Effect of Pressure and CO_2 Dilution on the Stability and the Flickering of Conical Laminar Premixed Flames

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1 Introduction

The flickering of a premixed flame is a well known phenomenon. The flame flickering motion has a distinct frequency of 10-20 Hz. This oscillation comes from the Kelvin Helmoltz instability and the interaction between hot and cold gases, which generates large vorticities. Several experimental studies have characterised this flickering [1-5]. In 1990, Durox et al [3], have observed the oscillation frequency according to the equivalence ratio, the flow velocity, the pressure from 0.01 to 0.1 MPa and the gravitational levels. In 1995, Kostiuk and Cheng [5] have extended this study by establishing an empirical relation, which expressed the ratio between the fluctuation and the buoyancy forces according to the Reynolds number. In a recent work, Gotoda at al. [4] have investigated the effect of buoyancy under swirl conditions. To address combustion instability issues encountered in practical premixed systems, a laminar Bunsen flame is analysed at high pressures in this work. Moreover, the use of diluted fuels such as the CH_4-CO_2-Air mixtures can be a good way to reduce pollutant emissions and to become a new fuel for future technology. In fact, the use of biogas from the methanisation (CH_4+CO_2), which means combustible gas generation from the degradation of organics or industrials wastes, is a renewable energy, which can be implemented in several applications such as the cogeneration gas turbines. Therefore CO_2 diluted flames are also investigated in this study.

2 Experimental Setup

The stainless steel cylindrical combustion chamber of ICARE can sustain premixed turbulent flames up to 1 MPa. The chamber consists of two cylindrical parts of 600 mm high, each equipped with 4 windows of 100 mm diameter for optical diagnostics. The internal chamber diameter is 300 mm and the chamber volume is about 80 litres. Water flows though the wall jackets for cooling the chamber. The central burner can be moved along the chamber vertical z-axis by means of a stepping motor. The chamber internal walls are painted black with a laser light absorbing paint resistant to high temperatures. Electrical resistance heaters keep the windows free from water condensation. A nitrogen flow is able to dry the windows during measurements if necessary. The internal pressure is set automatically using an electrical valve piloted by a PID controller. A pressure gauge and a thermocouple are used to check the internal burnt gas pressure and temperature.

The laminar burner generates a conical Bunsen flame configuration and it is composed of two blocks. The upper part of the burner has a convergent profile. A porous grid is placed in the burner to have a homogeneous flow. The diameter of the burner exit is 12 mm. The lower part is the fixation section to the chamber and the gas lines. Air flow is brought around the burner to avoid the extinction of the flame due to a lack of oxygen in the chamber. Dry air is provided to the premixer by a 1.3 MPa compressor and is cleaned by a sub-micron filter. CH_4 and CO_2 are supplied by compressed gas bottles. All flows are controlled by regulated thermal mass flowmeters.

The combustion reaction is given in Eq. 1, where x is the excess air parameter; β is the CO_2 mole fraction knowing that the (CH_4+CO_2) mole fraction is equal to 1:

$$\begin{aligned}&(1-\beta)\left[CH_4+(2-x)(O_2+3.78N_2)\right]+\beta CO_2\\&\rightarrow CO_2+2(1-\beta)H_2O+7.56(1-\beta)N_2+x(1-\beta)(O_2+3.78N_2)\end{aligned} \tag{1}$$

The mole fraction of CO_2 takes several values between 0 and 0.5. The equivalence ratio is equal to 0.88. The outlet velocity U is determined by the competition between the stability of the flame and a low Reynolds number condition to keep the flame under laminar conditions. If the outlet velocity is too low compared to the laminar flame speed, there is a flashback of the flame in the burner; and if the outlet velocity is too high, a blow off of the flame is observed.

3 Stability diagram

There are two types of stability criteria associated with laminar flames. The first is concerned with the ability of the reactant mixture to support the flame propagation, which includes the flammability limits and the quenching distance. The other type of stability limit is associated with the mixture flow and its relationship to the laminar flame itself, which includes the phenomena of flashback, blow off and the onset of turbulence. Both flashback and blow-off are related to matching the local laminar flame speed to the local flow velocity. A flame can be stabilized on the burner only between certain flow velocity limits. If the gas velocity is progressively reduced, a point will be reached eventually at which the burning velocity exceeds the gas velocity somewhere across the burner. At this point, the flame will propagate back down the burner. To represent the stability diagram, the burner velocity U versus equivalence ratio ϕ graph is used. The CH_4-air mixture stability diagrams are represented in Figure 1 for different pressures.

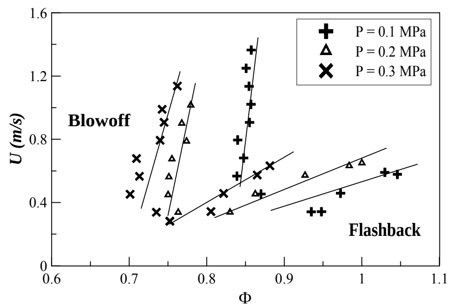

Figure 1: Stability diagrams for different pressures

The pressure effect on the flame stability is important. The flashback and blow off limits are displaced to the left of the stability diagram when the pressure increases. So the flashback and blow off limits are obtained at higher burner velocities and lower equivalence ratios with increasing pressure. Moreover, the slope of the flashback limits is increasing. This phenomenon can be explained by the turbulence effect since the Reynolds number is higher with pressure increase. It is found that, the CO_2 dilution has no any impact on the stability diagram. For a constant pressure case, the blow-off and the flashback limits do not change with an increase of the CO_2 percentage.

4 Flame Flickering

The flame fluctuation investigations were performed by using a high-speed camera, with an acquisition frequency of 40 Hz. The spatial resolution of the flame images is 34.8 μm/pixel. For different experimental conditions, the frequency of the natural oscillations is approximately of 10-20 Hz, and depends on the burner size, burner velocity and flame composition. These fluctuations are associated to the thermogravitational forces. Most of the existent studies are concerned with the effect of the gravity, the equivalence ratio or the burner velocity on the oscillation, but do not deal with the high pressure effect.

From 500 pictures, the natural flame oscillation frequency is determined at the tip of the flame by studying the flame height position spectrum, which gives a peak at the oscillation frequency. By this way, it is possible to study the effect of the pressure, and the CO_2 dilution. On Figure 2, it is observed that the flame oscillation frequency increases with the increase of pressure. In fact, the pressure increase induces the increase in hot gas density and also it implies an increase of the natural flame oscillation.

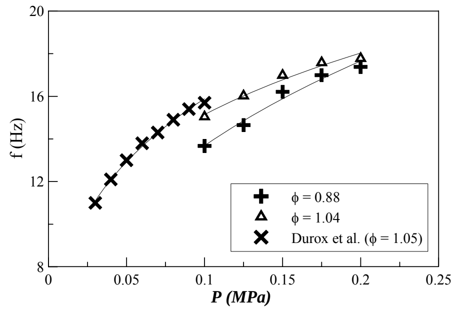

Figure 2: Flame tip oscillation frequency according to the pressure for U=0.7m/s

This phenomenon was already observed by Durox in 1990 for flames at low pressures. He established that the frequency is proportional to P^m, with m approximately equal to 0.3 for an equivalence ration of 1.05. In the present work, the factor *m* is found to be close to 0.3. For instance, for $U = 0.7$ m/s, *m* is equal to 0.36 for an equivalence ratio of 0.88 and *m* is equal to 0.27 for an equivalence ration of 1.04. Moreover, it is seen that this factor is constant with the variation of the burner velocity and decreases when the equivalence ratio increases.

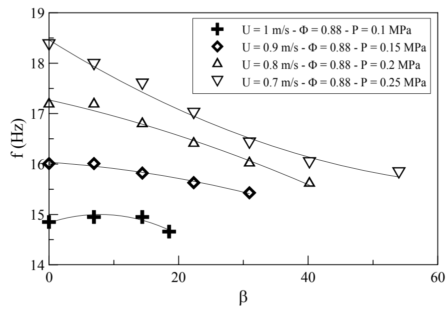

Figure 3: Flame tip oscillation frequency according to the CO_2 dilution

The flame oscillation frequency decreases with an increase in CO_2 dilution. This can be explained by the density modification of the mixture, which increases when the CO_2 mole fraction increases. In fact, it is also known that the natural oscillation is linked to the gravity effect.

Based on experimental results [2, 3, 5], an empirical correlation $St^*/Ri = 0.00028\,\mathrm{Re}^{*2/3}$ has been established in previous studies [4, 5]. *St**, *Ri* and *Re** are respectively the Strouhal number normalised by the heat release ratio ($1+\tau$), the Richardson number and the Reynolds number normalised by the heat release ratio. The heat release parameter $\tau = (T_{ad}/T_0 - 1) = (\rho_p/\rho_r - 1)$ takes into account the change in buoyancy forces under various ϕ, β and *P*.

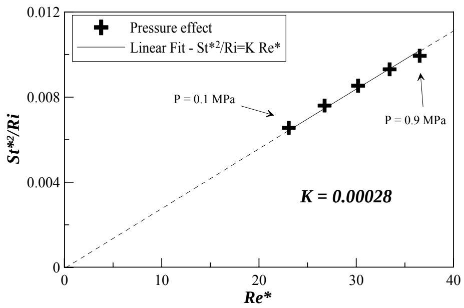

Figure 4: Empirical correlation for the oscillation frequency generated by conical flames

On Figure 4, the data was fitted by a linear equation passing through the origin, and the constant *K* is exactly equal to 0.00028, as the previous studies [4, 5]. Therefore, it is found that the empirical correlation is also valid for different pressures. It is also observed that, the non-dimensional numbers for different CO_2 percentage mixtures are very close to the numbers calculated for mixtures without CO_2, This shows that, the empirical expression is also valid for CO_2 dilution.

5 Conclusion

The stability diagram of laminar CH4/Air flames is affected by the pressure. When the pressure increases, the blow-off occurs at lower equivalence ratios and the flashback at higher equivalence ratios. However, the CO_2 dilution has no influence on the blow-off and flashback limits for lean mixtures. Flame tip flickering in premixed conical laminar flame has been investigated at high pressures and CO_2-diluted mixtures. The oscillation frequency is proportional to $P^{0.3}$. In fact, the variation of density between ambient air and burned gases is an important parameter that the pressure affects. On the other hand, the CO_2 dilution implies a decrease of the flickering. The empirical correlation $St^*/Ri = 0.00028\,\mathrm{Re}^{*2/3}$ is also valid for high pressure condition and CO_2-diluted mixtures.

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References

[1] B. Bédat, R. K. Cheng (1996). Effects of Buoyancy on Premixed Flame Stabilization. Combustion and Flame 107 pp 13-26

[2] D. Durox (1992). Effects of Gravity on Polyhedral Flames. Twenty-Fourth (International) on Combustion pp 197-204

[3] D. Durox, F. Baillot, P. Scoufflaire, R. Prud'Homme (1990). Some Effects of Gravity on the Behaviour of Premixed Flames. Combustion and Flame 82 pp 66-74

[4] H. Gotoda, K. Maeda, T. Ueda, R. K. Cheng (2003). Periodic Motion of a Bunsen Flame Tip with Burner Rotation. Combustion and Flame 134 pp 67-79

[5] L. W. Kostiuk, R. K. Cheng (1995). The Coupling of Conical Wrinkled Laminar Flames with Gravity. Combustion and Flame 103 pp 27-40