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Variation of Lift-off Heights with Fuel Mixtures for Flames in Vitiated Co-flows

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Abstract

This paper presents measurements of lift-off heights for turbulent non-premixed and partially premixed flames issuing from a round jet into a wide vitiated co-flow. The burner is already established as an appropriate model geometry for studying auto-ignition [1] only within the domain imposed by the co-flow. The lift-off height provides a global measure of the combined effect of mixing with the surrounding hot co-flow and the auto-ignition delay required by the "most ignitable mixtures". Earlier numerical and experimental studies of this burner flame have concentrated on two specific fuels mixtures (H_2/N_2=1/3 and CH_4/Air=1/2, by volume) [1, 4, 6]. The data base is extended here to cover other mixtures of CNG (90.1% CH4 by volume) as well as other fuels such as LPG (90.0% propane) and ethane. These were tested either as pure fuels as well as at different levels of partial premixing or with nitrogen dilution. Lift-off heights, L_H are reported here as a function of the co-flow temperature, T_c which is a key controlling parameter.

The general trends for the L_H-T_c plots are consistent with earlier findings and are similar for all fuels showing a decrease in L_H with increasing T_c and a strong significant sensitivity of the lift-off height to the temperature in the co-flow. A comparison of L_H for the range of pure fuels used here shows that CNG has the highest lift-off height and this is consistent with the fact that methane has a longer auto-ignition delay than propane or ethane. Conversely, ethane has the lowest lift-off heights and auto-ignites at lower co-flow temperatures than the other fuels. When partially premixed with air, it is found that for CNG, L_H increases with increasing partial premixing while the trend is reversed for LPG. Ethane is showing an intermediate trend where the lift-off does not change much with increasing the level of partial premixing from 25% to 100%. Such differing trends with partial premixing may be due to the different transport properties of the mixtures.

One dimensional Cantera simulations of the ignition delay of a stoichiometric mixture of each of the three fuels are also performed and compared with the experimental data. Results show that ethane and propane have a similar delay that is significantly shorter than that of methane.

Introduction

Auto-ignition is an important phenomenon in many industrial processes such as gas turbine engines, diesel engines, supersonic combustion ramjets and HCCI engines. Many experimental and numerical studies have been performed on auto-igniting flames of hydrogen and methane [2, 7, 10]. The Cabra and Dibble burner employs a wide vitiated co-flow of combustion products into which the fuel enters and auto-ignites [1]. The burner lends itself well to investigation due to its simple and well defined boundary conditions as well as good optical access. This burner has been computed by several groups using both probability density function (PDF) methods with detailed chemistry [4, 6] as well as Large Eddy Simulations (LES) with different combustion sub-grid scale models [3]. Direct Numerical Simulations (DNS) has also been employed by many for auto-ignition of hydrogen and methane [8, 9, 11, 13].

Key findings from this work so far are that auto-ignition is highly sensitive to the temperature of the surroundings and the most auto-ignitable mixtures are lean with relatively low scalar dissipation rates. The auto-ignition zones have been found to be marked with growing kernels of CH_2O in methane and HO_2 in hydrogen however studies involving other gaseous fuels have not been performed. Mastorakos gives a detailed review of the findings to date in this area [12].

The present investigation uses a version of the Cabra and Dibble burner for the purpose of investigating auto-ignition in a range of fuels. Flame lift-off height (L_H) is used as the dependant parameter and is a convenient measure of the auto-ignition delay. The independent parameters are the co-flow temperature (T_c) and the fuel mixture and the change in lift-off height is measured as these parameters are varied. Results for CNG have been repeated to establish a baseline comparison to previous data. Ethane and LPG are also tested and the effect of changing the inlet fuel/air ratio has been obtained for all three fuels. In addition, the effect of diluting with nitrogen has also been investigated.

The Burner

The burner is very similar to the Cabra and Dibble burner used for previous auto-ignition studies. The wide vitiated co-flow burns a premixed mixture of hydrogen/air through approximately 2200 holes in a perforated plate. The burnt velocity of the co-flow is constant for all cases at 4.2 m/s; it has been found previously that the co-flow velocity has only a minor effect on the flame lift-off heights [5]. The co-flow temperature is varied by changing the equivalence ratio within the range between 0.3 and 0.4. This produces a hot cone of combustion products in which the auto-ignition takes place. The single by-product of hydrogen combustion (H_2O) is expected not to influence the main auto-ignition chemistry greatly. The size of the "valid cone" has been measured to be 50 jet diameters downstream of the jet exit plane where the jet diameter (D) is 4.6mm. This measurement is based on the peak temperature at this axial location falling to 90% of the peak co-flow temperature at the exit plane. Subsequent flame lift-off measurements are therefore considered valid if they occur within this 50 diameter limit. All co-flow temperature measurements are made using a thermocouple (Pt-5%Rh/Pt-20%Rh, uncorrected for radiation) with a bead diameter of 0.2 mm and a wire thickness of 0.15 mm. The central jet diameter (D=4.6mm) allows for jet Reynold's numbers of well over 20,000 to ensure a fully developed turbulent flow.

The entire burner is housed inside a vertical wind tunnel in order to shield the burner from external air movements. It is also found that the presence of this air flow increases the length of the hot "valid cone".

Experimental method

Flame lift-off heights are determined from visual photographs of the flames. Twenty photographs are taken for the low temperature flames where the position of the flame base exhibits a high degree of variance and three photographs are taken in the high temperature region where the flame is significantly more stable. The average height is calculated from the images and the standard deviation is calculated in the cases where twenty images are used. Error bars are shown on the graphs to show plus or minus one standard deviation of the measurements. Visual determination of flame lift-off heights has been shown to be a simple but reliable method of determining the true auto-ignition location and has been found to correlate well with more sophisticated methods such as using a threshold concentration of the OH radical [6].

Boundary conditions for the flames vary somewhat due to the differences in properties of the fuels. In particular, large differences in density and viscosity cause significant differences in the Reynold's number at the exit plane of the jet. Table 1 details the important exit plane conditions for each of the fuels. Values for methane and propane are used as approximations for CNG and LPG respectively.

	Velocity (m/s)	Density[1] (kg/m^3)	Reynold's number[2]	Thermal diffusivity[2] (m^2/s)
Methane	100	0.67	27300	$2.3*10^{-5}$
Ethane	100	1.25	61100	$9.9*10^{-6}$
Propane	100	1.83	100000	$5.9*10^{-6}$

[1] Ideal gas at 20°C.
[2] Calculated from data taken from Perry's Chemical Engineering Handbook, 8th Edition, 2008, McGraw-Hill

Table 1- Boundary conditions for each of the pure fuels

Since heat transfer is an important process in the ignition of the flames, the thermal diffusivity of each of the fuels is presented. It is noted that the diffusivity for methane is approximately twice as large as that for ethane and four times that for propane. It is unknown how significant these values are for this burner although this is something that could be investigated numerically.

The data in table 1 is presented only for the pure fuels. Mixtures of these fuels with air or nitrogen will change the overall properties of the fuel jet.

Results

CNG

Flame lift-off heights for CNG fuel mixed with different percentages of air are presented in figure 1 (top). The steep increase in lift-off heights as temperature is decreased is consistent with previous results [5] although there is a shift in the graph with respect to co-flow temperature. This may be due to the measurement of the co-flow temperature using an uncorrected thermocouple. Due to the difficulty with reproducing existing data exactly, it is believed that replication of the established trends is sufficient.

The data shows that the lift-off heights tend to decrease with increasing percentage of CNG. This may indicate that the mixing time in these flames is small compared to the time required for the chemical kinetics to initiate reaction. This would imply that the premixing with air has affected the kinetics in such a way as to slow them down slightly.

Data are also collected for CNG/Nitrogen flames to determine the effect of dilution on the lift-off height. Figure 1 (bottom) shows the results for these flames. Similar trends are seen for the nitrogen flames as compared to the air flames, however it appears that for a given mixture, the nitrogen flames have higher lift-off heights than the corresponding air ones. While this trend is expected, since the mixing time required to reach an ignitable mixture would be greater for a nitrogen flame, the difference is only small. This helps support the theory, stated prior, that the role of turbulent mixing is small compared to the chemical kinetics. Despite this, dilution with large amounts of nitrogen will significantly affect the mixture fraction required to reach an ignitable mixture meaning that the lift-off heights are noticeably increased as nitrogen dilution is increased.

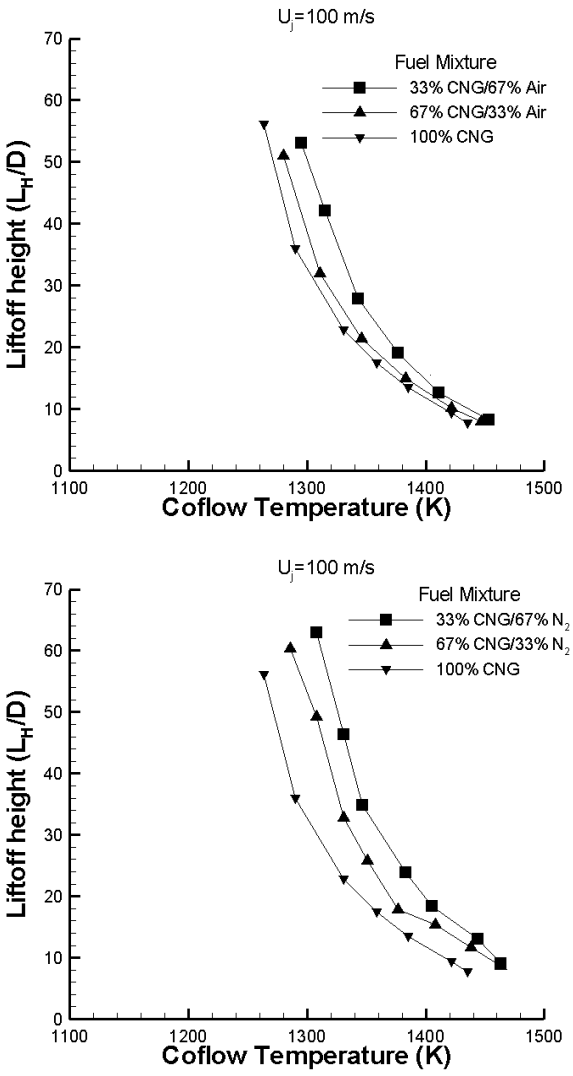

Figure 1 – Lift-off heights (L_H/D) of CNG/air (top) and CNG/N_2 (bottom) mixtures as a function of co-flow temperature (T_C).

Ethane

Data is collected for both ethane/air and ethane/nitrogen flames to investigate the effect of increasing the size of the hydrocarbon and results are shown in figure 2. Ethane is found to have significantly lower lift-off heights than CNG flames for all fuel

mixtures. The effect of changing the level of partial premixing is not as well defined as with the CNG flames. It appears as if the data is in a transition between the trend for CNG (partial premixing increasing L_H) and that for LPG (partial premixing decreasing L_H). The large uncertainty in the low temperature measurements is due to large fluctuations in the position of the flame base.

Ethane/nitrogen results showed that overall, nitrogen dilution has caused an increase in the lift-off height as would be expected. The trend displayed, as nitrogen dilution is increased, is not fully explicated however it seems that dilution up to a level of 50% N_2 has little effect on flame lift-off while dilution levels higher than 50% begin to cause an increase in lift-off height.

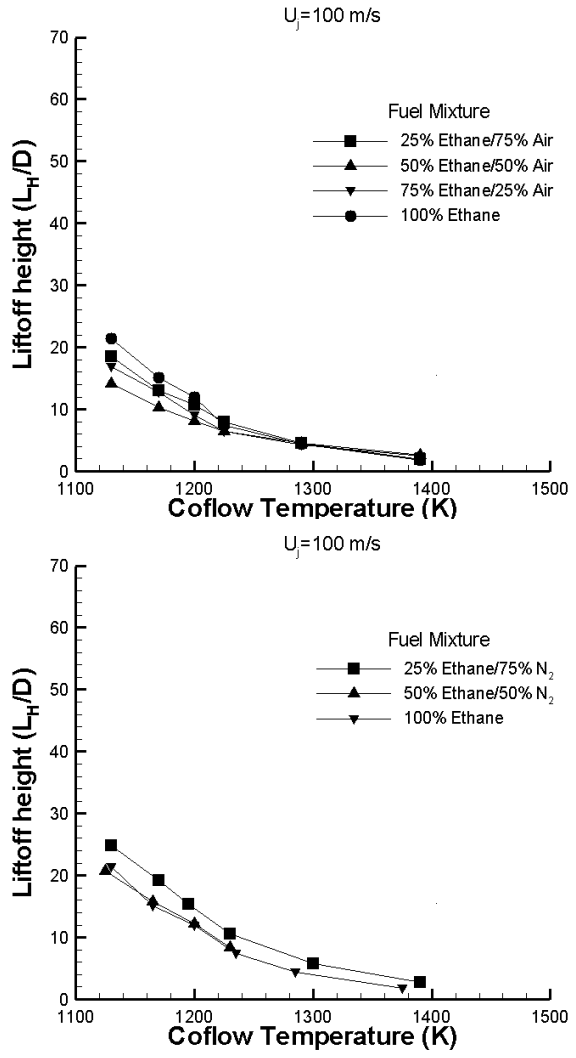

Figure 2 – Lift-off heights (L_H/D) of ethane/air (top) and ethane/N_2 (bottom) mixtures as a function of co-flow temperature (T_c). Error bars show plus and minus one standard deviation.

Propane

Finally, propane flame lift-off heights are determined for various fuel mixtures. As compared to the CNG/air flames, there is a complete reversal in the trend for the effect of partial premixing on propane flames whereby increasing partial premixing reduced the flame lift-off. There is no obvious explanation for this observation so detailed numerical modelling would be required to provide more information. The nitrogen dilution results are also in contrast to the CNG flames. Nitrogen dilution has little to no effect on the lift-off heights of the propane flames as compared to the CNG flames where the change in lift-off was significant.

Significant differences in the physical properties of the three fuels exist which could be used to help explain the significant differences in the lift-off height. The density of the fuels increases significantly with increasing number of carbon atoms and the dynamic viscosity is significantly lower for propane and ethane as compared to methane. This produces a significant increase in Reynolds number as the number of carbons is increased. It is possible that this then causes changes in the mixing and entrainment behaviour of the jet.

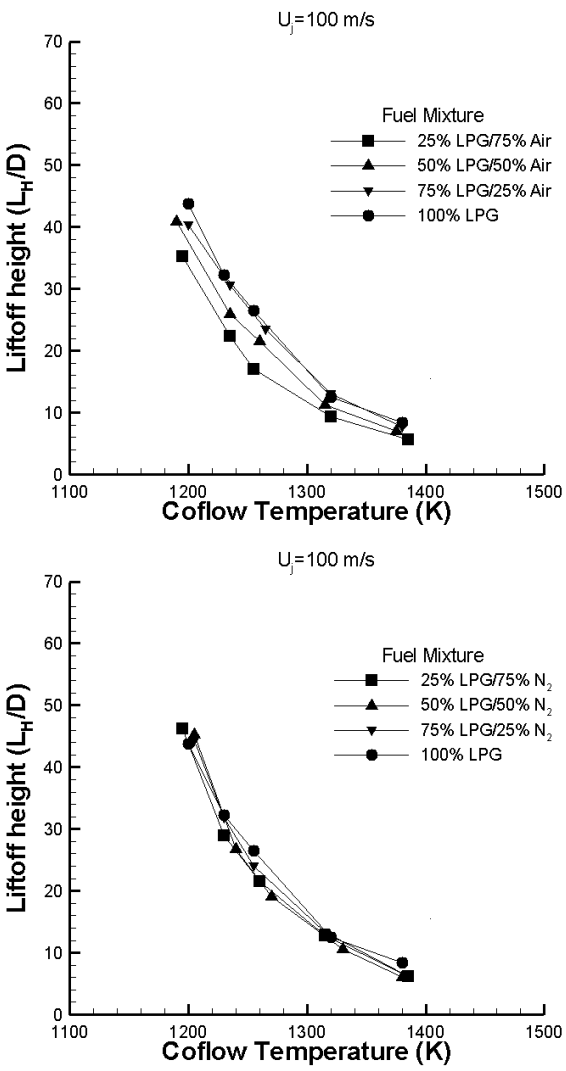

Figure 3 – Lift-off heights of propane/air (top) and propane/N_2 (bottom) mixtures as a function of co-flow temperature (T_c). Error bars show plus and minus one standard deviation.

Cantera Simulations

One dimensional, well stirred reactor auto-ignition calculations are performed in Cantera to determine the relative auto-ignition delays for the three fuels studied. While it is realised that the experimental burner has many complexities not simulated by this model, the simulations are only meant to provide a comparative evaluation of the chemical auto-ignition delays of the fuels to determine if there is a correlation with the experimental results.

The model is a static, fully mixed reactor where the initial temperature of the reactants is varied to produce corresponding ignition delays. The ignition delay is taken as the time taken to reach the adiabatic flame temperature of the mixture. All results are obtained for fully premixed mixtures so that consistency between fuels can be maintained. The GRI3.0 reaction mechanism is used for all fuels.

Plots of auto-ignition delay for each fuel as a function of the initial temperature are shown in figure 4. Qualitatively similar trends to the experimental results are observed. Methane has a significantly longer ignition delay than both propane and ethane while ethane's delay is only slightly shorter than propane's. This level of numerical modelling is a prelude to more detailed modelling of these flames to be performed in the future.

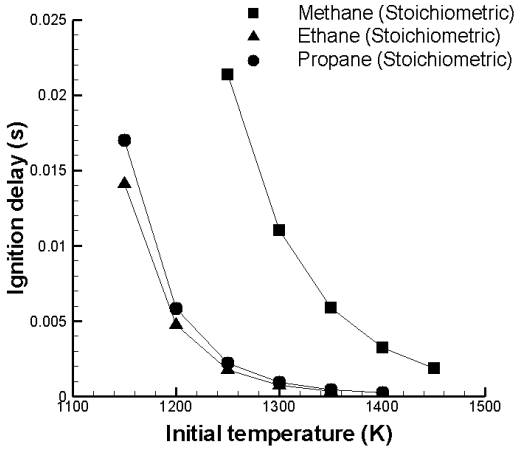

Figure 4 – Cantera simulations of the ignition delay for stoichiometric methane, ethane and propane. The delay is taken as the time taken to reach the adiabatic flame temperature.

Conclusions

Lift-off heights of three hydrocarbon fuels have been measured as a function of co-flow temperature. Results were obtained for both partially premixed flames and nitrogen diluted flames and comparisons were made between the cases. Ethane was found to have the lowest lift-off heights while CNG's were highest. Partial premixing was found to increase the lift-off of the CNG flames while reducing the lift-off of the LPG flames. Partial premixing of the ethane displayed results that indicated a slight decrease in liftoff although the trend is uncertain. In general, nitrogen dilution increased the lift-off heights although sensitivity to the level of dilution varied between fuels.

One dimensional Cantera simulations of the ignition delay were performed for stoichiometric mixtures of methane, ethane and propane. The results qualitatively agreed with the experimental data in that ethane had both the shortest ignition delay and the shortest lift-off heights while methane had the opposite trend.

These results indicate that the auto-ignition chemistry and/or mixing properties are significantly affected by the type of hydrocarbon used. Further experimental and numerical investigation would be required to fully elucidate these differences.

Acknowledgments

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