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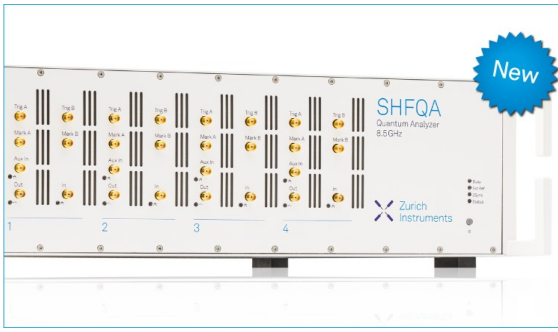

Analytical Comparison of Lean Premixed Turbulent Bunsen Flames at High Inlet Temperatures and High Operating Pressures

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Abstract The technology of premixed turbulent combustion is extensively used for energy conversion in piston engines, gas turbines, and aircraft after-burners. Current environmental regulation seeks newer methods to function on stringent lower emissions and to achieve improved combustion efficiency. This technology is seen as a solution, operating at low temperature combustion for fuel economy and reduced emission (HCs and NOx). However, it is still seen as an evolving study, for example, on flame extinctions, ultra-lean fuel/air mixtures and influence of high inlet temperatures and high operating pressures. Kobayashi's group [1] was among one of the first to carry out high-pressure experiments on Bunsen burner flames. They found that normalized turbulent flame speed is a strong function of equivalence ratio and high operating pressures. A detailed validation of this data has led to development of algebraic flame surface wrinkling by the present first author ([2]) and was subsequently validated for other configurations and varied conditions ([3]). In the current study, we analytically investigate a newer set of experimental methane flames, blended with hydrogen for a combination of inlet temperatures 473K and 673K for operating pressures 3 and 7 bar that have practical significance in gas turbines [4] [5]. We compare the analytical values with the experiments, for these high inlet temperatures and operating pressures.

INTRODUCTION

Enrichment of hydrogen-premixed fuel combustion is of great interest, both for its application and fundamental study. A significant number of experimental and numerical combustion simulations at high pressures for a varied lean single fuel/air mixtures and turbulence levels were carried out. However, only fewer studies are seen to, particularly for hydrogen doped fuels for the gas turbines conditions. A series of experiments on turbulent flames on a Bunsen burner show that turbulent burning velocity normalized by unstretched laminar flame speed, S_T/S_{L0} is pressure dependent and increases with increasing pressure [1]. Increasing need for more sustainable and eco-friendly fuels has driven the research into alternative fuels such as methane enriched with hydrogen. Kido et al. [6] gave a profound analysis from their experiments that turbulent burning velocity dramatically increases for lean mixtures by hydrogen enrichment. Mandilas et al. [7] found that for 30% H_2-enrichment of CH_4 lean mixture, turbulent burning velocity increases by two-fold. Schefer et al. [8] studied hydrogen infusion in methane/air flames premixed mode in a combustor at atmospheric pressure and for swirling flow conditions. An improved flame stability is postulated to be a direct result of boost in the key reaction rates due to the H, O, OH radical concentrations; specifically 13.8% hydrogen caused an increase of 44% in the maximum OH concentration, an indication of increased reaction rate. Wicksall et al. [9] examined flame and flow field interaction in an enclosed lean premixed swirl-stabilized combustor operated on methane (CH_4) and hydrogen (H_2). They observed that CH_4 flames are longer than those of the hydrogen-enriched. The latter flames are more stable and robust. The CH_4 flame is seen extinguished in the high velocity inlet jet region, where the H_2-enriched CH_4 flame was able to sustain combustion [9]. Guo et al. [10] found that the addition of hydrogen can substantially broaden the flammable region and extend the flammability limit to lower equivalence ratios. Lachaux in his doctoral thesis [11] has experimentally found that the effect of pressure on the turbulent flames is due to increased finer length scales that enhances flame surface density, despite the fact that high pressures has an opposite effect on laminar burning velocities [11, 12]. Another study shows similar findings that flames are accounted in the thin wrinkled flame regime at the atmospheric pressure but later it is seen as shifting towards the thickened wrinkled flame

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regime zone because of the flame front thickening effect of smaller scale turbulent eddies generated by increased pressure [13]. The flames at higher pressure show a fine, convoluted flame front structure and an enhanced small-scale wrinkling [6]. DNS of high pressure turbulent premixed CH_4/H_2 flames by Cecere et al. [14] showed an increase in the turbulent flame speed from ~5.7 ms^{-1} to ~10.7 ms^{-1} as the pressure increases further by reducing the total flame length (from ~ 0.011 m to ~ 0.006 m) at constant reactants bulk velocity, pointing towards increased mixture reactivity.

Here, an analysis of Bagdanavicius et al. [5] experiments for turbulent burning velocities of alternative gaseous fuels at elevated temperature and pressure are presented and compared with the combustion model values. The experiments are functioned on two methane–hydrogen compositions, with 15% and 30% by volume of hydrogen doping mixtures at two different inlet temperatures, 473 K and 673 K and two different high pressures, 3 bar and 7 bar. The tests were carried out inside a high-pressure optical chamber incorporated within the high-pressure combustion rig. A horizontally mounted burner confined in an optical pressure casing for firing into an inner combustion chamber. The cylindrical pressure casing with four quartz windows, offers visual access inside. The width and height of the combustion chamber is 150 mm are made in such a way that external cooling air passes into it. A Bunsen-type burner of diameter 25 mm is used to fire into the combustion chamber.

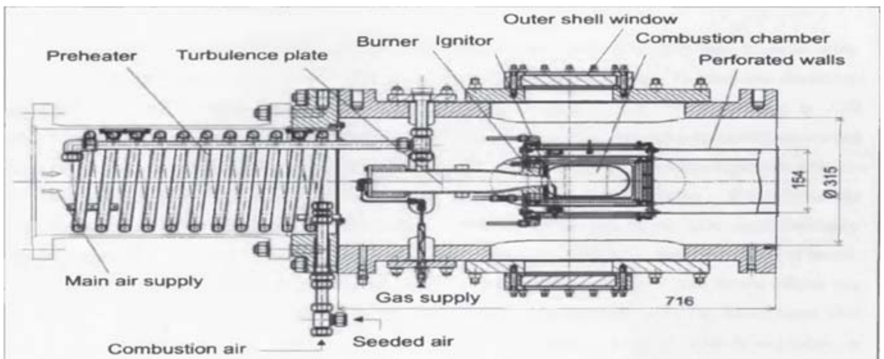

FIGURE 1. Averaged flame image contained in the cylinder [5]

RESULTS AND DISCUSSIONS

Lean premixed combustions on swirl-stabilised burner offers lower thermal NO_x emissions due to reduced flame temperature. However, lean combustion is often accompanied by stability problems that are not the subject of the study here. The essential parameter in the design of system affecting the flame quantities are stability and flame length.

According to Damkoehler theory, the increase in burning velocity is directly proportional to the increase in flame area $S_T / S_{L0} = A_T / \overline{A}$.

A closure of the this flame wrinkling ratio is given in using an algebraic parametric relation by Muppala et al. [2]

$$\frac{S_T}{S_{L0}} = \frac{A_T}{\overline{A}} = 1 + \frac{0.46}{e^{Le-1}} \mathrm{Re}_t^{0.25} \left(\frac{u'}{S_L} \right)^{0.3} \left(\frac{p}{p_0} \right)^{0.2}$$

This algebraic flame surface wrinkling (AFSW) model is validated using Bagdanavicius experimental data, for the inlet conditions given in Table 1. The measured values in comparison with the modelling ones are given in Figures 2 & 3.

TABLE 1. Experimental conditions, for (85% CH_4+ 15% H_2) or in short (85C+15H) and (70% CH_4+30% H_2) (70C+30H) mixtures. The quantity l-int is longitudinal length scale.

Test	T (K)	P (bar)	phi	S_{L0}	delta_l, mm	U m/s	u' (m/s)	l_int (mm)	Re	Le	u'/S_{L0}
1H43082	473	3	0.82	0.48	0.17	4.16	0.76	7	65	0.72	1.583333
1H63082	673	3	0.82	1.08	0.14	10.16	1.452	18	173	0.72	1.344444
1H47086	473	7	0.86	0.34	0.1	5.47	0.88	6	155	0.72	2.588235
3H63082	673	3	0.82	1.21	0.13	11.16	1.602	18	183	0.59	1.323967
3H47085	473	7	0.85	0.39	0.09	6.72	1.011	8	230	0.59	2.592308
3H43090	473	3	0.9	0.63	0.14	5.36	0.87	7	69	0.59	1.380952
3H63082	673	3	0.82	1.21	0.13	11.16	1.602	18	183	0.59	1.323967
3H63099	673	3	0.99	1.46	0.11	14.64	2.203	18	247	0.59	1.508904

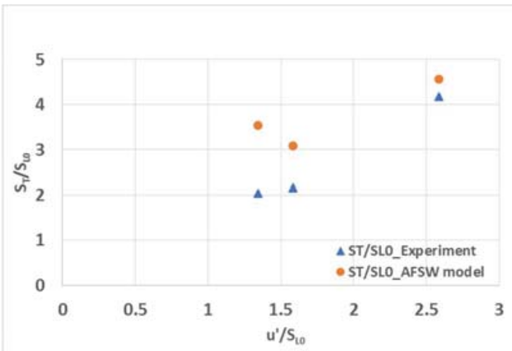

FIGURE 2. Comparison of analytical model values with experiments, for 85C+15H mixtures

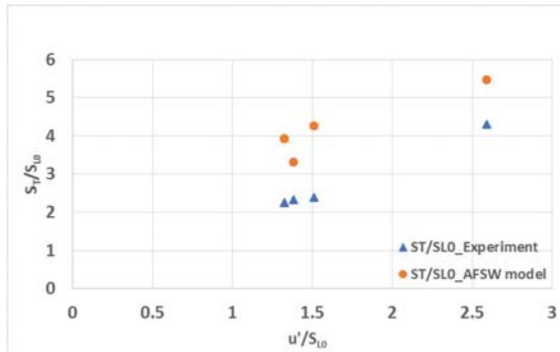

FIGURE 3. Comparison of analytical model values with experiments, for 70C+30H mixtures

As can be seen in Fig. 2, the AFSW model shows good to very good agreement with experiments for S_T/S_{L0} as a function of u'/S_{L0}. The over prediction of some data are possibly due to hydrodynamic instabilities in the vicinity of $u'/S_{L0} \approx 1$ that are not captured by the model. Inclusion of a stretch factor could enhance comparison. Fig. 2 shows good comparison for 85C+15H mixtures. The model predictions are equally good for higher hydrogen addition, (70C+30H). It is an indication, seconded by modelling results, addition of hydrogen to lean methane mixtures increases turbulent burning rate, attributed to improved flame stability.

For increase of 15% to 30% hydrogen by volume, S_T/S_{L0} increases by 24%. This increase is more predominant for higher inlet temperatures than compared to that for single fuel mixtures, keeping other conditions same. Hydrogen addition to methane has been found to considerably increase turbulent burning velocity even for smaller volumes of hydrogen addition. For lean hydrogen–methane mixtures, turbulent burning velocity increases with temperature and pressure, but more significantly with the latter quantity For 15% hydrogen addition at 3bar, increase in temperature from 473 K by 200K, shows marginal difference in S_T/S_{L0}. This is again the trend for same volume of hydrogen at 7 bar. Moreover, the effect of the temperature becomes more significant with increase of hydrogen addition. For 30% addition of hydrogen by volume at 673 K shows a considerable difference in S_T/S_{L0}. Increase in pressure has however a greater effect on S_T/S_{L0} for same percentage, for same mixture composition. Here, the model seems to overshoot for few data points in the vicinity of $u'/S_{L0} \sim 1.5$, especially for richer hydrogen mixtures. This could be attributed to flame instabilities. Increase in pressure has more pronounced effect on flame speed ratio than compared to increase in temperature.

CONCLUSION

This study analysed the experimental data for turbulent burning velocities of alternative gaseous fuels at elevated temperatures, 473 K and 673 K and pressures 3 bar and 7 bar, using the algebraic flame surface wrinkling model. The modelling results are in general in reasonable agreement, but it overpredicts 30% hydrogen and higher-pressure data. This needs further investigation. We found that there is an increase in the burning velocity for hydrogen enrichment of methane, from 15 to 30%. It is interesting finding that increase in temperature does not seem to have a remarkable effect on turbulent to laminar intensity ratio S_T/S_{L0} for an equal addition of hydrogen at same equivalence ratio. For higher proportions of hydrogen in methane/air mixture, the effect of temperature on S_T/S_{L0} becomes more significant. Finally, increase in pressure has stronger effect on S_T/S_{L0} for the same fractional addition of hydrogen to methane. Again, this increase is more evident for higher enrichment of hydrogen.

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