Stretch Effects on Premixed and Diffusion Flames – A Review

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Abstract— The purpose of this review is to have broad view of the effect of stretch on premixed and diffusion flames. Stretch is nothing but non-uniformities associated with flames and its surface in order to change geometry of flames, its burning rate and physical properties such as laminar burning velocity of flame (in case of premixed flames). In this paper along with stretch the effects of various diluents like CO_2, H_2O, CH_4 and N_2 are also studied. Properties of high pressure flames under curvature and wrinkling condition shows considerable change in intensity of turbulence. Various gaseous fuels like syngas, iso-octane, hydrogen, propane and heptane premixed with air forming premixed flames along with analysis of diffusion flames of these gaseous fuels are surveyed with available literature.
Key words: Stretch, Diluents, Flame Structure, Premixed Flame, Diffusion Flame

I. INTRODUCTION

Premixed flames are formed when fuel and air as an oxidizer are mixed before the burning, for example flame front formed in spark ignition engine. Diffusion flames are those flames which formed at boundary of diffusion or mixing, for example candle flame. The premixed flame and diffusion flames are associated with many physical and chemical properties. These physical and chemical properties are not only inter-related with each other but also influenced by each other. Their behavior changes when one or several properties are subjected to be changed. Various heat transfer phenomenon like convection, conduction and radiation also plays very important role in the self-sustaining nature of these flames. Transport properties like thermal diffusivity and molecular diffusivity which govern the heat loss in flames and maximum temperature attainment while burning. The laminar burning velocity is associated with premixed flames and it is strongly dependent on temperature and thermal and molecular diffusivities. It is also affected with stretch in flame. Stretch can be imparted or act as governing factor while assigning inter-relationship between various chemical and physical properties of premixed and diffusion flames.

II. LITERATURE REVIEW

R. Woolley et al. (2002) [1] studied iso-octane and methane-air premixed flames. These flames have been ignited in a spherical bomb stirred by fan apparatus in laminar conditions and flow fields of turbulent nature at pressure condition of 1 and 5 bar. Images in the form of sheet of the flames were captured using laser induced fluorescence of OH radicals. The spherically expanding laminar type of flames shows the shape of cusps in the flame surface to change from a dent with +ve Markstein numbers to a Huygen type cusp at lower Markstein numbers and at the end complete quench was observed at the cusp tip on flames

with -ve Markstein numbers. Rich iso-octane-air flames with turbulent nature (equivalence ratio =1.4) exhibited the distance between quench areas to increase as the turbulence intensity was raised. The high pressure 5 bar flames shows higher curvature than those at lower pressure 1 bar. The flame wrinkling and the curvature is studied with the influence of laminar flame and turbulent flow properties.

Hong G. Im et al. (2000) [2] studied stretch effects in unsteady manner on the laminar burning velocity of premixed hydrogen/air flames using 2D (dimensional) direct numerical simulation (DNS) with detailed chemical kinetics and transport properties. The fuel mass equivalence ratio from fuel-lean to fuel-rich conditions are varied to study preferential diffusion unsteady stretch interactions. The inter-relation of the laminar flame velocity with curvature and stretch is determined along with other propagation statistics of flame. It is found that definitions of burning velocity based on heat release and fuel consumption give rise to different correlations of burning velocity with curvature for some fuel-lean conditions. The burning velocity is dependent on strain and curvature. The observation to be noted is that the theory for flame propagation in the case of weak stretch is more widely applicable under turbulent stretch conditions. The strain contribution to the Markstein number is computed from the DNS data and compared against experimental analysis and numerical counterflow analysis data. An agreement between all three approaches is found in terms of the crossover value of the equivalence ratio from -ve to +ve Markstein numbers and for fuel-lean condition of stoichiometries. It is observed from DNS that strong stretch–preferential diffusion correlation exist in the turbulent flame, with computed Markstein numbers varying from 5.34 to 2.85 and area-weighted mean burning velocities of flame as high as 2.43 times the laminar burning velocity. It is further found that over a wide range of mixture stoichiometries, as the ratio of the characteristic turbulence to flame transit time decreases, the flame response to stretch is attenuated. This is resulting in a marked decrease in Markstein number. This is in line with linear theory and recent counterflow computations under unsteady conditions.

Joel Daou (2011) [3] provided a reversible chemistry model with an analytical description of the effect of preferential diffusion and volumetric heat loss on strained premixed flames. The model comprises a single reversible reaction of the form Fuel F ↔ Product P whose forward and backward rates follow rate of reaction with an Arrhenius law. An asymptotic analysis is carried out in the limit of infinitely large activation energy of the forward reaction. The study allows for non-unit Lewis numbers for the F and the P. Two main contributions are made which are as following. The first contribution is in identifying the fundamental differences in the asymptotic description of the non-adiabatic flame. The second contribution is with the

determination of the multiplicity and the domain of the solutions.

T. Yokomori et al. (2003) [4] investigated experimentally the effects of a spatially non-uniform stretch rate on the temperature of flame. A flame surface with a non-uniform stretch rate was formed by creating a wrinkled laminar premixed flame in a spatially lean propane/air mixture periodic flow field. The measured flame temperature was lower than the adiabatic flame temperature at flame segments with positive stretch rates and higher than adiabatic flame temperature at flame segments with negative stretch rate. This was a result of the effects of flame stretch and preferential diffusion for Lewis number greater than unity. The flame temperature calculated using the conventional flame stretch theory. It is based on a uniform stretch rate along the flame surface. But not agreed quantitatively with the measured temperature. Therefore, the theory is revised by taking heat transfer along the flame surface, which produced estimates that agreed with the measured temperature. It is found that the effect of flame stretch and preferential diffusion is changed along the flame surface which has spatially non-uniform stretch rate. This is causing a temperature gradient along the surface. This in turn transfers heat and changes the flame temperature. Thus, heat transfer along the flame surface is an important factor in calculating flame temperature. Therefore, heat transfer in conductive nature is believed to occur between the flame and the burned gas. The effect of the downstream heat transfer is not as significant as that of the heat transfer along the flame surface.

Y. Huang et al. (2004) [5] studied the laminar flame speeds of neat primary reference fuels (PRFs), n-heptane and iso-octane, PRF blends, reformer gas, and reformer gas/iso-octane/air mixtures. These are measured over a range of equivalence ratios at atmospheric pressure, using counterflow configuration and digital particle image velocimetry technique. Primary reference fuel blends with various octane numbers are analyzed. The synthetic reformer gas mixture used herein has a composition that would be produced from the partial oxidation of rich iso-octane/air mixture into CO and H_2, namely, 28% H_2, 25% CO, and 47% N_2. The experimentally calculated laminar burning velocities are simulated using the detailed kinetic models available in the literature. Both experimental and computational results shows that the flame speeds of hydrocarbon with air mixtures increase with addition of a little amount of reformer gas, and the flame speeds of reformer gas with air mixtures are dramatically decreased with addition of a small amount of hydrocarbon fuel. Furthermore, the density effect of seeding particles on flame speed calculation is estimated out, and the experimental uncertainties associated with the present digital particle image velocitmetry setup as well as the linear extrapolation method employed are discussed.

K. Safer et al. (2013) [6] reported a numerical study of syngas opposed flow diffusion flame structure and emissions. The numerical investigation is done over a wide range of operating conditions of pressure from 1 to 10 atm and H_2/CO ratio between 0.4 and 2.4. The study is focused on finding optimal operating conditions in regard to NOx emissions and NOx reactions pathways. The computational results revealed that flame structure and emissions are affected by syngas composition and pressure conditions. The maximum flame temperature shows a peak at an intermediate scalar dissipation rate for a given value of H_2/CO ratio. Flame structure is influenced by combined effects of adiabatic temperature and radiation heat loss for values of strain rate lower than the intermediate value, in this only adiabatic temperature effect is significant at higher values of strain rate. The flame temperature is higher for higher hydrogen content for strain rates values lower than intermediate value. The opposite behavior is observed at strain rate values higher than the intermediate value that is flame temperature is lower. NOx formation is function of flame temperature. Higher Hydrogen content syngas flames shows more NOx formation at lower strain rates while NOx levels increase towards lower hydrogen content syngas flames at higher strain rates.

Shih et al. (2011) [7] reported a numerical study on the extinction characteristics of opposed-jet syngas diffusion flames. One-dimensional model of opposed flow syngas non-premixed flames was formulated with constant strain rate. The model used detailed chemical kinetics and thermal and transport properties along with flame radiation by narrowband statistic radiation model. The analysis is done with detailed flame structures, species production rates and net reaction rates of key chemical reaction steps. The effects of varying syngas compositions, dilution gases like CO_2, N_2, and H_2O and pressures on the flame structures and extinction limits of H_2/CO flames were discussed. The flame structures and flame extinction are strongly affected by the compositions of syngas mixture. Flame temperature rises with increasing hydrogen content and pressure, but the flame thickness shows decrement with increasing pressure. The study of the dilution effects showed the maximum flame temperature is decreased the most with CO_2, while CO-enriched syngas flames with H_2O dilution has highest peak flame temperature. The extinction occurs due to the race between the chemical and radiation effects. At the end, extinction limits were obtained with minimum hydrogen content in syngas as the criteria at different pressures. This has provided a basic understanding of syngas combustion and applications.

S. Som et al. (2008) [8] presents a numerical and experimental investigation of the combustion and NOx characteristics of syngas under varying composition of its contents, pressure and strain rate. Experiments were done at atmospheric conditions and the numerical simulations considered at different pressures. Both experiments and simulations indicate that stable diffusion and partially premixed opposed flow flames (PPFs) can be established for a wide range of syngas compositions and different strain rates. In syngas partially premixed flames, the amount of NO formed first shows rapid increment with pressure, but then come to levels at higher pressures. At a given pressure, the peak NO mole fraction shows a non-monotonic variation with syngas composition, first decreasing to a least value, and then increasing as the amount of CO in syngas is raised. This underlines, there exists an optimum syngas composition that yields the lowest NO production in syngas partially premixed flames.

D.E. Giles et al. (2006) [9] reported a numerical investigation on the effects of syngas composition and diluents on the structure and emission characteristics of

syngas non-premixed flames. The counterflow diffusion syngas flames are simulated using two representative syngas compositions as main combustible gaseous components 50%H_2/50%CO and 45%H_2/45%CO/10%CH_4 by volume, and diluents as N_2, H_2O, and CO_2. The impact of these diluents is characterized in terms of their ability to reduce NOx production in syngas diffusion flames. Results show that syngas diffusion flames are influenced by relatively high temperatures and high NOx concentrations. The presence of methane in syngas shows decrement in the maximum flame temperature, but increment in the formation of prompt NO significantly. For above mentioned both mixtures of different H_2 and CO, diluents CO_2 and H_2O are more effective than N_2 in reduction of NOx in syngas diffusion flames. H_2O is the most effective diluent on a mass basis, and the in case of remaining diluents CO_2 is more effective than N_2. The high specific heat of H_2O decreases the thermal NO, and it reduces the concentration of CH radicals, which decreases the prompt NO. But the effectiveness of all three diluents is reduced with the presence of methane in syngas composition.

Jeong Park et al. (2009) [11] numerically studied chemical effects of added CO_2 on flame extinction characteristics in H_2/CO syngas non-premixed flames with dilution of CO_2. The two syngas composition of 80% H_2+20% CO and 20% H_2+80% CO are analyzed according to the composition of fuel mixture diluted with CO_2 and global strain rate. The concentration is focused on impact of chemical effects of diluent CO_2 on flame extinction characteristics. This is done through the comparison of the flame characteristics between well-burning flames far from extinction limit and flames at extinction. It is observed that chemical effects of diluent CO_2 reduce critical CO_2 mole fraction at flame extinction and thus extinguish the flame at higher flame temperature irrespective of global strain rate. This decreases reaction rate. These chemical effects of diluent CO_2 are similar in well burning flames far from extinction limit as well as flames at extinction. The anomalous behavior of a mismatching between critical CO_2 mole fraction and maximum flame temperature is observed at extinction.

III. CONCLUSION

Flame wrinkling and curvature effects on high pressure flames are significant. More curvature is observed for high pressure flames. Different correlation exists between laminar burning velocity and heat release rates and consumption rate. The flame temperature is higher than adiabatic flame temperature with negative stretch rate and lower with positive stretch rate. The heat transfer along the flame surface is an important factor in estimating flame temperature. The flame speeds of hydrocarbon with air mixtures increase with addition of a little amount of reformer gas, and the flame speeds of reformer gas with air mixtures shows decrement with addition of a small amount of hydrocarbon fuel. The flame temperature is higher for higher hydrogen content. But there exists an optimal composition of syngas which gives lowest NO production. In case of diffusion syngas flames most effective is H_2O diluent, then comes CO_2 and last is N_2.

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