

# Three-dimensional Visualization of Flame-Vortex Entrainment in Hydrogen/Methane air Mixtures

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## 1 Introduction

The introduction of hydrogen into the energy sector in the form of fuel blends with natural gas to reduce carbon emissions has revealed new gaps in our understanding of how these blends behave. In terms of industrial process safety, one concern is the potential for flame acceleration after accidental ignition, especially in congested environments. Despite methane (the primary component of natural gas) and hydrogen having similar burning expansion ratios, the physical properties of hydrogen-air and methane-air flames, including flame thickness and flame time, differ significantly. Methane is considered a relatively unreactive fuel, with a low burning velocity and long flame time. In contrast, hydrogen is much more reactive.

Following the ignition of a flame in a duct, the characteristics of the flame-driven flow play an important role in the propagation and acceleration of the flame. When bluff body obstacles are present in the duct, vortical structures are formed in the flow downstream of the obstacle. The subsequent interaction of the flame with these vortices is believed to generate substantial flame deformation and acceleration. In the present study, we investigate the deformation of the flame resulting from its interaction with these vortices. The experiments were performed in stoichiometric hydrogen-air, methane-air, and an equimolar blend of hydrogen and methane with air at ambient conditions. The obstacle downstream of the flame front is intended to simulate conditions near a vented explosion.

In the second set of the experiments, two parallel mirrors positioned at a 45-degree angle are installed on the top and bottom walls of the shock tube to visualize the third dimension of the flame along width of the shock tube. This method is applied for the first time in this study to visualize flame three-dimensionally, and the shadowgraph technique is used to capture the flame evolution.

The flame acceleration of pure fuels has been extensively studied, however, the behavior of fuel blends in this regard remains unclear. Johansen and Ciccarelli investigated the flame acceleration process in an obstructed square cross-section channel. They found that the initial rates of flame acceleration were higher for large blockage ratios due to enhanced turbulence production and increased bulk burning rate associated with a larger flame area [1]. W.L. Roberts et al. studied the effects of flame curvature for flames with Lewis numbers less than and above unity [2]. For flames with Lewis numbers less than unity, where there is a strong positive flame curvature, the reaction rate is enhanced. These results agree with the analysis of Law [3], who showed how the reaction rate should increase where the local burned

gas temperature is enhanced by the thermodiffusive effects. For flames with Lewis numbers greater than unity, positive flame curvature causes a reduction in the reaction rate [2]. Shi et al. studied the effects of differential diffusion of hydrogen (H<sub>2</sub>) on flame structure in laminar premixed fuel-lean H<sub>2</sub>/CH<sub>4</sub>/air polyhedral flames. The results reveal that the positively curved troughs have significantly higher H<sub>2</sub> mole fraction compared to the negatively curved cusps, due to the respective focusing/defocusing effect of curvature on highly diffusive H<sub>2</sub>. Consequently, the local equivalence ratio and temperature in trough regions are higher than those of cusps [4]. Dejoan et al. had numerical study of the propagation of isobaric premixed flames in narrow channels [5]. They investigated the effects of thermal expansion, Lewis number and heat losses in planar channel geometry. Like the results presented in [6] in narrow channels, for mixtures with Lewis numbers below one, even just slightly below, there is always a critical channel width beyond that the non-symmetric solutions appear. Based on their conclusion, at least two different kinds of instabilities/effects contribute simultaneously to the emergence of non-symmetric flames in narrow channels. The first one is the differential-diffusion instability, and the second one is the Landau–Darrieus instability.

The present study examines and compares flame acceleration and vortical structure entrainment in three mixtures, stoichiometric hydrogen-air, methane-air, and equimolar blend of methane-hydrogen with air. We study this experimentally using a thin 19 mm rectangular cross-sectioned shock tube (Fig. 1) in which a cellular flame is ignited near a closed end using a long wire ignition technique. A single rectangular obstacle with a 50 percent blockage ratio is placed ahead of the flame, and the far end of the tube is opened to the ambient environment, such that the flame propagation is not restricted by a closed wall. To visualize the third dimension, two parallel prism mirrors with a base length of 19 mm are installed on the top and bottom walls of the shock tube (Fig. 1). The evolution of the flame as it passes over the obstacle is visualized using shadowgraph technique. Prior to each experiment, the shock tube was evacuated to a pressure of no more than 425 Pa before being filled with atmospheric pressure with a reactive mixture. The pressure evolution was measured using pressure transducers placed along the top and bottom walls of the shock tube.

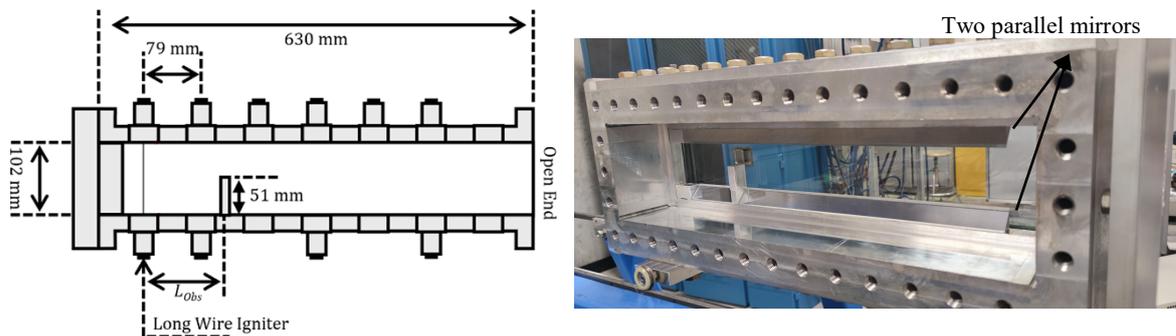


Figure 1: Diagrams of the experimental setup and shock tube configuration. The width of the shock tube is 19 mm(left). Mirrors configuration inside the shock tube for three-dimensional visualization(right).

## 2 Results and discussion

Selected frames that summarize the evolution of the flames as they propagate through the channel can be seen in Fig.2. By propagating the flames inside the channel and the volumetric expansion of the burned gas, flame-induced flow is created ahead of the flames. With the presence of an obstacle downstream, a pressure gradient is generated, resulting in flames deformation and stretch as they approach the obstacle.

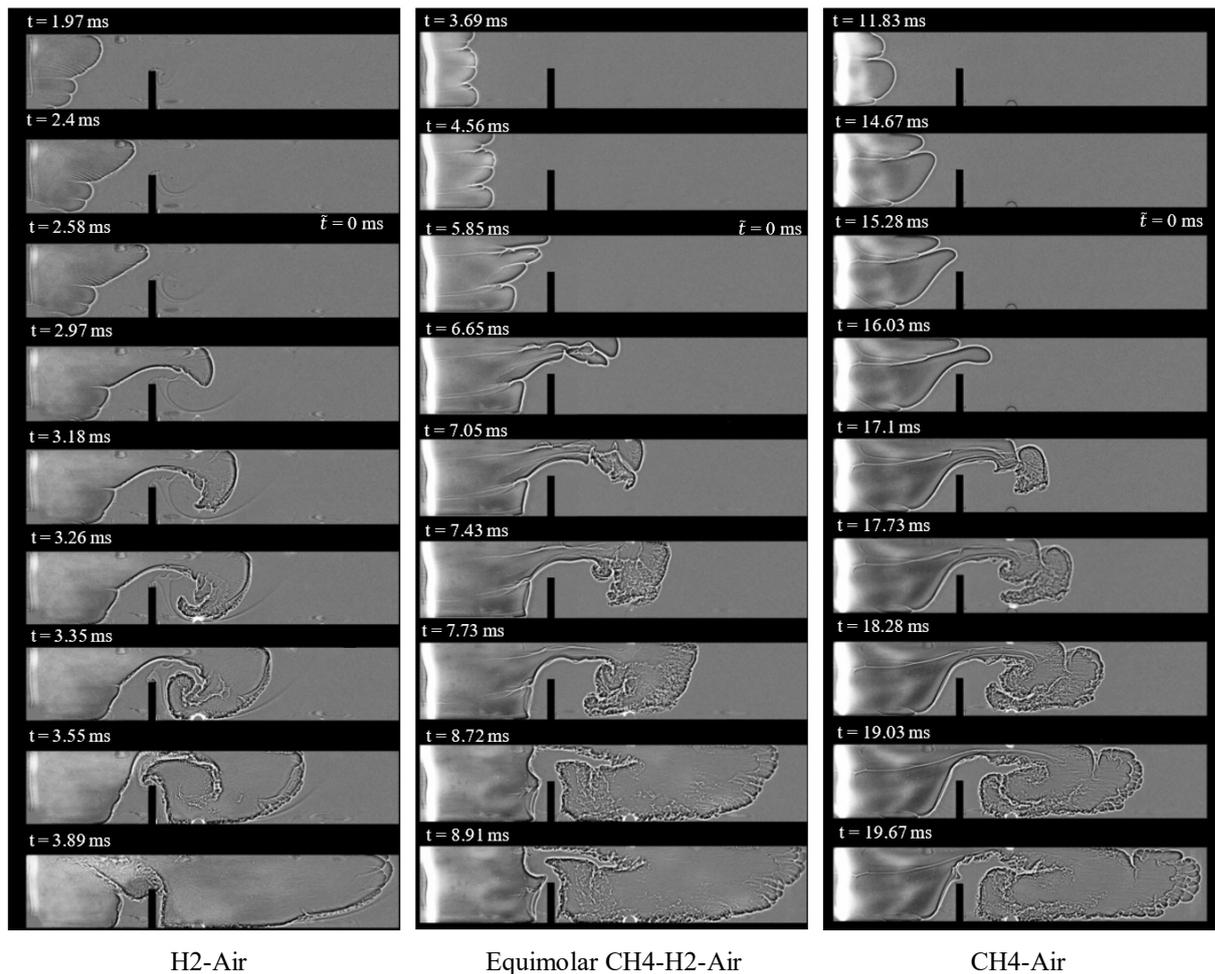


Figure 2. Evolution of the flame visualized using shadowgraph technique. Times are shown above each frame,  $t=0$  is the time when the flame ignites, and  $\tilde{t} = 0$  is the moment the flame tip crosses the leading edge of the obstacle.

Shortly thereafter, the flames are entrained into a vortical structure, which is the result of the flame-driven flow over the obstacle since the ignition of the flame and Kelvin-Helmholtz instability. As a result of this flame entrainment, the flame front surface area grows considerably and increases the combustion rate. This more rapid combustion causes a stronger flow and flame acceleration in the channel. On the other hand, as the flame area and fuel consumption rate increase, a strong compression wave propagates downstream and the flame accelerates, an expansion wave will propagate in the opposite direction, resulting in a pressure decay in the shock tube.

These three flames interact differently with vortical structures. The hydrogen-air flame as a reactive fuel, has a smaller flame time compared to the other mixtures and consumes the vortex rapidly as it rolls up into it. It is less prone to disturb by vortex and turbulent shear layer above the obstacle. In contrast, vortices disturb and break the flame structure in methane and equimolar mixtures, causing these flames to get entrained into them for a longer time.

Fig.3 illustrates the evolution of flame tip velocity over time. The velocity is measured as the forward most flame front location along the horizontal axis in experimental photographs. To assess repeatability, more than ten experiments were carried out for each mixture. Each curve has been adjusted in time such that the flame tip crosses the leading edge of the obstacle at  $t = 0$ . It is evident that the hydrogen flame propagates significantly faster than the methane flame, while the equimolar blend propagates at a speed in-between the two extremes throughout the experiment.

The flame tip velocity evolves similarly in each mixture. Initially, there is a gradual increase in velocity for negative times, which is associated with the initial growth of cellular structures along the flame surface from a relatively flat ignition kernel. Shortly before time zero, a much sharper increase is observed. This increase in flame tip velocity is the result of the flame's deformation in the vicinity of the obstacle. This deformation is caused by the Rayleigh-Taylor mechanism induced by flow gradients that occur due to the acceleration of the flow through the vena contracta. The velocity field of the flow ahead of the flame dictates both the propagation and deformation of the flame. When the flame passes through the vena contracta, there is a sudden enlargement in cross-sectional area and causes flow diverging. Due to this flow expansion and flame entrainment in vortices, flame tip velocity decreases for a short period (see Fig.3). This decrease in flame speed continues until a minimum is reached. At this point, there is a reactive coupling between the increase in burning rate associated with the enhancement in flame front area resulting from the flame roll-up, and the strong acceleration of flow induced ahead of the flame by the rapid expansion of the burned gases. This acceleration of the flame tip continues until the flame exits the field of view.

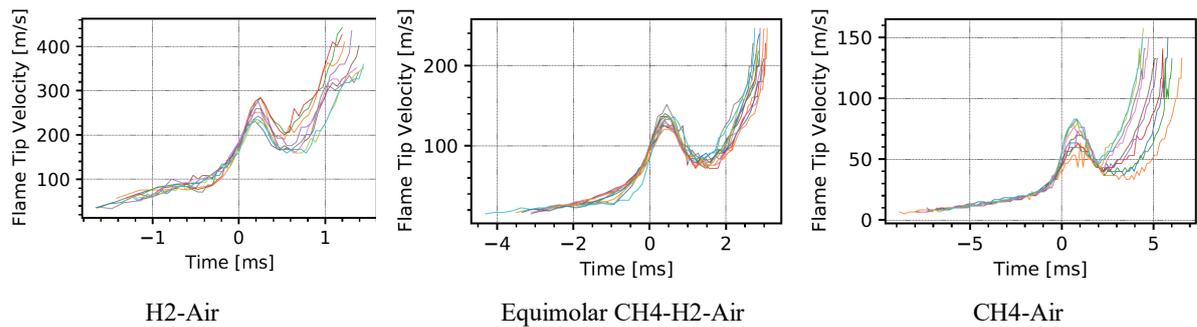


Figure 3: Evolution of the flame tip velocity over time. Time  $t = 0$  is defined as the moment when the flame tip crosses the leading edge of the obstacle.

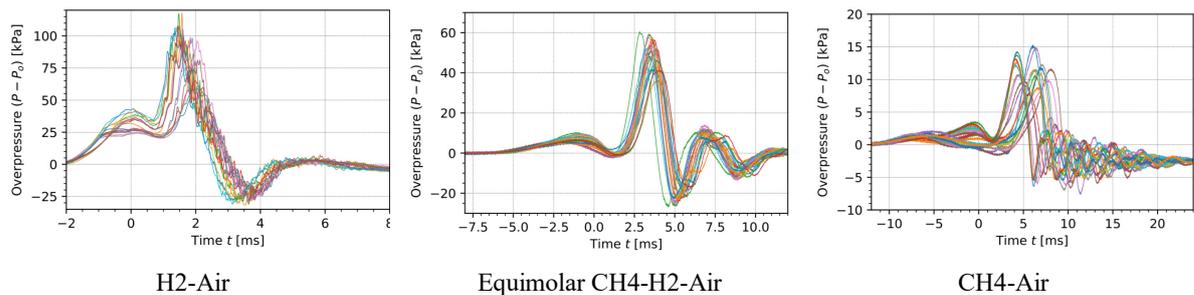


Figure 4: Evolution of the pressure over time, for experiments in each mixture, measured near the obstacle. Time  $t = 0$  is defined as the moment when the flame tip crosses the leading edge of the obstacle.

The evolution of the pressure inside the shock tube is presented in Fig. 4, where the pressure is plotted against time. The hydrogen flame exhibits the highest overpressure peak, reaching up to one atmosphere, while the methane flame generates the weakest overpressure, with a 15 kPa peak. The overpressure peak for the equimolar blend is around 60 kPa inside the shock tube. Like the flame tip velocity, the pressure evolves similarly in each mixture. There is an initial increase in pressure associated with the initial increase in cellular structure of the flames. When the flames reach the vena contracta, due to sudden depressurization in the throttle, there will be a pressure decay for a short period of time (Fig.4). As the flames roll up into vortical structures, the flame front surface area increases considerably which causes an increase in fresh gas combustion rate and pressure inside the shock tube. With the increase in flame area and fuel consumption, and the acceleration of the flames, an expansion wave will propagate in the opposite direction, resulting in a pressure decay in the shock tube.

## 2.1 Flame area amplification in the mixtures

To identify the deformation and area enhancement of these flames, we can express the pressure and velocity measurements obtained from the experiments in a non-dimensional form. This approach effectively eliminates the dependence on the distinct laminar burning velocities of each mixture. The overpressure inside the tube is scaled by  $\rho_u \sigma^2 S_L^2$  and flame tip velocity is normalized by the factor  $\sigma S_L$ . Where  $S_L$  is laminar flame speed,  $\sigma$  shows expansion ratio and  $\rho_u$  is density of unburned gas. Fig.5 and Fig.6 show the non-dimensionalized flame tip velocity and pressure over time.

Fig.6 illustrates the non-dimensionalized overpressure inside the shock tube over time. The normalized pressure of both the equimolar blend and methane-air flames ends up being much higher than that of hydrogen-air flames. The maximum normalized pressure in the equimolar blend flame is amplified to almost double the amplitude of the maximum scaled pressure in the methane-air mixture. When scaling the flame propagation velocity and pressures, it becomes apparent that the hydrogen flame has a smaller surface area enhancement compared to the methane and equimolar flames. Hydrogen-air has a much shorter flame time compared to the other mixtures, allowing it to consume vortices more quickly and less prone to disturb by the flow field. Also in hydrogen flame, the smaller folds in flame front are used up faster than they can expand, and the increase in the surface area is thus mainly due to the deformation of the larger scales of the flame surface. In the methane and equimolar flames, the efficient folding of the flame surface at smaller scales also contributes to their larger surface areas, as the consumption of these folds cannot keep pace with their growth. In these two flames the vortical structures disturb flames and the flames get entrained into vortices for a longer time. This difference in flame interaction with vortex between these three mixtures can be seen in Fig. 2.

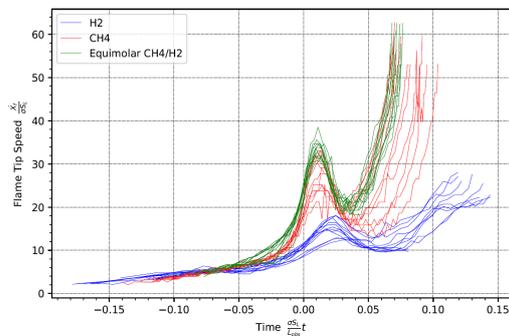


Figure 5. Scaled flame tip velocity as a function of scaled time

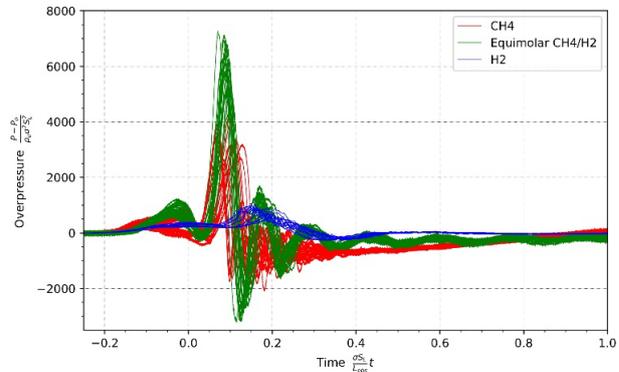


Figure 6. Scaled overpressure as a function of scaled time

## 3 Three-dimensional Visualization

In the present study, a novel method is introduced for visualizing the third dimension of a flame as it propagates inside a shock tube for the first time. Two parallel mirrors, positioned at a 45-degree angle, are installed on the top and bottom walls of the shock tube to visualize flame three-dimensionally. Selected frames in Fig.7 summarize and compare the evolution of the flames as they propagate through the channel and the third dimension of flames evolution can be seen along the bottom of each frame. It is observed that hydrogen and equimolar mixtures exhibit more 3D effects than methane flames. Hydrogen and equimolar flames tend to incline along the width of the shock tube (appears as double line in the flame front) and exhibit this behavior more intensely when they become entrained in the vortical structures and accelerate. On the other hand, methane flame is less prone to inclining in the third dimension or showing 3D effects, tending to propagate more uniformly compared to the other two.

One possible explanation for this behavior could be the effect of the Lewis number. Hydrogen and equimolar flames, with Lewis numbers below unity, are more prone to show 3D effects compared to methane flames, which have Lewis numbers close to unity. Dejoan [5] and Kurdyumov [6] studied the propagation of flames in narrow channels for mixtures with Lewis numbers smaller than one. They demonstrated that for Lewis numbers below one, even just slightly below, there is always a critical channel width beyond which the flames tend to exhibit a non-symmetric formation. In our experiments, this non-symmetric shape appears as an inclination along the width of the shock tube and can be seen clearly in hydrogen and equimolar mixtures in Fig.7.

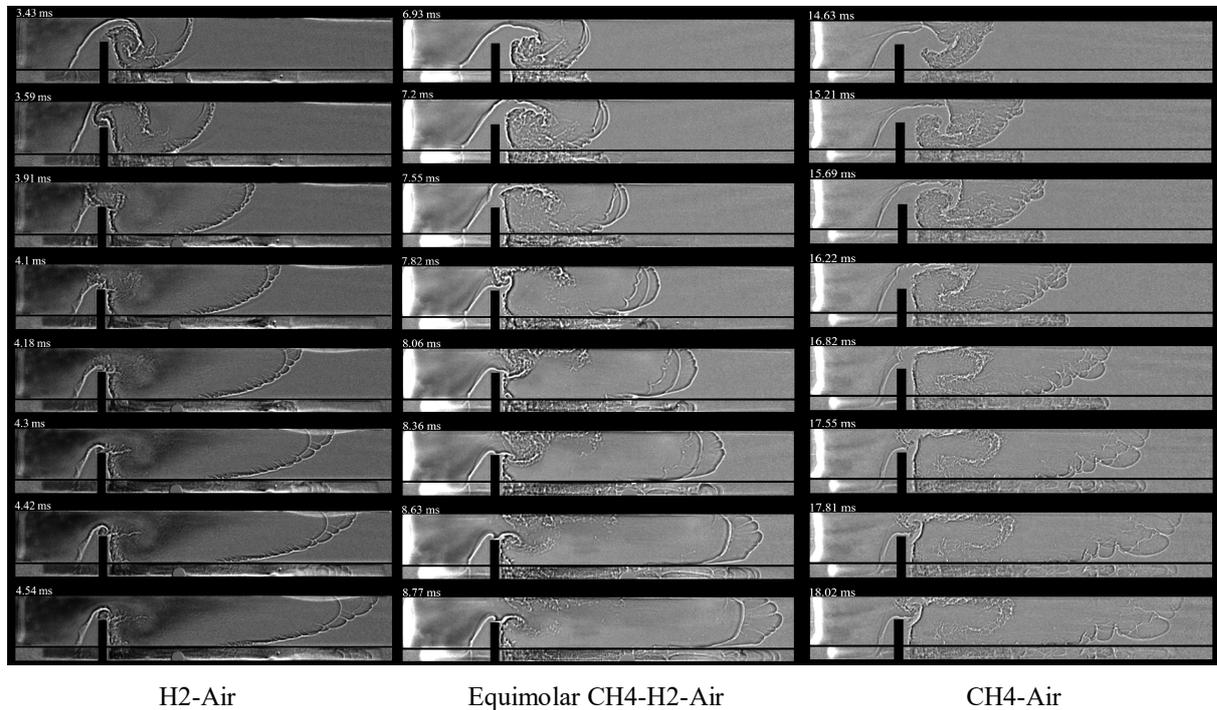


Figure 7. Three-dimensional visualization of the flame using shadowgraph technique. Times are shown above each frame,  $t=0$  is the time when the flame ignites

## 4 Conclusion

In this study experiments were conducted to characterize the differences between flames propagating through stoichiometric mixtures of hydrogen, methane, and an equimolar hydrogen-methane blend with air. When a bluff body obstacle is present downstream of the flames, vortical structures are formed in the flow field. The subsequent interaction of the flame with these vortices is believed to generate substantial flame deformation and acceleration. The measured evolution of the flame speed and overpressure inside the shock tube highlights the higher reactivity and flame acceleration of the hydrogen-air flame compared to methane-air and equimolar blend-air mixtures. The pressures and flame tip velocity measured in the equimolar blend fall somewhere between these two extreme mixtures.

To identify the deformation and area enhancement of these flames, the pressure and velocity measurements obtained from the experiments were normalized by  $\rho_u \sigma^2 S_L^2$  and  $\sigma SL$  respectively. This approach effectively eliminates the dependence on the distinct laminar burning velocities of each mixture. Interestingly the equimolar blend mixture has the highest normalized velocity and overpressure, followed by the methane mixture. The hydrogen mixture exhibits the lowest scaled velocity and overpressure inside the shock tube. Hydrogen-air has a much shorter flame time compared

to other mixtures, allowing it to consume vortices rapidly and less prone to disturb in vortical structures. In the other mixtures, vortices can disturb and break the flame structure, causing these flames to get entrained into them for a longer time. The efficient folding of the flame surface at smaller scales also contributes to their larger surface areas, as the consumption of these folds cannot keep pace with their growth.

For methane and equimolar mixtures with a Damköhler number less than unity, all the eddies, including the length scale vortex of the turbulence spectrum, have the capability to disrupt the preheat zone and wrinkle the flame front area [7]. A smaller Damköhler number for the methane mixture results in more disturbance of the flame structure and local extinction compared to the equimolar blend. Additionally, in the equimolar flame, due to an increase in the concentration of hydrogen in the positive curvatures of the flame front compared to its planar form, the amount of local quenching induced by turbulence is reduced. As a result, the equimolar mixture records a higher normalized pressure than the methane mixture. On the other hand, for the hydrogen-air mixture with a Damköhler number greater than unity, the flame time is shorter than the characteristic time of the vortical structure. As a result, the flame can withstand the effects of turbulence and is less prone to deformation. This leads to a smaller flame surface enhancement, normalized pressure, and normalized flame tip velocity compared to the methane-air and the equimolar blend mixtures.

Hydrogen and equimolar flames show more 3D effects than methane flame. Hydrogen and equimolar flames tend to incline along the width of the shock tube and exhibit this behavior more intensely when they get entrained into the vortical structures and accelerate. On the other hand, methane flame is less prone to inclining and tend to propagate more uniformly in the third dimension compared to the other mixtures.

These results indicate that the higher normalized pressure and flame tip velocity in the methane and equimolar blend flames are not due to the 3D effect, as the hydrogen flame exhibits greater 3D effects, but has lower normalized pressure and flame tip velocity compared to the methane flame. This suggests that the Damköhler number has a more significant impact than the Lewis number.

## 5 References

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