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Fractal turbulence enhancing low-swirl combustion

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ABSTRACT

The use of fractal grids in a low-swirl burner can significantly increase the turbulent combustion rate, realizing a higher power density in these flames. The standard turbulence generating blocking grid has been replaced by one consisting of a pattern of cruciform structures of different sizes, forming a multi-scale grid derived by truncating an underlying fractal structure. It is shown that the turbulence is intensified when comparing the flow behind the multi-scale grid to the reference situation, where a standard single-scale grid is used. This increase is expressed by more than doubling of the r.m.s. of the velocity fluctuations, while only marginal changes in pressure drop are observed. From the energy spectrum of the velocity it becomes clear that not only the largest scales are more energetic; also smaller scales are introduced as the spectrum is further extended into the high-frequency range. By means of planar OH-LIF the flame geometry was assessed, showing an increase in flame surface density and widening of the flame brush as well as much finer wrinkling of the flame front for the cases involving a multi-scale blocking grid. Here the turbulent flame speed (local consumption speed) is doubled. The grid parameters that were varied are the level of 'fractality' and the blockage. For both properties their effect on the flow and combustion are evaluated. The blockage mainly affects the stabilization mechanism, while the level of 'fractality' determines the increase in turbulence and combustion rate. Finally, it is shown that the low NO_X emission levels that characterize the low-swirl mode of combustion are not affected.

1. Introduction

It is known that fractal grids can efficiently produce turbulence. The extensive study on fractal-grid-generated turbulence by Hurst and Vassilicos [1] marks the start of intense interest in fractal grids. With a flat partially blocking object placed in a flow that is constructed according to an iterative multi-scale pattern, i.e., a fractal, turbulence can be generated at different scales simultaneously. This leads to an elongated region behind the fractal object where intense turbulence is produced before it decays further downstream. A fractal grid acts as a 'magnifying lens' for the non-equilibrium region as stated by Valente and Vassilicos [2]. There is a significant amount of research on the decay of this fractal-grid-generated turbulence [2–8] which appears to extend classical theory on homogeneous decaying turbulence, in which the dissipation rate, $\varepsilon \propto u'^3/L$ [9], where u' and L denote the r.m.s. of the velocity fluctuations and integral lengthscale, respectively. However, the fact that turbulence is intensified, measured by u', starting from several mesh-sizes downstream of the grid is indisputably established.

Many practical applications can benefit from the efficient generation of turbulence. As mixing is enhanced as shown in [10,11], it can be of use in mixing of product streams in process technology, in premixed combustion [12–14] or even in environmental fluid mechanics as fractal fences [15]. Fractal grids could also be used as air brakes on planes having in addition considerable noise reduction [16,17] or in the form of fractal flanges for more efficient flow metering [18–21] or flow conditioning [22]. An alternative approach to enhance mixing can be found in the effect of time-modulated turbulence [23–27]. By modulating the rate at which energy is supplied to the flow at a frequency close to the inverse of the large-eddy turn-over time, the turbulence tends to be more receptive to the supplied energy, resulting in a higher turbulent kinetic energy. This effect has been observed in both numerical simulations [23–25] and experiments [26,27]. An active grid as used in [27] is quite laborious and typically used in wind tunnels only. A much simpler and more compact active grid is proposed in [28], however the authors did not report a particular frequency of the forcing at which the turbulence response was maximal. In

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that respect, fractal grids provide a more convenient static agitation to raise the level of turbulence, especially for the incorporation into practical applications.

In this paper it is demonstrated that fractal grids can be used to increase the power density of a practical, industrial low-swirl burner [29]. Up to now only academic flames have been subjected to fractal-grid-generated turbulence. Goh et al. [12] investigated a counter-flow flame and V-flames have been examined by Soulopoulos et al. [13,14]. The combustion in a low-swirl burner takes place in mid-air and is dominated by a diverging mean flow field generated by a flow consisting of an outer swirling part and a central purely axial part with turbulence generated by a blocking grid (see Fig. 1). Recent work also shows the importance of the turbulence generated by the shear layer between the two flows [30], especially in view of the stability of these flames. However, in the center region it can be considered as a freely propagating turbulent flame. This makes the low-swirl flame by its very nature ideal to study the effect of the fractal-grid-generated turbulence on the combustion rate of premixed flames.

In the center region of the low-swirl flame there is a relatively low level of turbulence compared to the outer regions where large shear stresses are observed [31]. This results in limited wrinkling of the flame [32] and therefore a limited combustion rate. To increase the combustion rate in this central region, the turbulence should be enhanced, since the turbulent flame speed, S_T, linearly relates to u' as demonstrated by [33]. By replacing the central blocking grid (see Fig. 1) that is balancing the central and swirling flow, while also generating the turbulence, by a fractal grid, we exploit the beneficial properties of fractal-grid-generated turbulence in a practical burner. While the used thermal power of 30 kW on its own cannot be considered as industrial scale, the mean axial velocity, being a more relevant scaling parameter, (here 8.4 m/s) is comparable with those of small industrial burners [29]. Hence, it is expected that the findings presented in this paper are of relevance to industrial applications. Further engineering optimization may be required in actual products – this is beyond the scope of this paper.

The organization of the paper is as follows. In Section 2 we describe the fractal grids that are investigated as well as the low-swirl burner and the experimental conditions. The properties of the iso-thermal flow are reported in Section 3. Here a distinction is made between a fractal grid placed in a pipe flow and a fractal grid placed inside a low-swirl generator. In Section 4 the burning configuration is analyzed. Concluding remarks are made in Section 5.

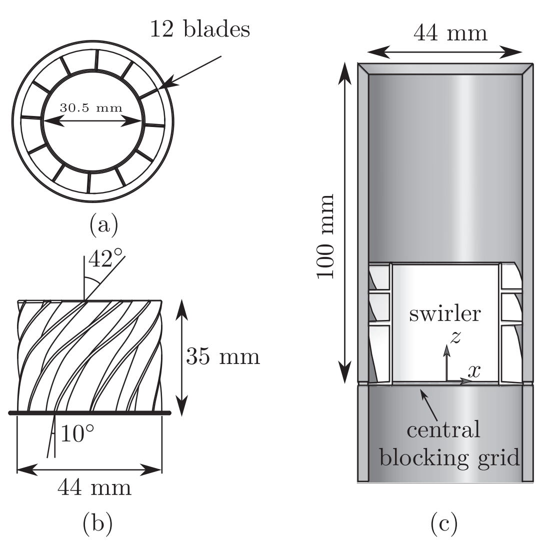

Fig. 1. (a) Top view of the low-swirl generator. (b) Side view of low-swirl generator. (c) Cross section of complete burner arrangement.

2. Fractal grid suitable for low-swirl burner

In this section we first discuss the design of the fractal pattern that is used in combination with the low-swirl burner Subsection (2.1) and proceed with the actual dimensions of the grids Subsection (2.2). The low-swirl generator itself is described in Subsection 2.3.

2.1. Different fractal patterns

Several families of fractal grids have been studied by Hurst and Vassilicos [1]. Each family of grids studied in [1] is based on a different fractal-generating pattern, being a 'cross', an 'I' or a 'square'. Of these families, the 'square'-family is most extensively studied. Other multi-scale grid patterns are studied by Nicolleau et al. [19], where instead of a flange with a single large opening, a fractal distribution of holes of different sizes is used as well as openings with fractal perimeters. For all these types of grids it is known that the turbulence downstream is enhanced. However, the grid used in combination with the low-swirl burner should yield a flow field that is compatible with the flame stabilization mechanism. This requires a mean axial velocity, $\overline{U}$, that remains constant in radial direction or it should be a slightly convex function as function of the radial distance from the center-line [33].

Isothermal RANS simulations were performed to investigate the applicability of the various grids. The flow domain included the low-swirl generator as depicted in Fig. 1c, as well as 100 mm length of pipe upstream of the grid. Downstream of the burner exit the domain extends 80 mm in radial direction and 100 mm in axial direction. The domain was discretized using 325,000 tetrahedral elements with an edge size of approximately 2 mm in the region up to the burner exit. Downstream of the exit the elements are gradually increased to 15 mm. The number of elements was considered sufficient as increasing the number did not change the obtained velocity profiles at the burner exit significantly. The RANS simulations are performed using the commercial software Ansys CFX 14, with the $k-\varepsilon$ turbulence model applied. The axial velocity is evaluated for the different blockage grids far enough downstream of the low-swirl generator to allow for the development of the flow, but still upstream of the flame. Here, 4 mm downstream of the burner exit is used.

A grid of the fractal 'square' and 'cross'-family and fractal orifices from [19] denoted by 's2f1' and 's2f2' where used, as well as a classical grid. For each of these grids the resulting mean velocity profile is depicted in Fig. 3. The classical grid yields a constant velocity profile as function of the radial direction and the fractal cross grid results in a slightly convex profile. Both these grids are therefore considered as compatible with the low-swirl burner. The velocity profiles determined for the other grids show a concave profile, which is due to the relatively low blockage in the center of the grid. The high axial velocity in the center results in poor stabilization as observed in preliminary measurements rendering these grids unsuitable for the current combustion applications.

In Fig. 2a the fractal cross pattern is defined. Three iteration levels are used and the pattern is subsequently cropped circularly to fit inside the pipe or low-swirl generator. Each grid is completely defined by four parameters. These are the length of the largest bar, L_0, the number of iterations, N, thicknesses of the largest bar, t_0, and the ratio of the consecutive bar-thicknesses, $R_t = \frac{t_{i+1}}{t_i}$. L_0 is equal to the pipe diameter or the inner diameter of the low-swirl generator. In this study we limit ourselves to $N = 3$. Although it is possible to manufacture a grid with four iterations, this limits the range of varying R_t and t_0, which are the parameters that are investigated in this work. The blockage ratio, σ, which is often used as a parameter to describe a grid, follows from R_t and t_0.