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The structure of turbulent flames in fractal- and regular-grid-generated turbulence

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ABSTRACT

This study reports on the use of fractal grids as a new type of turbulence generators in premixed combustion applications. Fractal grids produce turbulence fields which differ from those formed by regular turbulence generators such as perforated plates or meshes. Fractal grids generate high turbulence intensities over an extended region some distance downstream of the grid with a comparatively small pressure drop. Additionally, the integral scale of the flow does not change downstream of the grid. The extended region of high turbulence can also be optimized for the specific application at hand by changing certain parameters of the grid which makes it possible to design the downstream development of the turbulence field. Four space-filling fractal square grids were designed to independently vary the resulting turbulent field and a regular square mesh grid with similar turbulent intensity acted as a reference case. The structure of the resulting premixed V-shaped flames was investigated using Conditioned Particle Image Velocimetry (CPIV). At the same downstream position, flames in the turbulence field of fractal grids showed larger turbulent burning velocity compared to flames in regular grid generated turbulence. However, when compared for the same turbulence intensity, flames in fractal grid generated turbulence produced similar turbulent burning velocities compared to flames in regular grid generated turbulence. In particular, it could be shown that theories such as Taylor's theory of turbulent diffusivity and Damköhler's theory of premixed flame propagation, which were deduced from regular turbulence fields, adequately described the increase of effective flame surface area due to the increase in turbulence intensity. Using fractal grids allows the independent variation of the turbulent fluctuations, the integral length scale and the turbulent Reynolds number. An unexpected finding was that the burning velocity ratio, s_t/s_l was negligible influenced by the integral length scale. A correlation between the burning velocity ratio, s_t/s_l, and the normalized velocity fluctuations of the flow, u'/s_l, showed a negligible influence of the integral scale on the turbulent burning velocity. A literature review revealed that the influence of the integral scale on the turbulent burning velocity is still unclear and further research is required. In this context, fractal grids are particularly helpful as they cover a wider range of integral length scales for sufficiently turbulent flows, $u' \geqslant s_l$, compared to regular grids.

1. Introduction

Turbulent premixed flames are of great importance for technical combustion systems as these can produce high power densities and low pollutant emissions at the same time. The impact of turbulent flow field characteristics on the flame is of importance in technical applications because it greatly increases the apparent propagation speed – the so-called "turbulent burning velocity" and knowledge of the dependence of the magnitude of the turbulent burning velocity on the turbulence is valuable and interesting. For basic research into the dependence of the characteristics of the turbulence, it is convenient to use turbulence generating grids such as perforated plates or meshes. These grids are usually placed at distances of several characteristic mesh sizes upstream of the flame to ensure a well-developed velocity field. Although such grids can generate high levels of turbulence near the grid, the turbulence decays quickly with downstream distance [1], and, as a consequence, the resulting flames are exposed to rather low turbulence intensities.

Correlations for the dependence of the turbulent burning velocity on the turbulent characteristics of the flow field have long been

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produced and mostly incorporate a dependence on the flow integral length scale. In an experiment, the mean velocity is typically changed in order to produce larger turbulent fluctuations; however, it has been shown, for example, that allowing a simultaneous change of the mean velocity and the turbulent characteristics can produce misleading correlations, [2]. Consequently, the ability to independently vary the turbulent quantities it is of great importance. To achieve this, we utilize fractal grids in premixed turbulent combustion experiments.

Vassilicos et al. [3–6] proposed fractal grids as a new type of low blockage turbulence generators with a number of potential applications [7–14]. Fractal grids consist of structures with multiple length scales rather than one length scale. Extensive wind tunnel measurements have shown that fractal grids generate a long region of downstream evolution of turbulence which is fundamentally different from Richardson–Kolmogorov cascading turbulence [15]. The turbulence intensity initially builds up in a distinct production region until it reaches its maximum value and then decays further downstream at a rate that is different to that of regular turbulence grids. Moreover, during the decay of turbulence the integral length scale of the flow remains almost constant whereas the integral scale in regular turbulence fields usually increases with downstream distance. The downstream position of the maximum turbulence intensity is determined by the blockage ratio (the ratio between the area occupied by the grid and the enclosing duct area) and the ratio between the sizes of the largest and the smallest structures of the fractal grid [3]. It has also been shown that when both grids have the same blockage ratio, fractal grids can produce more than 30% higher turbulence intensities than regular grids [5]. These characteristics might have potential for technical combustion applications because larger flame surfaces per unit volume (*i.e.* power densities) can be achieved due to the higher turbulence intensity. Moreover, the increase in turbulence intensity with increasing distance from the grid seems attractive because this implies larger turbulent flame speeds at some distance from the grid than with a regular grid.

Recently, it has been shown by Mazellier et al. [16] that flow fields with similar turbulence characteristics to those of the mentioned fractal grids can be generated using an arrangement of multiple perforated plates with blockage ratios of 50–70%. These so-called multi-scale injectors produce turbulence levels comparable to fractal grids, albeit at a much greater pressure drops.

In this work we use fractal grids designed in a similar way to those in [3] as low blockage ($\sigma \approx 35\%$) turbulence generators in a premixed combustion application to study the effect of fractal grid generated turbulence on the structure of premixed flames and to validate existing, semi-empirical correlations of turbulent burning velocity. With these grids, and current manufacturing limitations, turbulence intensities of around 15% can be achieved at distances of 15–20 characteristic lengths from the grids. The fact that the velocity fluctuations generated by fractal grids increase over a long downstream distance is particularly interesting in premixed combustion as this makes it possible to achieve the highest turbulence intensity well downstream of the grid, at the location of the flame. As the downstream position of the maximum turbulence intensity can be changed by varying the design parameters of the grid, fractal grids could also be used to tailor the turbulence field in the region of the flame, according to the requirements of the particular combustion application. A recent comparison [14] of flames in fractal and regular grid generated turbulence has shown that for the same downstream position fractal grids produce flames with more wrinkling, a higher flame surface density and higher turbulent burning velocities.

The turbulent burning velocity, s_t, is often an important quantity in premixed combustion when it comes to assessing the burning rate at which unburnt gases are consumed by the flame. Based on numerous experimental investigations some obvious qualitative trends of the turbulent burning velocity in the region of moderate turbulence are well-known: the increase of s_t with increasing root-mean-squared velocity fluctuations of the flow, u', and the increase of s_t with increasing laminar burning velocity, s_l. Notably, Damköhler [17] was one of the earliest to provide a theoretical explanation for the increase of a flame's burning rate in the presence of a turbulent flow field. He deduced the well-known relation whereby the increase in turbulent burning velocity can be associated with the increase in effective flame surface area, $s_t/s_l \propto A_t/A_l$. He suggested that for large-scale turbulence (now called the corrugated flamelet regime) the interaction between flow field and flame front is purely kinematic and that the turbulent burning velocity should therefore depend only on the root-mean-squared velocity fluctuations of the flow, $s_t \propto u'$. For small-scale turbulence (now identified with the thin reaction zone regime) he suggested that rate of transport between the unburnt gases and the reaction zone of the flame is increased. Thus, the turbulent burning velocity should not only depend on the velocity ratio, u'/s_l, but also on the turbulence length scale of the flow, L. Damköhler proposed to use the relation $s_t/s_l \propto (D_t/D_l)^{1/2} = (u'L/s_l\,\delta_l)^{1/2}$, where $D_t = u'L$ and $D_l = s_l\,\delta_l$ are the turbulent and laminar diffusivity of the flow, respectively, δ_l is the thermal flame thickness and L is the integral length scale of the flow.

Over the last decades a number of investigations were dedicated to investigate the effect of turbulence on the turbulent burning velocity. Articles by Bray [18], Bradley [19] and Abdel-Gayed et al. [20] reviewed the experimental data that was available to them and discussed the many physical parameters that affect the burning rate of a flame, such as the Karlovitz [21], Markstein [22], Zeldovich [21] or Lewis numbers [23]. In aiming toward a fundamental theoretical description of the turbulent burning velocity many authors during the 1980s and 1990s noticed the self-similar appearance of the flame surface [24] and proposed that Damköhler's flame surface area ratio may be expressed in terms of an outer and inner length scale of the flow, $A_t/A_l \propto (\varepsilon_o/\varepsilon_i)^{D_f-2}$, with D_f as the fractal dimension [25] (note that this "fractal dimension" is not related to the existence of a fractal grid). By choosing the integral scale L as the outer cut-off frequency and the inner cut-off frequency as either the Kolmogorov scale η [26] or the Gibbson scale λ_G [27], a large number of correlations of the turbulent burning velocity [18,21,24,28] evolved as a function of two dimensionless quantities: the turbulent Reynolds number, $Re_t = u'L/\nu$, and the velocity ratio u'/s_l. One prominent result of this theoretical approach is the correlation by Gülder [28], $s_t/s_l = 1 + 0.62Re_t^{1/4}(u'/s_l)^{1/2}$. Although Gülder [29] later concluded that fractal theory is not suitable for a description of the turbulent burning velocity, which is widely accepted today, the turbulent Reynolds number and the velocity ratio, u'/s_l, nowadays still remain two of the most important dimensionless quantities used for the prediction of the turbulent burning velocity. Often the equation, $s_t/s_l = 1 + C(u'/s_l)^n$, is used for empirical correlations of the turbulent burning velocity, where n is an adjustable parameter with a value close to 0.5 [22,30] and C depends either on the length scale ratio, L/δ_l, as originally proposed by Damköhler [17] and theoretically argued by Peters [31], or C is expected to be proportional to the turbulent Reynolds number, $C \propto u'L/\nu$. The current FLUENT code, for example, uses the empirical correlation $s_t/s_l = 1 + A(u'L/\nu)^{1/4}(u'/s_l)^{1/2}$ based on Ref. [32].

In this paper we investigate the effect of fractal grid generated turbulence on the structure of premixed flames, evaluate the validity of existing semi-empirical correlations of turbulent burning velocity as applied to flames subjected to turbulence derived from fractal grids and assess the potential benefits of using fractal grids as turbulence generators in premixed combustion applications.