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Investigation of curvature effects on the reactivity of premixed ammonia-air flames

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Introduction

Ammonia-air flames are characterized by low flame speeds, thick flames and low reactivity. To enhance the reactivity of these flames, the impact of different parameters on the inner structure of the flame must be studied. One of the parameters that could influence the reactivity is the curvature effect. Turbulent flames are known to induce such curvature and strain which may aid to modify the reactivity of a flame. There are several studies done on swirl flows [1, 2] and on turbulent flows [3, 4]. However, turbulence is very complex in nature. The elementary way to study curvature effects is to study a perturbed laminar flame. In this work, acoustic perturbations generating flame-acoustic interactions are used to study the curvature effects on premixed ammonia-air flames. There is hardly any experimental work done on studying perturbed laminar ammonia flames. However, there are some numerical simulations performed. Netzer et al. [5] studied the curvature effects on NO formation and emphasized on the diffusion effects of lighter species and its effect on local curvature. From the work done by Wei et al. [6], it can be concluded that the PDF of HRR (heat release rate) indicated that the HRR was more likely to occur at slightly negatively curved flames. From our previous work [7], the inner structure of stationary premixed ammonia-air flames on a Bunsen burner at atmospheric conditions for equivalence ratios ranging between 0.9 and 1.4 was thoroughly investigated. It was concluded that NH* and NH_2* are good indicators of HRR. Since NH_2* has a higher emission signal when compared to NH*, tracking NH_2* alone as an indicator of HRR should give sufficient information. This study focuses on the curvature effects induced from the acoustic perturbations on NH_2* for φ= 1.4 at atmospheric conditions on a Bunsen burner.

Materials and Methods

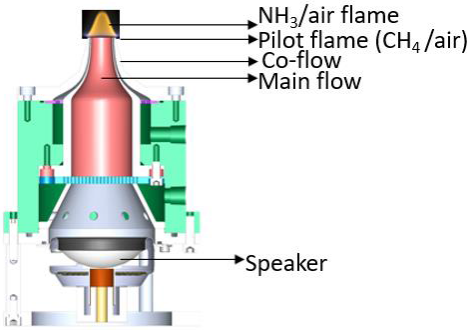

Fig. 1. The schematic diagram of the Bunsen burner

The experiments were performed on a Bunsen burner set-up at atmospheric conditions for φ= 1.4. Fig. 1 shows a schematic diagram of the burner. A pilot flame consisting of methane-air at stoichiometry is used to stabilize the main flame. Tests have been carried out to ensure that there is no interference of the pilot flame with the parameters of interest that are monitored in this study. Moreover, the main study has been formed away from the base of the flame. Rotameters are used to control the flow of the pilot flame and mass flow controllers are used to control the feed to the main flame. For the acoustic generation, a speaker is placed at the bottom of the burner and is connected to an amplifier which is further connected to a wave generator. Using the wave generator, the type of the wave, the amplitude and the frequency of the wave can be controlled. Upon performing several tests, it was decided that sin waves with a forcing amplitude of 0.5 V and forcing frequency of 40 Hz was to be used to generate the desirable perturbation. A low speed sCMOS camera (KURO) was used to capture the images. An objective lens used for the visible range spectrum is attached to the camera. To monitor NH_2*, a filter at 632 nm was initially mounted on the objective lens and it was noticed that the signal-to-noise ratio for this dynamic flame was too low. Since there are several bands of NH_2* emission peaks in the visible region, tests were done to study and compare

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the images of stationary flames with and without the NH_2* filter and it was concluded that indeed, without using the NH_2* filter a collective information on all NH_2* band spectrum is obtained.

Results and Discussions

Half of the inverted Abel transformed images of the flames at φ=1.4 is shown in Fig. 2 respectively. The blue dotted line represents the central axis. These images were captured at almost the same instant in order to have a similar flame response. To assess the curvature effects, the mean curvature was found along the contour at different positions marked in loops at the outermost contour of these images. By convention, negative curvature is associated with a concave front towards the burned gas and a positive curvature is associated with a convex front towards the burned gases. It was seen that the mean curvature effects did not afford any usable information and so this mean curvature was further split into two principle curvatures, k_1 along the contour of the flame and k_2 along the circumferential direction. To assess the reactivity, two parameters: thickness along the normal to the front and the maximum intensity along the normal to the front were used. Thickness is defined as the FWHM (full width half mean) of the Gaussian curve with a 95% confidence interval obtained when moving along the normal to the front. On plotting the four parameters against each other, it was seen that k_1 and thickness had similar trends and could be correlated. Therefore, only these two parameters are discussed here.

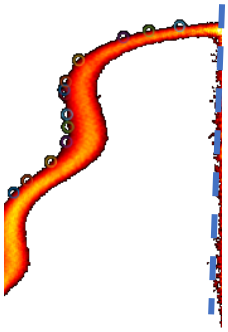

Fig. 2. Left half of inverted Abel transformed image of FAI at φ=1.4. Coloured loops representing the selected points.

Le is slightly more than 1 and so the thermal diffusion rate of the burned gases towards the fresh gases is slightly more than the molecular diffusion of the fresh gases to the burned gases. The thickness of the flame clearly varies along the contour and it was seen that the variation was associated with k_1. Here, the more positive the k_1, the higher the thickness and vice-versa. The large variation in thickness associated to minor variation in k_1 implies that Le is not the only parameter that influences the flame response and its reactivity. It was seen that the intensity of the flame decreased from the base to the tip irrespective of the value of the curvature. Upon, performing several tests to capture different flame responses to the same excitation, this observation was confirmed. It is understood that the convective-diffusion velocities played a major role in the reactivity rather than the acoustic perturbation itself. The effect of preferential diffusion on the reactivity of curved flames has been highlighted by Mizomoto et al. [8]. On computing the Damköhler number, Da it was seen that this value was close to 1 indicating that the time scale of the perturbation was not sufficient to see the curvature effects on the species reactivity when compared to the chemical scale. The convective velocity was about 25 times the diffusion velocity of ammonia into air at ambient conditions. This indicates that it is not ammonia that directly diffuses onto the sides of the flames but ammonia itself decomposes into lighter species that diffuses faster than the convection flow. The preferential diffusion of H_2 and other species towards the sides play a major role in enhancing the local reactivity.

Conclusions

Flame-acoustic interactions were performed to study the curvature effect on the reactivity of the species. These experiments were performed for premixed ammonia-air flames on a Bunsen burner at atmospheric conditions for φ=1.4 with an acoustic perturbation of forcing amplitude 0.5 V and forcing frequency of 40 Hz. It was seen that for the given perturbations, the Lewis number had a more dominant effect on the reactivity implying that at least for these conditions, even though the perturbations were high enough for the flame to respond with alternative curved fronts, the Damköhler number shows that for these thick flames, the time scale of the perturbation was not sufficient to induce a change in reactivity due to the imposed curvature effects. It may be concluded that for thick flames, the preferential diffusion effects play a large role in any changes in reactivity and as far as curvature effects are concerned, the effect of k_1 can be seen as a change of thickness with positive k_1 leading to an increase in thickness and vice-versa.

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