbulent Reynolds numbers, respectively defined to be

$$Ka = \left(\frac{u'}{S_L} \right)^{3/2} \left(\frac{l_L}{l_\lambda} \right)^{1/2} \quad Re_t = \frac{u' l_\lambda}{S_L l_L} \quad (1)$$

where u' and l_λ are the turbulent intensity and integral length, S_L and l_L are the laminar flame speed and laminar flame thickness, respectively.

A particular focus was placed on the flame transition from thin reaction zone to distributed zone with increasing turbulence intensity. The turbulent velocity to laminar flame speed ratio was 4.18-40.96, corresponding to a maximum Reynolds number of 67.71 and Karlovitz number of 204.

2 Numerical Approach

The reacting Navier-Stokes equations are solved here with six order spatial differential scheme and third order Runge-Kutta scheme for time advancing. A forcing term is added to the momentum equations to initialize the cold flow of hydrogen/air mixture with the equivalence ratio of 0.7 until a developed turbulent field is obtained. The forcing method follows the approach by Haugen [3]. The one dimensional unstretched laminar flame is computed incorporating chemical, transport and thermodynamics models [4], and then superimposed to the turbulent field in the three dimension simulations of the transient turbulent flame evolution.

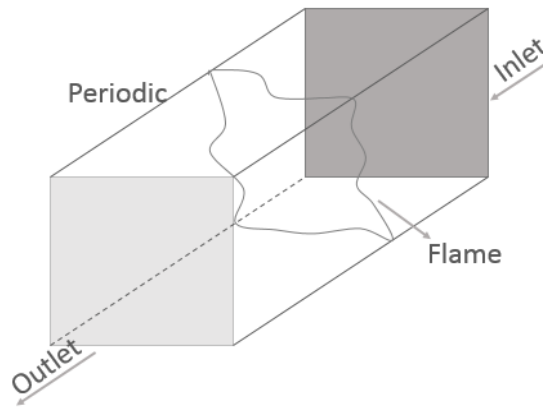


Fig 2. Schematic diagram of the computing configuration. Periodic boundary conditions are adopted in the lateral directions while inflow and outflow boundary conditions are imposed in the flow direction.

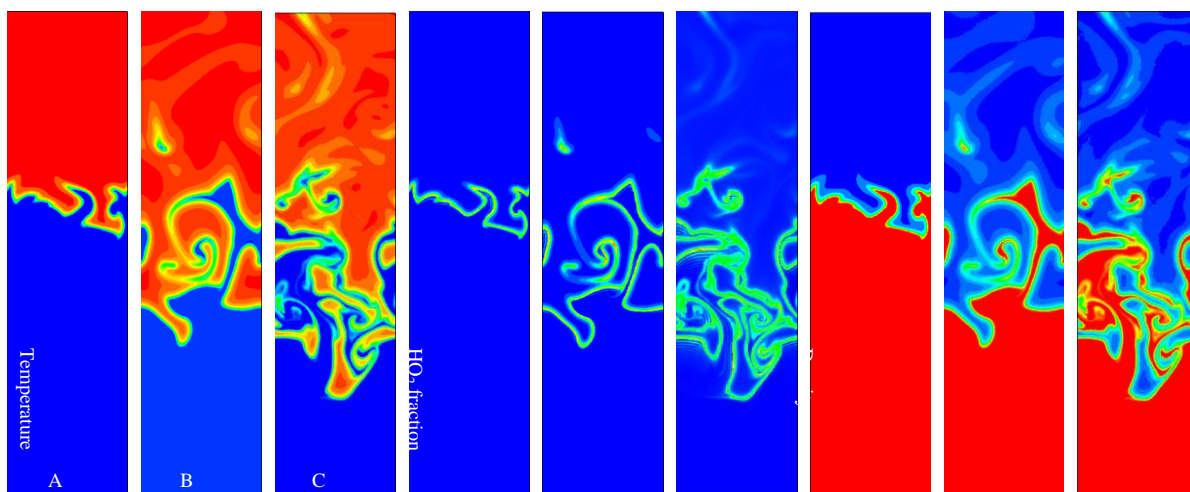
Flame properties are summarized in Table 1. The aspect ratio of the computing domain is 1:1:4, allowing sufficient space for the turbulent flame to develop. The flame zones are resolved with nine grid points in all the three cases, which is considered to be sufficient.

Table 1: Turbulent flame parameters for the three different cases

Case	A	B	C
Equivalence ratio (φ)	0.7	0.7	0.7
Flame speed (S_L) (cm/s)	160	160	160
Flame thickness (l_L)(cm)	0.0313	0.0313	0.0313
Integral length(l_λ) (cm)	0.045	0.045	0.052
Length ratio	1.44	1.44	1.65
RMS velocity (u')(cm/s)	668	1946	6554
Velocity ratio	4.18	12.16	40.96
Turbulent Reynolds number(Re_t)	6.04	17.72	67.71
Kalovitz number(Ka)	7	35	204

3 Results and discussion

Flames with different turbulent Reynolds number and Karlovitz numbers are shown in Figure 3 after reaching the statistically steady state. The lowest turbulent intensity is only able to wrinkle the flame front, which still remains a continuous surface. Flame B, with a moderate Karlovitz number, consists of large cellular structures as smaller turbulent eddies have been consumed before they wrinkle the flame front. As Karlovitz number increases, the burning zone has been broadened to several times thicker than the laminar flame, as can be seen in Flame C, which is known as the flame brush effect. For the highest turbulent intensity, the flame area has also been significantly increased. High turbulent velocity results in higher curvature of the flame front, giving rise to higher OH mass fraction concentration and fuel burning rate. Turbulence is able to carry the fresh gas to the product and there is no longer sharp interface between the burned and unburned gas. It is worth noting that the individual structures of Flame C are smaller due to the strong effects of turbulence despite a slightly larger initialized integral turbulence length. The results show that at high turbulent Reynolds numbers, small eddies can penetrate flame front, generating unburned fuel pockets in the product zone. The obtained physical insight and statistical analysis can be incorporated into hydrogen turbulent flame modeling.

Fig 3. Two dimensional snapshots for temperature, HO_2 fraction and density for Flame A, B and C.

References

- [1] Strakey P, Sidwell T, Ontko J. Investigation of the effects of hydrogen addition on lean extinction in a swirl stabilized combustor[J]. Proceedings of the combustion institute, 2007, 31(2): 3173.
- [2] Peters N. Turbulent combustion[M]. Cambridge university press, 2000.
- [3] Haugen N E L, Brandenburg A, Dobler W. Simulations of nonhelical hydromagnetic turbulence[J]. Physical Review E, 2004, 70(1): 016308.
- [4] Ströhle J, Myhrvold T. Reduction of a detailed reaction mechanism for hydrogen combustion under gas turbine conditions[J]. Combustion and flame, 2006, 144(3): 545.