Turbulent premixed flames on fractal-grid-generated turbulence

N Soulopoulos¹, J Kerl¹, T Sponfeldner¹, F Beyrau¹, Y Hardalupas¹, A M K P Taylor¹ and J C Vassilicos²

¹ Mechanical Engineering Department, Imperial College London, London SW7 2AZ, UK
² Department of Aeronautics, Imperial College London, London SW7 2AZ, UK

E-mail: ns6@ic.ac.uk

Received 29 June 2012, in final form 6 February 2013
Published 14 August 2013
Online at stacks.iop.org/FDR/45/061404

Communicated by A Gilbert

Abstract

A space-filling, low blockage fractal grid is used as a novel turbulence generator in a premixed turbulent flame stabilized by a rod. The study compares the flame behaviour with a fractal grid to the behaviour when a standard square mesh grid with the same effective mesh size and solidity as the fractal grid is used. The isothermal gas flow turbulence characteristics, including mean flow velocity and rms of velocity fluctuations and Taylor length, were evaluated from hot-wire measurements. The behaviour of the flames was assessed with direct chemiluminescence emission from the flame and high-speed OH-laser-induced fluorescence. The characteristics of the two flames are considered in terms of turbulent flame thickness, local flame curvature and turbulent flame speed. It is found that, for the same flow rate and stoichiometry and at the same distance downstream of the location of the grid, fractal-grid-generated turbulence leads to a more turbulent flame with enhanced burning rate and increased flame surface area.

(Some figures may appear in colour only in the online journal)

1. Introduction

Lean premixed combustion of gaseous fuels is currently one of the most important technologies to achieve low pollutant emissions at high efficiencies in the power generation sector (e.g. McDonell 2008). Reduction of NOₓ emissions is a direct outcome of the lower combustion temperatures when burning a lean mixture and complete combustion prevent the creation of unburned hydrocarbons and carbon monoxide. The thermal efficiency advantage provides also the added benefit of smaller CO₂ emissions.
However, for example in gas turbines, flame stability and flashback are problematic areas, among others (Bernier et al 2004, Dhanuka et al 2009). Flame stability is related to, e.g., flame extinction as the lean limit is approached and flashback can be a problem at low heat release rates. In both cases the turbulent flame speed is a determining parameter and, in general, higher turbulent velocities are preferred. The turbulent flame speed is, for any given fuel, largely determined by the turbulent fluctuations of the flow (Abdel-Gayed et al 1987), as quantified by the stretch rate—which includes strain rate and curvature effects, so controlling the local turbulence level is highly desirable in a variety of situations. There is also evidence (Filatyev et al 2005) that the geometry of the burner and the boundary conditions affect the turbulent burning velocity. Computational studies of the stretched laminar flame speed help us to elucidate the effect of strain rate and curvature (e.g. Malik 2012), and can also study the flame response due to other effects, such as pressure fluctuations (Malik and Lindstedt 2012).

Turbulent premixed flames are studied in various configurations: bunsen burner-stabilized (Frank et al 1999) and wire-stabilized flames (Soika et al 1998, Robin et al 2008) outward propagating spherical flames (Bradley et al 2003), flat flames stabilized in low swirl conditions (Cheng 1995) and flames stabilized in opposed-jet flows (Korusoy and Whitelaw 2002). In most cases the fuel/oxidizer mixture flows through a burner and turbulence is generated by the shear flow or by the use of grids upstream of the flame stabilization location. Typical turbulence generators include regular square mesh grids made of bars, ribbons, holes, etc where ‘regular’ refers to the fact that the forcing of the incoming flow happens at one length scale. By changing the pressure drop across the grid or the downstream location of flame stabilization, a range of turbulent fluctuations and integral length scales are obtained. The root mean square (rms) of the turbulent fluctuations and the integral length scale are related through the kinetic energy dissipation rate, so they cannot be varied independently of each other; this also implies that different burners, grids or boundary conditions are needed in order to achieve a range of required turbulent conditions. The turbulent fluctuations downstream of a regular grid decay following a power law, so flames are usually established very near the grids. However, in this region, turbulence decays rapidly after a relatively short development length.

In this paper, we propose the use of a new turbulence generator, a so-called fractal grid to generate the turbulence in a premixed flame experiment. Conceptually, a fractal grid differs from a regular square grid because it creates turbulence by exciting simultaneously many length scales, rather than a single one, so the underlying mechanism that generates turbulent fluctuations is different for the two types of grids (Mazellier and Vassilicos 2010). By using a fractal grid, a flow field is generated where the turbulence intensity keeps increasing with downstream distance. High turbulence intensities can be generated at a particular location downstream of the grid—generally, much further downstream than a corresponding (with the same solidity) normal square grid—and, in addition, this location depends on the grid design; also, the pressure drop is minimal in order to achieve a given level of velocity fluctuations at the peak turbulence intensity location. Finally, the characteristics of the turbulent flow field can, to a certain extent, be designed to achieve desired values of, e.g., velocity fluctuations and length scales.

The grid we use possesses a space-filling property that relates to the fractal dimension, $D_f$, of the grid having the value 2 and is elaborated upon in Hurst and Vassilicos (2007), where it was also shown that the space-filling grid achieves flow homogeneity faster than fractal grids with other dimensions $D_f$. A fractal grid can be ‘tailored’ to generate the maximum of the turbulent intensity at just any required distance downstream of the grid by using different grid designs. We choose to compare the fractal grid with a square grid of the same blockage ratio, defined as the ratio of the area covered by the grid to the cross-sectional area of the burner.
We use the same burner and the same mean velocity so as to eliminate influences of the geometry and the boundary conditions on the comparison.

At this point, we emphasize that the fractal-grid-generated turbulence is by no means related to fractal flame theories\(^3\). In the latter case, an effort was made to describe the surface area of a flame as a fractal object with a characteristic fractal dimension which led to models for the flame surface density and the turbulent burning velocity (Gouldin 1987); measurements of the flame fractal dimension also exist (Gulder et al 2000). In contrast, in turbulence generated by a fractal grid, we do not try to describe the turbulent flow field or the flame using fractal theory; we only construct a grid that resembles a fractal object and we study the ensuing turbulent properties and their effect on premixed combustion.

The structure of the paper is as follows. Section 2 describes the design and properties of the space-filling fractal grid and the burner, the flames studied and the diagnostics used. The results are presented in section 3 and a summary of the main conclusions is reported in section 4.

2. Experiment

2.1. The fractal grid

The fractal grid, of the same design as in Seoud and Vassilicos (2007) and Mazellier and Vassilicos (2010), consists of a main geometric pattern that is repeated at smaller scales and, as the scale decreases, the number of repeated patterns increases. In the grid used in the present measurements the main pattern is a square, whose bars have length \(L_0 = 36.8\) mm and width \(t_0 = 2.70\) mm. At each successive iteration of the main pattern, there are four times as many squares as in the previous iteration, and the length and width of the grid bars change as \(L_j = R_L^j L_0\) and \(t_j = R_t^j t_0\), respectively, where \(j = 0, 1, \ldots, N - 1\) and \(N\) is the number of iterations. The present fractal grid has \(R_L = 1/2\), \(R_t = 0.4\) and \(N = 3\) and is shown in figure 1.

\(^3\) Fractal flame theories are part of the broad research activity on the physics of fractals and spirals which started in the 1980s and continues to this day (see e.g. Gilbert (1988), Berry (1989), Sapiwall and Gordon (1993), van den Berg (1994), Fleckinger et al (1995), Vassilicos (1995), Angilella and Vassilicos (1998), Gurbatov and Trousssov (2000), Malik and Fung (2000) and Go and Pyun (2007)).

Figure 1. An image of the fractal grid used in the measurements with relevant geometric quantities. The values used are \(L_0 = 36.8\) mm and \(t_0 = 2.70\) mm.
Figure 2. The decay of the turbulent fluctuations, $u'/U$, with downstream distance. Open symbols correspond to the square grid and filled symbols correspond to the fractal grid. In this plot the point $z = 0$ corresponds to the axial position of the grid. The normalization of the downstream distance is with $z_*$, as introduced in the text. The conditions in this plot correspond to a bulk velocity $U = 4.3 \text{ m s}^{-1}$, slightly lower than the bulk velocity in flame conditions.

The blockage ratio, $\sigma$, of the fractal grid is defined as the ratio of the area covered by the grid to the area of the duct and is $\sigma = 0.22$ for both the grids used in these experiments. An effective mesh size is defined as

$$M_{\text{eff}} = \frac{4d^2}{P} \sqrt{1 - \sigma},$$

where $d$ is the size of the side of the square duct burner (introduced in section 2.2) and $P$ is the perimeter of the fractal grid; here $M_{\text{eff}} = 13 \text{ mm}$. The effective mesh size formula when applied to a square mesh grid returns this grid’s mesh size.

As mentioned in section 1, one of the defining characteristics of this particular design of fractal grids is the difference in the production and decay of the turbulence intensity as compared to a standard square mesh grid. In a standard grid, after a few mesh lengths where the turbulence is produced, there is a long region where the turbulent fluctuations decay following a power law (Comte-Bellot and Corrsin 1966) of the form $\langle u'^2 \rangle \sim z^{-n}$, where $\langle u'^2 \rangle$ is the variance of the velocity fluctuations, $z$ is a normalized downstream distance and angle brackets denote averaging. In contrast, it has been shown (Hurst and Vassilicos 2007, Mazellier and Vassilicos 2010) that with the fractal grid used here the turbulence takes a long while to be fully produced and increases up to a peak value at some far distance downstream of the grid before starting to decay. The peak of the turbulent intensity was found to occur at a downstream distance $z_{\text{peak}} \approx 0.5z_*$, where the wake interaction length scale is

$$z_* = \frac{L_0^2}{t_0},$$

where, for the values of the $L_0$ and $t_0$ of the present grid, $z_{\text{peak}} = 226 \text{ mm}$. To demonstrate this, hot wire anemometry is used to measure the turbulent fluctuations. Figure 2 shows the downstream evolution of the centreline turbulent intensity, $u'/U$ (where $u'$ is the rms of the
velocity fluctuations and $U$ is the local mean velocity), for the fractal grid and a square mesh grid having the same blockage ratio and mesh size. There are three sets of points for each grid in this figure, each set represented by different markers. We use three different duct lengths, see section 2.2, to change the distance downstream of the grid. For a given duct length, velocity measurements are taken at positions both upstream and downstream of the duct exit. In this way, the positions downstream of the duct exit for a duct length coincide with the positions upstream of the exit for a larger duct length.

In figure 2, the square mesh grid follows a standard power law decay whereas the turbulent fluctuations in the fractal grid increase with downstream distance before following a slow decay. Furthermore, for downstream distances larger than $\sim 7$ mesh sizes from the grids, both the Taylor and integral length scales are continuously larger for the fractal-grid-generated turbulence. Similarly to Hurst and Vassilicos (2007) and Mazellier and Vassilicos (2010) (also for grids with $N = 3$), the Taylor length scale is practically constant with downstream distance, whereas the integral length scale increases very slowly. So, the Taylor-based and turbulent (based on the integral length scale) Reynolds numbers have downstream evolutions of a similar form to the evolution of the turbulent intensity. Finally, for positions on the centreline and off-centreline, the power spectra of the velocity fluctuations show a broad continuous power-law scaling region for both grids.

The observed difference in the downstream behaviour of the fractal grid turbulence, as compared to the square mesh grid, has been explained in Mazellier and Vassilicos (2010) by considering the interaction between the wakes generated from the fractal grid bars, each bar having a different size; schematically, this is shown in figure 3. The smaller wakes reach their peak turbulence intensities closer to the grid. They mix and would decay if it were not for the next size iteration of wakes which reach turbulence intensities further down and thereby help the turbulence to build up to higher intensities further away from the grid rather than decay. The smaller wakes reach their peak turbulence intensities, and start to mix with each other, closer to the grid. Before the turbulence generated starts decaying, it has reached the downstream position where the wakes of the larger size bars meet. Consequently,
turbulence builds up to higher intensities further away from the grid rather than decaying. This process continues for as many fractal size iterations as are present on the grid with the result of obtaining, without much pressure drop, a high turbulent intensity with good profile homogeneity at a distance $z_*$ from the grid (Seoud and Vassilicos 2007, Mazellier and Vassilicos 2010). This distance, $z_*$, is given by equation (2), as explained by the following argument (Mazellier and Vassilicos 2010). The wake width, $s$, scales as $s \sim \sqrt{tz}$, where $t$ and $z$ are the bar width and the downstream distance, respectively. Taking into account that the largest bar (with width $t_0$ placed at the furthest distance from the centreline) will create the largest wake, which will contribute more to the turbulent intensity, and assuming that this wake will reach the centreline at $s \sim L_0$, we can arrive at the distance $z_*$ introduced earlier by equating these scalings to obtain $L_0 \sim \sqrt{t_0z_*}$.

It has been shown in Mazellier and Vassilicos (2010) that the mean profile structure of the fractal-generated flow does not change with mean flow velocity and, in particular, that $z_*$ is independent of the mean velocity. Increasing the number $N$ of fractal iterations and/or the thickness ratio $t_r$ (defined as $t_0/(t_N−1)$) improves the homogeneity of mean profiles at distances beyond $z_*$. Increasing the overall combustor size and, therefore, the overall fractal grid size makes it easier to use a large number of iterations and therefore works favourably. As shown in Hurst and Vassilicos (2007) and Mazellier and Vassilicos (2010) following fluid dynamic experiments in two wind tunnels of different sizes, scaling up does not change equation (2) even though it obviously changes $z_*$, $L_0$ and $t_0$.

The present attempt to generate turbulence differs from similar previous efforts (e.g. Frank et al (1999), Coppola and Gomez (2010)). In the past the motive was to generate as high turbulent fluctuations as possible and, on a second level, maintain a homogeneous field. Commonly, increasing the pressure drop led to higher fluctuations close to the turbulence generator with field homogeneity improving with downstream distance, while the turbulence intensity decays. The fractal grid used here, which is one design of many possible with all having the same pressure drop, also achieves large turbulent fluctuations, but further away from the grid and as the flow homogeneity improves with downstream distance, it could be possible to have the largest turbulent fluctuations within a homogeneous flow field (see section 3.1 for particulars of the present design). However, the main motive behind the present experiments is the turbulent properties that this grid generates, which are fundamentally different from established results (Stresing et al 2010). We want to study the effect of this new type of turbulence on premixed combustion.

2.2. Burner configuration and flame conditions

The experimental burner consists of two square ducts, each of inner side $d = 62$ mm, oriented vertically upwards. The upstream duct is $L = 500$ mm long and the mixture of fuel and air is injected through four inlets at the bottom of this duct. A mixing region filled with glass beads is followed by a section that comprises a perforated plate with 4 mm holes and a mesh screen, which are used to break the large-scale structures formed by the four incoming jets. After a settling region of 150 mm, a second flow conditioning section is placed, with a 50 mm long honeycomb with 4 mm holes followed by a mesh screen, in order to straighten and laminarize the flow and produce a uniform flowing stream of fuel and air. The turbulent intensity at the position where the grids are placed is around 1%.

Turbulence generating grids are placed 100 mm downstream of the final mesh screen, at the position where the second, downstream, duct is connected to the upstream one. Three different square ducts can be placed at this position, having lengths 50, 100 and 200 mm and premixed, V-shaped flames are stabilized on a 2.5 mm diameter rod, which is placed 50 mm
Figure 4. A cross section of the burner. The z-direction is along the axis of the burner and the x-direction is the cross-stream direction. The grid location is indicated in the plot and the flames are established 50 mm downstream of the exit plane of the final duct.

Table 1. The flame parameters. The equivalence ratio is $\phi$, the laminar flame speed is $s_L = 0.25$ and $0.2 \text{ m s}^{-1}$, for $\phi = 0.77$ and 0.7, respectively, and $u'$ is the rms of the velocity fluctuations. The flame thickness is $l_F = 0.59$ and 0.72 mm, for $\phi = 0.77$ and 0.7, respectively. The angle between the two branches of the flame is $\alpha$ and the turbulent flame speed is calculated as $s_T = U \sin \alpha / 2$, where $U$ is the local mean velocity at the flame stabilization position. The turbulent Reynolds number, $R_T$, is based on the standard deviation of the velocity fluctuations and the integral length scale, $l$. The distance downstream of the grid is $L$.

| $\phi$ | $L$ (mm) | Grid | $U$ (m s$^{-1}$) | $u'/s_L$ | $R_T$ | $l/l_F$ | $\alpha$ (°) | $s_T/s_L$ |
|-------|---------|------|-----------------|----------|-------|--------|-------------|----------|
| 0.77  | 250     | Square | 4.5          | 0.76      | 83    | 11     | 20          | 3.2 |
|       |         | fractal | 5.4          | 1.25      | 148   | 11.8   | 20          | 3.9 |
| 0.7   | 250     | Square | 4.5          | 0.95      | 83    | 9      | 14          | 2.8 |
|       |         | fractal | 5.5          | 1.58      | 147   | 9.7    | 19          | 4.6 |

downstream of the exit plane of the burner. The mesh size and the solidity of the standard square mesh grid are the same as the effective mesh size and the solidity of the fractal grid, respectively. The burner is shown in figure 4.

Lean, premixed, methane flames are stabilized in the burner for each one of the two grids. The air and fuel flow rates are controlled with volume flow meters, and flames are stabilized at 250 mm downstream of every grid. Flames with equivalence ratio $\phi = 0.7$ are measured using high-speed OH PLIF and flames with $\phi = 0.77$ are measured using OH$^*$ chemiluminescence. Relevant parameters for all flames are shown in table 1 and the position of each flame in the combustion regime diagram (Peters 2000) is shown in figure 5. We mainly concentrate on the flames with $\phi = 0.7$ and OH PLIF measurements, because from these results we can extract most relevant parameters, such as flame curvature, flame surface density, etc.
2.3. Measurement techniques and data processing

2.3.1. Hot wire anemometry. The mean, the fluctuations and the length scales of the flow field in ambient conditions are measured using a hot wire anemometer (DANTEC). The length of the sensing wire is 1.25 mm and the acquisition frequency is 6 kHz, with a low-pass filter set at 3 kHz. The signal is acquired with a 16-bit A/D card (National Instruments NI 6013) and 2^16 samples are collected for every condition. The velocity calibration is performed at the potential core of a laminar jet flow and a fourth-order polynomial is fitted to the calibration results to obtain the velocity as a function of the measured voltage.

The time-dependent velocity signal is transformed to a velocity signal in the spatial domain by using Taylor’s hypothesis. An autocorrelation function is calculated from the fluctuating velocity signal as $R(\Delta x) = \langle u(x)u(x+\Delta x) \rangle / \langle u^2 \rangle$, where $x$ is the spatial coordinate, $u$ is the velocity deviation (instantaneous minus the mean) and $\langle \rangle$ denote spatial averaging. The Taylor length scale is obtained from a parabolic fit at the origin of the autocorrelation function and the integral length scale from the integral of the autocorrelation function to the first zero crossing.

2.3.2. High-speed OH fluorescence imaging. The principle of planar laser-induced fluorescence measurements can be found in Eckbreth (1996). A high-speed frequency doubled Nd:YAG laser (Edgewave Innoslab IS8II-DE) is used to pump a narrowband, frequency doubled dye laser (Sirah Allegro) that generates around 0.16 mJ per pulse at 5 kHz repetition rate. Owing to the rather low pulse energies at this high repetition rate, the laser is tuned to excite the strong OH $Q(6)$ transition in the (1,0) band of the OH A–X system near 283 nm; the spectral linewidth of the dye laser is 0.6 cm$^{-1}$. The beam is formed into a light sheet resulting in laser irradiance far below saturation giving a linear dependence of the signal on laser pulse energy. The fluorescence from the (1,1) and (0,0) bands of OH is collected between 305 and 320 nm using a high-speed CMOS camera (LaVision HighSpeedStar 6) coupled to a two-stage high-speed intensified relay optics (LaVision Highspeed IRO). A WG295 Schott glass filter is mounted in front of the $f = 105$, $f/2.8$ UV camera lens to eliminate any scattered laser
light and a UG11 filter is used to suppress flame luminescence and PAH fluorescence. The intensifier gate width is adjusted to 100 ns.

The thickness of the laser sheet at the measurement location is estimated to be 0.2 mm and the field of view of the camera is $30 \times 30 \text{ mm}^2$ giving a resolution of 0.03 mm per pixel. The integral time scales of the flow are 1.50 and 1.45 ms for the square and the fractal grids, respectively, so that the measurement duration was longer than 600 integral time scales (alternatively, the large eddy turnover time for the square and the fractal grid is 34 and 21 ms, respectively, so the measurements were at least 30 turnover times long).

The raw OH fluorescent images are processed, using the method developed in Pfadler et al (2007), in order to extract the instantaneous distributions of the progress variable, $c$. The progress variable is a non-dimensional number having the value 0 at the reactants and the value 1 at the products and is defined either as a normalized temperature or product mass fraction (Peters 2000). From the mean progress variable, $\langle c \rangle$ (where $\langle \rangle$ denote time averaging), the flame surface density, which is the area of the flame per unit volume, the flame angle (using the $\langle c \rangle = 0.5$ iso-contour) and the flame brush thickness (the distance between the $\langle c \rangle = 0.1$ and 0.9 iso-contours) are also calculated. The processing is shown in figure 6, which displays a raw, instantaneous OH PLIF image in grey scale with the flame contour superimposed. The algorithm identifies accurately the flame contour, and more details of the errors can be found in Pfadler et al (2007).

2.3.3. OH* chemiluminescence. The chemiluminescent intensity of OH* is measured with an intensified CCD camera (Andor) using a UG11 bandpass filter (transmission in the range 250–375 nm) in front of a UV camera lens ($f = 105 \text{ mm}$, $f/4.5$). The gating time for the intensifier depends on flame conditions and is between 50 and 100 $\mu$s; the magnification is 0.078 mm per pixel.

In order to measure the flame angle from the chemiluminescence measurements, the following procedure is applied to the mean OH* chemiluminescence images. At every
downstream distance the cross-stream OH\textsuperscript{*} profile is fitted to the sum of two Gaussian functions. Figure 7(a) shows the mean OH\textsuperscript{*} distribution for $\phi = 0.77$ with the flame stabilized at 250 mm downstream of the square grid. A measured cross-stream OH\textsuperscript{*} profile is shown in figure 7(b), which also shows the corresponding fitted profile. This verifies that the sum of two Gaussian functions fits very well both the locations of the peak OH\textsuperscript{*} intensity and the width of each of the two branches of the flame. This is also true for all downstream distances and is further shown in figure 7(a), where the centres of the Gaussian functions are shown as symbols. These values also identify a characteristic surface at each branch of the flame and the flame angle is defined as the angle between these two surfaces. The flame angles from the OH\textsuperscript{*} images are calculated by using the Gaussian fits from $z/d = 0.1$ to 0.3.

2.3.4. Experimental uncertainties. The uncertainty in the equivalence ratio and in the mixture velocity result from the uncertainty in the calibrated flow meters, which have an accuracy of 2.5% of the full scale. Therefore, the uncertainties in the equivalence ratio and the bulk mixture velocity are $\pm 0.025$ mixture fraction units and $\pm 0.08$ m s\textsuperscript{-1}, respectively. The statistical uncertainty in the measured standard deviation of the velocity fluctuations is $\pm 8 \times 10^{-4}$ or $\pm 16 \times 10^{-4}$ m s\textsuperscript{-1}, for the square and the fractal grids, respectively. The laminar burning velocity is calculated from a third-order polynomial fit to experimental data, (Gu et al 2000) as $s_L = 0.25$ and 0.2 m s\textsuperscript{-1}, for $\phi = 0.77$ and 0.7, respectively, and the laminar flame thickness is estimated from the data of Lafay et al (2008) as $l_F = 0.59$ and 0.72 mm, for $\phi = 0.77$ and 0.7, respectively.

3. Results

3.1. Isothermal velocity field

Another difference between the square and the present fractal grid, apart from the downstream evolution of the turbulent intensity (figure 2), is the nozzle exit velocity profiles presented in figure 8. This shows the velocity across the burner at the exit plane, for both grids, at a distance 250 mm downstream of the grid; the error bars correspond to one standard deviation.
of the velocity fluctuations at each position. The velocity measurements are made at a bulk velocity $U = 4.3 \text{ m s}^{-1}$, which is slightly lower than the mixture bulk velocity in the flame conditions. In both cases, the profiles show that the flow is symmetric and in the square grid the flow is also uniform across the burner. In contrast, the fractal grid imposes a velocity distribution across the burner with higher velocities at the centreline; it should be noted that the velocity near the duct wall is lower in the case of the fractal grid, so integrating the full velocity profile (including these boundary layers) gives the same area-averaged velocity for both grids. The reason for this inhomogeneity in the case of the fractal grid is probably the limited number of fractal iterations. For fractal grids of the same design it has been shown (Hurst and Vassilicos 2007, Seoud and Vassilicos 2007, Mazellier and Vassilicos 2010) that the mean and turbulent velocity profiles across the mean flow direction become more and more homogeneous as the number of iterations increases and are, practically, homogeneous beyond $z_{\text{peak}}$.

Similar cross-stream velocity profiles are found at other downstream distances as well and figure 9(a) shows the downstream variation of the mean velocity at the centre of the burner. The large opening at the centre of the fractal grid, cf figure 1, imposes a non-uniform pressure distribution across the grid, resulting in the observed overshoot of the centreline velocity. With increasing downstream distance, the centreline velocity relaxes to the bulk velocity. On the other hand, given that there is a pressure drop across the burner, the square grid shows the expected recovery of the centreline velocity with downstream distance.

The variation of the Taylor length scale with downstream distance is shown in figure 9(b) for both grids and which demonstrates another difference of the turbulence generated by the fractal grid as compared to previous attempts to generate turbulence for studies of premixed flames. It is unexpected to observe that the Taylor length scale in the case of the fractal grid remains constant, irrespective of the downstream distance, whereas the Taylor length scale of the square grid grows linearly. So, for example, this means that it is possible to change

4 The anomalous point on the lower curve is an ‘off’ point, a fact we have verified in further tests.
independently the velocity fluctuations and the inner length scales of turbulence by moving along the centreline. In these experiments, the Taylor length scale is also the same at different locations across the duct.

3.2. Flame results

The position of the flames in the flow field produced by the two grids is shown in figure 10, which shows the turbulent fluctuations normalized by the laminar flame speed as a function of the downstream distance, for both grids. This figure is produced by fitting smooth lines (which are only used to aid the demonstration) through the points of figure 2, dividing by the appropriate $a_L$ and plotting the various flames as they appear in table 1. The flames are at the same distance downstream of the grids, slightly past the peak of the velocity fluctuations for the fractal grid, so they are situated at locations where we expect the flow field to be as homogeneous as possible for both grids. Indeed, in regular mesh grids, the flow starts to approach a homogeneous state after about 20 mesh sizes (here, 260 mm downstream distance) (Mohamed and Larue 1990), whereas in fractal grids the flow becomes nearly homogeneous after the location of $z_{peak}$ (Mazellier and Vassilicos 2010) (here, 226 mm downstream distance—note, however, that the approach to homogeneity in the fractal grid might depend on the number of iterations). It is an advantage of these flame experiments that the flames are established at these downstream distances (for either grid), where the flow starts to better approximate homogeneity, in contrast to the usual practice of stabilizing a flame very near a turbulence generating grid.

We note that the normalized turbulent fluctuations along the measured flames (i.e. along the length of the arrows in figure 10) decay only a little for all flames. The variation of $u'/a_L$ for the square grid between the start and the end of the imaging region is 8%, and in the case of the fractal grid the variation is 5%.

Figure 11 shows pairs of instantaneous OH$^*$ chemiluminescence images for the flames at $\phi = 0.77$ for both grids. Figure 11(a) shows that the flames are slightly distorted by the flow.
Figure 10. The downstream variation of the turbulent fluctuations normalized by the laminar flame speed for both grids. The dotted line corresponds to the square grid and the dashed line to the fractal grid, for $\phi = 0.77$ and $s_L = 0.25 \text{ m s}^{-1}$. The measured flames are shown as symbols; the open symbols correspond to the flames with $\phi = 0.77$ and the filled symbols to the flames with $\phi = 0.7$. The extent of the $x$-axis on this plot is the same as the extent of the $x$-axis in figure 2. The horizontal arrow shows the axial extent of the imaging measurements.

Figure 11. Pairs of instantaneous OH$^+$ chemiluminescence images. The distance downstream of each grid is $L$. The colour scale is not comparable between images in different conditions. (a) Square grid, $L = 250 \text{ mm}$, $u'/s_L = 0.76$ and (b) fractal grid, $L = 250 \text{ mm}$, $u'/s_L = 1.25$.

field and seem to follow the large-scale movement of the instantaneous flow. The position of the flames in the wrinkled flamelet regime in the regime diagram of figure 5 can justify this appearance. In the case of the fractal grid (figure 11(b)), the flames show smaller scale corrugations in comparison to the square grid flames and appear thicker, with the peak OH$^+$ intensity being more distributed and not as smooth as in figure 11(a).

Sample instantaneous OH PLIF images are shown in figure 12, for $\phi = 0.7$ at $L = 250 \text{ mm}$ downstream of the grid. While the large-scale structure of the flames seems to be similar between the two grids, the fractal grid flames show more pronounced corrugations and the various structures seem more acute.

The mean distributions of OH$^+$ chemiluminescence and of the progress variable are shown in figure 13. These images show that the fractal grid flames have larger angles, implying
Figure 12. Raw, instantaneous, sequential OH PLIF images, for $\phi = 0.7$. The top row is the square grid and the bottom row is the fractal grid. The time step between consecutive images is 400 $\mu$s, twice the image acquisition time step (= 200 $\mu$s).

a larger turbulent burning velocity (since all flames have the same mean velocity), and wider distribution of the progress variable, implying a larger flame brush.

The OH PLIF images offer the possibility to calculate the curvature of the flame, using the instantaneous flame contour (Pfadler et al 2007). With increased turbulent fluctuations, compared to the laminar flame speed, the flame will become more and more corrugated. For $\phi = 0.7$, where the OH PLIF measurements are obtained, the square grid flame sits at the borderline between the wrinkled and corrugated flamelets regimes, whereas the fractal grid flame is in the corrugated flamelets regime, closer to the thin reaction zones regime. Consequently, for the fractal grid flame, the motion of turbulent eddies will dominate over the movement of the flame front with the laminar burning velocity, these two effects being of comparable magnitude at the square grid flame. Quantitatively this difference is shown in figure 14, which plots the probability density functions of the curvature for the two flames (positive curvatures denote flame front ‘excursions’ towards the reactants). The mean values of curvature are very similar for both grids. The distributions are symmetric and similar to each other near the mean value. The tails of both distributions are more pronounced than a normal distribution (with the same mean and standard deviation) and become increasingly asymmetric at larger curvature values, more so for the square grid flame, where large positive curvature values are less likely than large negative ones. The pdf of the fractal grid flame shows that somehow larger positive curvature values are found, in comparison with the square grid flame.
The downstream dependence of the flame brush thickness, $\delta T$, is shown in figure 15. The flame thickness is calculated from the flame surface density distribution, which is derived from the progress variable, but not shown here, using a procedure outlined in Pfadler et al (2007). We fit the sum of two Gaussian functions to the transverse flame surface density profile at each downstream distance and calculate the flame brush thickness as the average of the standard deviations of the two Gaussian functions. The flame brush thickness is an indication of the average movement of the flame due to movements of the instantaneous flame induced by the turbulent flow field. The presented flames are situated in the flamelet regime, so large-scale effects, e.g. of the order of the integral length scale, are expected to be more important. Smaller scale wrinkling of a flame would be more pronounced as one reaches the $Ka = 1$ line in the combustion regime diagram. This would increase the flame brush and figure 15 verifies this expectation, since the fractal grid flame is thicker than the square grid flame, as one moves further downstream of the stabilizing rod.

Finally, figure 16 shows the turbulent flame speed as a function of the normalized turbulent fluctuations for all the flames. The comparison of the characteristics of all flames
is interesting since they are all established in the same burner with nearly the same flow rate, so the bulk velocity is almost constant for all flames\(^5\).

Using the square grid, the flames produced have normalized velocity fluctuations of the order of 1 and their respective normalized turbulent burning velocities are similar, having values around 3. In the case of the flames using the fractal grid, the normalized turbulent fluctuations increase between the two flames studied, from 1.25 to 1.6, and the turbulent burning velocities correspondingly increase, attaining values up to about 5. Pairs of these

\(^5\) The values of the mean velocity in table 1 refer to the local mean velocity at the position of the stabilizing rod and, for example, by averaging the mean cross stream velocity profiles from \(x/d = -0.1\) to 0.1 (cf figure 13) the differences in the mean velocity between flames are of the order of ±10%.
flames, one each using the square and the fractal grid, are established at the same distance downstream of the grid at flow fields quite homogeneous. The fractal grid flames, for the two different equivalence ratios, have higher turbulent burning velocities, since they have been subjected to more corrugations, evident from the curvature distributions. So it has been possible, just by using a different grid, to increase the turbulent burning velocity at a particular downstream distance, with respect to using a normal square grid. It is interesting to note further that the integral length scales of the pairs of flames at the same equivalence ratio have nearly identical integral length scales.

4. Conclusions

The main result of the present experiments is that by using a fractal grid instead of a regular square mesh grid, in an otherwise identical burner configuration and at the same downstream position, the response of turbulent premixed flames changes. It is shown that the turbulent burning velocity of a flame stabilized on fractal-grid-generated turbulence is higher than the corresponding burning velocity when using a standard square mesh grid.

The presented results demonstrate the effect and the value of the fractal grid as a turbulence generator in premixed turbulent combustion. By using the fractal grid, more intense turbulence can be generated at a given downstream distance compared to a normal square mesh grid and, as a consequence, the turbulent fluctuations and the turbulent flame speed are increased. In fact, the turbulent flame speed increases by more than 40% on average by using the fractal grid. This can prove beneficial, e.g., for extending the lean stability limit for a given heat release rate. Analysis of the flame quantities reveals that both the curvature and the flame brush thickness of the fractal grid flame are more pronounced, in the sense that the flame presents larger corrugations and more intense burning than the normal grid flame.

This stems from the unique properties of the turbulence generated by the multiscale/fractal grid. The maximum of turbulence production is achieved at a well-defined downstream distance from the grid. At this location, relatively high levels of turbulent

Figure 16. The normalized turbulent flame speed as a function of the normalized turbulent fluctuations for all the flames. The open symbols correspond to $\phi = 0.77$ and the filled symbols to $\phi = 0.7$. 

**Flame Dyn. Res. 45 (2013) 061404**

N Soulopoulos et al
fluctuations can be achieved, while, at the same time, the turbulence reaches homogeneity in terms of mean flow and turbulent intensity profiles, when the number of fractal iterations is 4 or higher and the thickness ratio, $t_r$, is large enough. Finally, downstream of the maximum turbulent intensity location both the Taylor and the integral length scales remain constant. A practical benefit is that the characterization of the turbulence can be more accurate than when establishing a flame in the decaying turbulent field of a regular square mesh grid, which has a length scale that changes with downstream distance.

Acknowledgments

Financial support from Imperial Innovations Group plc for part of the project is gratefully acknowledged. We thank Ms Monica Luegmair for her help with the high-speed measurements.

References

Abdel-Gayed R G, Bradley D and Lawes M 1987 Proc. R. Soc. Lond. A 414 389–413
Angilella J R and Vassilicos J C 1998 Physica D 124 23–57
Bernier D, Lacas F and Candel S 2004 J. Propulsion Power 20 648–56
Berry M V 1989 Physica D 38 29–31
Bradley D, Haq M Z, Hicks R A, Kitagawa T, Lawes M, Sheppard C G W and Woolley R 2003 Combust. Flame 133 415–30
Cheng R 1995 Combust. Flame 101 1–14
Comte-Bellot G and Corrsin S 1966 J. Fluid Mech. Digit. Arch. 25 657–82
Coppola G and Gomez A 2010 Phys. Fluids 22 105101
Dhanuka S K, Temme J E, Driscoll J F and Mongia H C 2009 Proc. Combust. Inst. 32 2901–8
Eckbreth A C 1996 Laser Diagnostics for Combustion Temperature and Species (London: Gordon and Breach)
Filatov S A, Driscoll J F, Carter C D and Donbar J M 2005 Combust. Flame 141 1–21
Fleckinger J, Levitin M and Vassiliev D 1995 Proc. Lond. Math. Soc. 71 372–96
Frank J H, Kalt P A M and Bilger R W 1999 Combust. Flame 116 220–32
Gilbert A D 1988 J. Fluid Mech. 193 475–97
Go J Y and Pyun S I 2007 J. Solid State Electrochem. 11 323–34
Gouldin F 1987 Combust. Flame 68 249–46
Gu X J, Haq M Z, Lawes M and Woolley R 2000 Combust. Flame 121 41–58
Gulder O L, Smallwood G J, Wong R, Snelling D R, Smith R, Deschamps B M and Sautet J C 2000 Combust. Flame 120 407–16
Gurbatov S N and Troussov A V 2000 Physica D 145 47–64
Hurst D and Vassilicos J C 2007 Phys. Fluids 19 035103
Korusoy E and Whiteley J H 2002 Exp. Fluids 33 75–89
Lafay Y, Renou B, Cabot G and Boukhalfa M 2008 Combust. Flame 153 540–61
Malik N 2012 Combust. Sci. Technol. 184 1787–98
Malik N A and Pung J C H 2000 Phys. Rev. E 62 6636–47
Malik N and Lindstedt R 2012 Combust. Sci. Technol. 184 1799–817
Mazellier N and Vassilicos J C 2010 Phys. Fluids 22 075101
McDonell V 2008 Lean Combustion—Technology and Control ed D Dunn-Rankin (New York: Academic) pp 121–60
Mohamed M S and Larue J C 1990 J. Fluid Mech. 219 195–214
Peters N 2000 Turbulent Combustion (Cambridge: Cambridge University Press)
Pfadler S, Beyrau F and Leipertz A 2007 Opt. Express 15 15444–56
Robin V, Mura A, Champion M, Degardin O, Renou B and Boukhalfa M 2008 Combust. Flame 153 288–315
Sapoval B and Gordon T 1993 Phys. Rev. E 47 3013–24
Seoud R E and Vassilicos J C 2007 Phys. Fluids 19 105108
Soika A, Dinkelacker F and Leipertz A 1998 Int. Symp. on Combustion vol 27 pp 785–92
Stresing R, Peinke J, Seoud R E and Vassilicos J C 2010 Phys. Rev. Lett. 104 194501
van den Berg M 1994 Probab. Theory Relat. Fields 100 439–56
Vassilicos J C 1995 Phys. Rev. E 52 R5753–6