Fuel effects on diffusion flames at elevated pressures

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This study addresses the influence of elevated pressures up to 1.6 MPa on the flame geometry and the flickering behavior of laminar diffusion flames and particular attention has been paid to the effect of fuel variability. It has been observed that the flame properties are very sensitive to the fuel type and pressure. The shape of the flame was observed to change dramatically with pressure. When the pressure increases, the visible flame diameter decreases. The height of a flame increases first with pressure and then reduces with the further increase of pressure. The cross-sectional area of the flame ($A_{cs}$) shows an average inverse dependence on pressure to the power of $n (A_{cs} \propto P^{-n})$, where $n = 0.8 \pm 0.2$ for ethylene flame, $n = 0.5 \pm 0.1$ for methane flame and $n = 0.6 \pm 0.1$ for propane flame. It was observed that the region of stable combustion was markedly reduced as pressure was increased. High speed imaging and power spectra of the flame chemiluminescence reveal that an ethylene flame flickers with at least three dominant modes, each with corresponding harmonics at elevated pressures. In contrast methane flames flicker with one dominant frequency and as many as six harmonic modes at elevated pressures.

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1. Introduction

The understanding of combustion has been enhanced considerably by studies of laminar flames based on atmospheric and low-pressure conditions. Considerable amount of literature has been published on laminar diffusion flames at atmospheric pressure but many practical combustion devices operate at high pressures to increase thermodynamic efficiency and decrease their physical size [1]. The current understanding of the influence of pressure on thermo-physical properties of sooty flames is very sketchy [2,3].

It is well known that increased pressure plays a significant role in increasing soot production in spray combustion, premixed and diffusion flames [4–9]. Also, pressure has significant effects on parameters such as temperature, flow velocity, flame structure and thermal diffusivity [10].

Miller and Maahs [11] designed and constructed a high-pressure flame system for studying methane–air diffusion flame in the pressure range of 0.1–5 MPa. It is reported [11] that a very marked change occurred in the shape and structure of the methane–air diffusion flame as pressure was increased. Also the region of stable combustion was markedly reduced.

Soot spectral emission and line-of-sight integrated soot volume fractions versus pressure have previously been reported [1–3,12,13] to assess the pressure sensitivity of soot formation. These studies also reported that the physical shape of the methane, ethylene and propane diffusion flames are very sensitive to the increase of pressure. The flame changes in height and becomes considerably narrower with the increase of pressure. It is also found that buoyancy induced instabilities lead to flame flicker at slightly elevated pressures as buoyancy forces scale with pressure [1,2].

The phenomenon of flame flickering in diffusion flames is well known and has been extensively studied at atmospheric and sub-atmospheric pressures. However, the exact mechanism of this buoyancy induced instability has not been fully understood. In recent years more focus has been placed on the understanding of complex turbulent flame structures. In particular, in modern combustion systems which typically operate at high pressures exhibiting a wide range of local conditions where flame–vortex interactions are mainly dominant [14]. In such applications, the turbulent combustion zone can be considered as a collection of elementary flame–vortex interactions of different size and strength. This is coupled to the fundamental aspects of flow, transport and combustion phenomena present in turbulent flames. An elementary flame–vortex interaction is typically periodic and regular in nature and can therefore be easily characterized than is typically the case in direct investigations of turbulent flames. The flickering of a laminar diffusion flame is known to be caused by the interaction of the flame and the vortices both inside and surrounding the flame jet as discussed below. Therefore the study of laminar flame dynamics is of great importance to the understanding of not only the laminar diffusion flame itself but also turbulent flames.

The presence of elementary flame–vortex reactions in diffusion flames was independently observed by Kimura [15] and Toong et al. [16]. They suggested that the flickering of a diffusion flame
at low frequency, typically ranging from 10 to 20 Hz (first reported by Chamberlin and Rose [17]) could be explained by the formation of buoyancy induced outer toroidal vortices causing the flame front to regularly oscillate or flicker. Recently, the presence of these vortices has been confirmed experimentally and numerically [18–23]. The generation of the outer vortices has been attributed to a Kelvin–Helmholtz instability driven by a buoyancy induced shear layer surrounding the flame surface [15,21,23–25].

For diffusion flames with high enough Reynolds number in the transitional regime Chen et al. [19] employed a planar visualization technique and visualized two distinct vortices; large toroidal vortices outside the luminous flame and small roll-up vortices inside the luminous flame. The frequency of the toroidal vortices was found to correlate with the flame oscillation flicker frequency (f). Under normal gravity conditions this can be approximated by the empirical relation with the burner diameter, D:

\[ f \approx 1.5D^{1/2} \]  

This relation remains valid for small fuel jet velocities since the jet momentum compared to the buoyancy effect is too weak to notably influence the flickering frequency [19,23,25,28].

The buoyancy effect on the shape and flickering frequency of a diffusion flame has been studied by various researchers in the literature [18,29–33]. Buoyancy is directly related to the Froude number which is defined as [29,30]

\[ Fr = \frac{U^2}{gd} = \frac{16m^2}{\pi^2gd^3} = \frac{C}{g^{1/2}} \]  

where \( \rho \) is the fuel density, \( U \) is the average burner exit velocity, \( d \) is the burner diameter, \( m \) is the fuel mass flow rate, \( g \) is the gravitational acceleration and \( P \) is the ambient pressure. The density was replaced using the ideal gas law. For a specific burner, the parameter \( C = 16m^2R^2T^2/\pi^2d^3 \), where \( R \) is the gas constant, which is fixed by fuel temperature \( T \) and mass flow rate \( m \). Thus, for a given Reynolds number, the buoyancy varies with Froude number, which is inversely proportional to the product of gravitational acceleration and square of the ambient pressure. Using quantitative rainbow schlieren deflectometry, Albers and Agrawal [18] have shown that the flickering frequency of a diffusion flame varies linearly with the ambient pressure. This concurs with a dimensional analysis by Katta and Roquemore [22] relating the vertical velocity of the burnt gases to the characteristic flame height leading to the following relation \( f \propto q^{1/2} \). Durox et al. [28] experimentally measure the flickering frequency at sub-atmospheric pressures and reduced gravity levels. They have shown that the relationship between flickering frequency and pressure is given by \( f \propto (P_0g)^{1/3} \) which is valid if the mean width of the flame is greater than the burner nozzle diameter. Otherwise the linear relationship between pressure and frequency holds. At reduced gravity or ambient pressure various researchers have shown that a diffusion flame is wider and longer than their normal gravity flame counterparts [32,33].

Some experiments have been conducted under increased gravity levels with the flame placed in a centrifuge [31,34–36] such as the recent work by Sato et al. [36] with artificial gravity levels created up to 14 G. In these investigations increased gravity levels leads to an increase of the flickering frequency but it is hard to distinguish between a 1/2 power or 1/3 power dependency of the gravity due to the coriolis forces present in this type of experiment [31]. The authors also found that at increased gravity levels the length and surface area of a diffusion flame decreased and the flickering behavior become more prominent. This was explained by the enhancement of air entrainment which was caused by increased buoyant flow in the flame at higher gravity levels.

In the present research, we investigate the flame geometry, instability regions and flame dynamics of low velocity jet diffusion flames at elevated pressures up to 1.6 MPa. Research on laminar diffusion flames at high pressures has been limited to a number of studies focused on the soot and temperature profiles within a stable laminar flame at pressures up to 5.0 MPa [1,3,11,12,37]. There is a lack of knowledge on the influence of elevated pressure on the flame dynamics of a laminar/transitional diffusion flame. To the authors’ knowledge there has been no quantitative study on the effect of elevated pressures greater than 0.2 MPa on the structure and flickering frequency dynamics of a diffusion flame. Most of the current investigations have been conducted at pressures below atmospheric pressure to reduce the effects of buoyancy. This study also highlights the fuel variability effect on the flame dynamics of a jet diffusion flame at elevated pressure with a comparison of methane and ethylene fuels. Recent studies in atmospheric and pressurized gas turbine test rigs have shown that changes in fuel composition can cause changes in the combustion instabilities observed [38,39], however, there is a lack of quantitative investigations on the fuel variability effect on the flame dynamics of jet diffusion flames, especially at high pressures. In the following sections a description of the high pressure burner and experimental setup is presented and the results are discussed and concluded.

### 2. Experimental setup

The co-flow diffusion flame was studied with the optical diagnostic methods over the pressure range of 0.1–1.6 MPa for ethylene (C\(_2\)H\(_4\)) and methane (CH\(_4\)) and 0.1–0.7 MPa for propane (C\(_3\)H\(_8\)) diffusion flames. A commercial CCD camera and a visible narrowband filter (516 ± 2.5 nm) are used for the measurement of visible flame geometry and height. It is known that a typical CCD camera may be sensitive to infrared radiation. The application of the narrow band filter prevents both the infrared radiation and the saturation of flame during imaging. High speed imaging and chemiluminescence measurement have been employed to study the flame dynamics.

The high pressure burner used in this study is designed for working pressures up to 1.8 MPa. This burner is similar to the design of Miller and Maahs [11]. The chamber, which has an internal diameter of 120 mm, is shown schematically in Fig. 1. A classic over ventilated Burke–Schumann [40] laminar diffusion flame is produced which is stabilised on a nozzle with an exit diameter of
4.57 mm which is tapered to reduce the formation of turbulent eddies in the air and fuel flow. Methane, ethylene and propane were the selected fuels supplied from a compressed gas cylinder, regulated by a needle valve, and measured by a calibrated mass flow meter with 1% full scale accuracy. For the first set of experiments the mass flow rates for methane, 0.12 slpm (standard litres per minute), ethylene, 0.1 slpm and propane, 0.06 slpm were kept constant for all pressures for the same global heat release rate. Also for the unstable flame dynamics measurement, both methane and ethylene flow rates were kept constant for all pressures at 0.21 slpm. Co-flow air is supplied from a compressed air bottle into the burner and is diffused using a layer of glass beads and is followed by a honeycomb structure with 1.5 mm diameter holes which straightens the flow. Co-flow air was controlled by a needle valve to produce a constant mass flow rate of 15 slpm for all the diffusion flames. Table 1 shows the physical properties of fuel and air streams at atmospheric pressure.

To pressurise the chamber, nitrogen flow was introduced through the base of the burner using a ring of 1.5 mm diameter holes. The nitrogen flow also keeps the chamber walls cool and the window ports free of condensation and soot. Increasing the pressure within the vessel was achieved by increasing the flow rate of nitrogen and simultaneously decreasing the flow rate of the exhaust by adjusting the back-pressure regulating valve which can maintain the chamber pressure anywhere between 0.1 and 1.6 MPa. Optical access to the burner is provided by four windows which have a diameter of 50 mm and a thickness of 20 mm; two are made from fused-silica, and two from high-resistivity float-zone silicon (HRFZ-Si). The fused-silica windows provide optical access in the visible band whilst the HRFZ-Si windows provide access in the far infrared which were used for a different study based on terahertz-time domain spectroscopy [41,42].

The optical system used for the real-time measurement of flame light emissions is shown schematically in Fig. 2. With optical access through one of the fused-silica lens, the total flame surface area is focussed using a spherical lens onto a 5 mm diameter bundle of fine fibre optical cable. The bundle of fine fibres is bifurcated randomly into two equal subdivisions to produce two channels of light signals of the same intensity from the same imaged volume. Each channel is then guided to two individual photomultiplier tubes (ORIEL model 70704). At the end of each channel a CH* and C2 interference filter at wavelengths of 430 ± 5 nm and 516 ± 2.5 nm were used, respectively. Obviously, what is measured is the summation of the soot light and chemiluminescence of CH* and C2. The two chosen wavelengths for a diffusion jet flame. Nevertheless the availability of two wavelengths may provide qualitative information on flame chemistry. The intensity of the filtered light is converted into voltage signals which is captured by an analogue to digital data acquisition card (National Instruments PCI-MIO-16E-1) at 5000 samples per second averaged over a duration of 4 s. Real-time signal processing was performed by using a LabVIEW 8.5 virtual instrument (VI) to obtain the flame flickering frequency spectrum of the flame light emission. Optical access gained through the second fused-quartz window is used to capture the evolution of the structure of the flame using a high speed camera capable of capturing a maximum of 500 frames per second.

For flame geometry measurements, the high speed camera was replaced by a commercial charge-coupled device (CCD) digital camera (Olympus E-100RS) was utilised to capture the colour photographs and also the narrow band photos of the flame.

3. Results and discussion

The stable operating range for the burner is shown in Table 2. The onset of flame flickering occurs in methane flames from the flame tip at 0.8 MPa and became visually unstable (the instability was extended towards the burner nozzle) at 1.2 MPa for a flow rate of 0.12 slpm. However, for a lower flow rate of 0.05 slpm the burner has a stable flame in the entire operating regime of the burner. In contrast a propane diffusion flame was far more stable than a methane flame. The main reason for this stability may be attributed to the stronger soot formation tendency of propane in comparison with methane and the impact of soot on reduction of flame flicker [43]. It is worth mentioning here that the maximum operating range for propane is 0.73 MPa since propane liquefies above this pressure at a room temperature (21 °C). A propane flame is stable in all the stated flow rates in Table 2.

Table 2
Stable operating flow regimes of the high-pressure burner

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Fuel flow rate (slpm)</th>
<th>0.05</th>
<th>0.12</th>
<th>0.21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>Stable</td>
<td>1.2 MPa</td>
<td>0.2 MPa</td>
<td></td>
</tr>
<tr>
<td>Ethylene</td>
<td>Stable</td>
<td>Stable</td>
<td>Stable</td>
<td></td>
</tr>
<tr>
<td>Propane</td>
<td>Stable</td>
<td>Stable</td>
<td>Stable</td>
<td></td>
</tr>
</tbody>
</table>

Table 1
Physical properties of fuels and air streams during the experiments at atmospheric pressure

<table>
<thead>
<tr>
<th>Gas type</th>
<th>Volume flow rate (slpm)</th>
<th>Mass flow rate (g/s)</th>
<th>Velocity (m/s)</th>
<th>Re no.</th>
<th>Pr no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH4)</td>
<td>0.12 2.00E-06</td>
<td>1.36</td>
<td>0.122</td>
<td>34.45</td>
<td>0.332</td>
</tr>
<tr>
<td>Methane (CH4)</td>
<td>0.21 3.50E-06</td>
<td>2.38</td>
<td>0.213</td>
<td>60.32</td>
<td>1.016</td>
</tr>
<tr>
<td>Ethylene (C2H4)</td>
<td>0.1 1.67E-06</td>
<td>1.96</td>
<td>0.102</td>
<td>57.52</td>
<td>0.230</td>
</tr>
<tr>
<td>Ethylene (C2H4)</td>
<td>0.21 3.50E-06</td>
<td>4.12</td>
<td>0.213</td>
<td>120.79</td>
<td>1.016</td>
</tr>
<tr>
<td>Propane (C3H8)</td>
<td>0.06 1.00E-06</td>
<td>1.91</td>
<td>0.061</td>
<td>70.04</td>
<td>0.083</td>
</tr>
<tr>
<td>Air</td>
<td>15 2.50E-04</td>
<td>301</td>
<td>0.178</td>
<td>57.57</td>
<td>0.704</td>
</tr>
</tbody>
</table>

Fig. 2. Schematic of the experimental setup.
flame becomes visually unstable at a pressure of 0.6 MPa with a flow rate of 0.21 slpm.

In all flames at atmospheric pressure, the flame had a bulbous appearance and is wider than the burner nozzle exit diameter. By increasing pressure it was observed that the flame narrows and its width at all heights within the flame decreased. At elevated pressures, due to the increased presence of soot which acts as a reaction intermediary, the reaction processes are different from those acting at atmospheric pressure [11]. This may explain the significant change in flame shape with the increase of pressure. Soot particles are higher in density than other combustion products, and cannot diffuse away from the primary flame region as easily a gaseous product might. Combustion must therefore be maintained by oxygen diffusing inward to the primary flame region, resulting in a narrowing flame structure [11]. As pressure increases, the density will increase as well. By keeping the fuel mass flow rate constant ($\rho UA_{cs} = \text{const}$) at all pressures, the mass conservation equation leads to the narrower flame cross section area at elevated pressures. It has been described by Liu et al. [13] that the physical effect of pressure affects the flame and soot formation through the pressure dependence of the mixture density ($\rho \sim P$), the binary diffusion coefficient ($D_{ij} \sim P^{-1}$), and the potential change in residence time due to change in the flame shape and possibly the processes of particle coagulation and agglomeration.

As the pressure was increased, axial flame diameters decreased, giving an overall stretched appearance to the flame as noted by Flower and Bowman [44] and Thomson et al. [2]. This effect increases the flame height up to a specific pressure with further increases in pressure causing a decrease in flame height. Despite the flame being over-ventilated with co-flow air, for the ethylene and propane flames an extended line of soot at the flame tip appears at a pressure of 0.4 MPa which increases with intensity and the black coloured soot spreads downward toward the base of the flame with the further increase of pressure (see Fig. 3). Fig. 4 shows the narrow band images ($C_2$ filter) of propane-air co-flow diffusion flame at different pressures at a camera shutter speed.

![Extended Line of Soot](image1)

**Fig. 3.** Appearance of the extended line of soot at the tip of (a) propane and (b) ethylene diffusion flames at 0.4 MPa. The smaller visible flame in the background was a reflection of the flame itself on one of the windows.

![Propane-Air Diffusion Flame](image2)

**Fig. 4.** Photos of propane (0.06 slpm) – air (15 slpm) diffusion flame by applying $C_2$ filter (camera shutter speed 1/80 s).
of 1/80 s. Due to the clear boundaries of flame in these narrow band photos the measurement of flame geometry (height and width) can be achieved with greater accuracy.

The comparison of ethylene (0.1 slpm), methane (0.12 slpm) and propane (0.06 slpm) flame heights at different pressures are presented in Fig. 5. The visible flame heights were measured from the tip of the fuel nozzle to the tip of flame in the photos captured by applying a narrow band filter (516 nm). The peak flame heights were observed to occur at a pressure of around 0.4 MPa for ethylene and propane flames and at around 0.6 MPa for methane flame. This flame height decrease at higher pressures is due to the increase in soot production. The soot zone was observed to extend down toward to the burner nozzle as pressure increases. The increase in the ethylene and propane flame heights between 0.1 and 0.4 MPa are approximately 28% and 21%, respectively with a decrease of 35% and 14% above 0.4 MPa to their lowest values at 1.6 and 0.7 MPa for ethylene and propane flames, respectively. This trend is consistent for methane flames with 18% increases from 0.1 to 0.6 MPa and an average decrease of 27% between 0.6 and 1.6 MPa. Furthermore, the onset of flickering with a methane flame occurs at 0.8 MPa with an rms of about 1 mm and the flickering amplitude increased with pressure to its maximum amplitude, approximately 3.5 mm, at 1.6 MPa (as shown in Fig. 5 by vertical error bars).

When the pressure was increased, axial flame diameters were observed to decrease, giving an overall stretched appearance to the flame as noted in previous works [1–3,10,12]. The cross-sectional area of the flame (measured from the radius defined by the outer edges of the sooting region at each height) shows an average inverse dependence on pressure to the power of 0.8 ± 0.2 (1/P^{0.8 ± 0.2}) for ethylene flames, 0.5 ± 0.1 (1/P^{0.5 ± 0.1}) for methane flames and 0.6 ± 0.1 (1/P^{0.6 ± 0.1}) for propane flames. As an example the cross-sectional area of the ethylene-air co-flow diffusion flame at different heights and pressures is presented in Fig. 6.

![Fig. 5. Co-flow laminar diffusion flame heights at different pressures (vertical error bars shows the rms of flickering).](image)

![Fig. 6. Cross-sectional area (Acs) of the ethylene (0.1 slpm) – air (15 slpm) flame at different pressures and heights.](image)

![Fig. 7. (a) Methane diffusion flame pictures, taken by a digital camera at shutter speed of 1/2000 s for pressures 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 MPa (from left to right, respectively), (b) and (c) are high speed images at pressures of 0.8 and 1.6 MPa, respectively. The framing rate is 500 fps and the time interval between two consecutive images is 2 ms.](image)

![Fig. 8. (a) Ethylene diffusion flame pictures, taken by a digital camera at shutter speed of 1/2000 s for pressures 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 MPa (from left to right, respectively), (b) and (c) are high speed images at pressures of 0.8 and 1.6 MPa, respectively. The framing rate is 500 fps and the time interval between two consecutive images is 2 ms.](image)
According to the results of this study the flame cross-sectional area decreases with pressure according to the fuel type as $P^{-0.5}$ to $P^{-1}$. Through scaling reasoning, Glassman [10] concluded that the flame cross-sectional area should decrease with pressure as $P^{-0.5}$. McCrain and Roberts [1] observed that this area scaled with pressure as about $P^{-0.9}$ for methane–air flames and $P^{-1.1}$ for ethylene–air flames. However, the recent studies by Thomson et al. [2], Liu et al. [13] and Bento et al. [3] in a similar burner show that the visible flame cross-sectional area decreases with pressure as $P^{-1}$. The variation of flame cross-sectional area scaling with pressure may be attributed to differences in burner configuration, co-flow air or fuel velocities and the nozzle diameter. The effects of these parameters are worthwhile for further investigation.

The ethylene flame exhibited good stability at all pressures up to 1.6 MPa. In propane flame at 0.3 MPa a small amount of local flickering occurs at the tip of the flame (see Fig. 5). However, the flickering disappears at pressures greater than 0.4 MPa due to the appearance of a long line of the soot (see Fig. 3). This phenomena is in agreement with the very recent finding of Katta et al. [43] that soot can influence flame flicker to such an extent that the oscillation is completely suppressed. In the methane flame, the flame dramatically changed to an unstable flame beyond 1.2 MPa. The flickering at the tip of flame with an rms of about 3.5 mm was observed at 1.6 MPa and this instability moves down towards the burner nozzle. These results are in agreement with the observations of other literatures [1–3,11,12,45].

The effect of elevated pressure on flickering phenomena of diffusion flames can be clearly observed in the unstable regime of methane and ethylene flames; a chosen flow rate of 0.21 slpm was used for flame dynamic measurements for both methane

![Frequency spectra for methane and ethylene diffusion flames at elevated pressures](Fig. 9). Frequency spectra for methane and ethylene diffusion flames at elevated pressures: (a) methane at 0.1 MPa, (b) methane at 0.8 MPa, (c) methane at 1.6 MPa, (d) ethylene at 0.1 MPa, (e) ethylene at 0.8 MPa and (f) Ethylene at 1.6 MPa.
and ethylene. Observations of the effects of pressure on the physical characteristics of the flame were similar to those made by Miller and Maahs [11]. Images of methane and ethylene flames are presented in Figs. 7a and 8a, respectively. At atmospheric pressure, the flame shape is convex and its maximum width is wider than the burner nozzle exit diameter. Soot formation is more dominant at the tip of the flame. At higher pressures the flame luminosity dramatically increases. The soot formation increases and the flame narrows with a concave shape. Previous high pressure studies of diffusion flames have been focused on soot studies of stable flames at lower flow rates. For higher flow rates obvious flame necking starts to occur. The necking of the flame can be explained by the presence of local buoyancy induced toroidal vortices which are formed at the flame surface bringing in fresh air to mix with the fuel at the flame front. The higher fuel flow rate means that the fuel jet is able to induce stronger vortex which would then produce better fuel and air mixing. As a result, the fuel could be burnt faster near the vortex which causes the necking to occur. The effect of increased buoyancy at higher pressures is clearly highlighted in the high speed images shown in Fig. 7b and c for methane flame and Fig. 8b and c for ethylene flame with a periodic necking of both methane and ethylene flames. At higher pressures, a larger surface area of the flame tip is detached and burnt out (see Figs. 7c and 8c). This may be explained by the scaling of buoyancy with pressure (see Eq. (1)) which will increase the convective velocity at the flame surface, causing an increase in the acceleration of toroidal vortices which correlate with the flame surface oscillations at the same frequency [19]. The vortices bring in more fresh air to the flame surface, therefore a stronger local fuel-air diffusion occurs, resulting in local necking of the flame and larger break-up of the flame tip at elevated pressures.

The difference between the ethylene and methane flames at elevated pressures is very pronounced as can be seen in the high speed images (see Figs. 7 and 8). The break-up of the methane flame at 1.6 MPa is very uniform with a pair of equal size pockets of flame highlighting the structure of the outer toroidal vortex at the base of flame bulge with further separation at the tip of the breakaway flame as it is burning out. Whilst the flame tip of the ethylene flame at the same pressure is burnt out in a more turbulent manner, with a wrinkled flame surface consisting of small roll-up vortices of varying amplitude.

The power spectra of the chemiluminescence from the flame are shown in Fig. 9, which shows that atmospheric flames of ethylene have a peak frequency of 12.75 Hz which is half of the peak frequency of propane shown in Fig. 9a. Two other noticeable peak frequencies at 6.75 Hz and 13.75 Hz are observed for the power spectra of ethylene flame shown in Fig. 9d. This concurs with the spectra obtained of an ethylene diffusion flame by Chen et al. [19] at a downstream location of 21 burner diameters. They suggested that the sub-harmonic frequency (6.75 Hz) results from vortex pairing; where the convective velocity of the vortex slows down as it moves up and outward allowing the next vortex formed at the burner exit to catch up producing a sub-harmonic frequency. Under elevated pressure the methane flame exhibits frequency spectra with as many as six harmonics of the peak flickering frequency (see Fig. 9b and c). These observed harmonics indicate that the flame has a clearly defined coherent structure which can be confirmed from observing flame images in Fig. 7. In contrast, the power spectra in Fig. 9e and f show that the ethylene flame has a far more complex spectrum. The dominant flickering frequency is found to match the methane flicker frequency. However, the existence of other discrete peak frequencies are observed, each with their corresponding harmonics. The frequency spectra reflect the more complicated flame dynamics of the ethylene flame discussed earlier as shown in Fig. 8.

The influence of pressure on the flickering frequency of ethylene and methane is shown in Fig. 10. For both fuels the dominant flickering frequency is very similar (21.5 Hz at 0.2 MPa) and varies linearly with pressure from 0.2 MPa onwards, which is in agreement with previous works [18,28]. The power spectrum of the ethylene flame may appear complex at first glance, but the linear variance of the alternate frequency modes with pressure as shown in Fig. 10. The second and third dominant peaks indicate that the flame consists of a collection of elementary flame–vortex interactions which varies in of different size and strengths.

The experimental results clearly demonstrate that fuel types have a strong effect on flame dynamics. From published data and our experience it is known that the Reynolds number has little effect on flame flickering frequency in the laminar flame regime and at atmospheric condition. The pressure is observed to have effect on the flame flickering frequency. The pure fluids effect caused by pressure change must be small if the mass flow rate is the same. The recent work of Katta et al. [42] may be of importance. They reported that the strong radiation heat loss from the soot was able to modify the flame stability significantly. This is one of the areas worth of further investigation. It is known that the pressure would affect the soot production significantly. The different reaction mechanisms of each fuel may also play an important role. A manifestation of this is the clearly observable different soot number density for burning each fuel.

4. Conclusion

Experiments were conducted in a high-pressure burner on the influence of elevated pressure on flame shape and buoyancy induced instabilities with ethylene, methane and propane fuels. The results show that the flame dynamics is dependent on the fuel used. It was observed that flame properties are very sensitive to elevated pressures. The shape of the flame changes dramatically with increasing pressure. When the pressure increases, the axial flame height increases initially and then starts to decrease with further increases in pressure. The average cross-sectional area of the flame \( A_{\text{c}} \) shows an inverse dependence on pressure to the power of \( n = 0.8 \pm 0.2 \) for ethylene flames, \( n = 0.5 \pm 0.1 \) for methane flames and \( n = 0.6 \pm 0.1 \) for propane flames.

It was observed that the region of stable combustion was markedly reduced as pressure was increased. The experiments confirm that a linear dependency between the dominant flickering frequency of the flame and pressure exists. Harmonic frequencies
were observed for both methane and ethylene at elevated pressures. In particular, for the ethylene flame a complex power spectrum was observed consisting of at least three peak frequency modes with their corresponding harmonics. High-speed images illustrate the uniformity of the methane flame at elevated pressures with a pair of vortex rings breaking away at the tip of the flame. In contrast, the ethylene flame consists of a vortex ring which breaks away in a more turbulent manner which can be split into at least three dominant coherent structures. Each have their own harmonics that are most likely formed as the vortices break up towards the tip of the flame as confirmed in the power spectra.

To date, there is a lack of in depth investigation on the formation of these harmonic and further investigations are required, especially on the fuel variability effect on the diffusion flame dynamics at elevated pressures, where vortex dynamics seem to play a vital role in the formation of different flickering modes in fuels such as ethylene.

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