Multi-scale high intensity turbulence generator applied to a high pressure turbulent burner

Romain Fragner[1], Nicolas Mazellier[2], Fabien Halter[1,2] Christian Chauveau[1], Iskender Gökalp[1]
[1] CNRS ICARE
1C, Avenue de la Recherche Scientifique, 45072 Orléans Cedex 2 France

[2] Laboratoire PRISME/ Université d'Orléans
8 Rue Leonard de Vinci, 45071 Orléans Cedex 2 France

romain.fragner@cnrs-orleans.fr, nicolas.mazellier@univ-orleans.fr, fabien.halter@univ-orleans.fr
christian.chauveau@cnrs-orleans.fr, iskender.gokalp@cnrs-orleans.fr

ABSTRACT
This study is performed to investigate the interactions between a turbulent flow field and a premixed flame. Comparisons between the turbulence generated by a multi grid turbulence generator and a single grid turbulence generator are made. For this comparison we used the data of Lachaux et al. (2005) for a methane-air premixed flame with an equivalent ratio of 0.6. The turbulence intensity is found to be 40% higher in the isotropic and homogeneous zone of the potential core for the multi grid configuration compared to the single grid configuration. It is also found that the isotropy and homogeneity levels are lower for the multi-grid than for the single grid turbulence generation. Kolmogorov scales are found 2 times lower for a multi grid generation than for a single grid generation at equivalent pressure conditions; Taylor length scales are found lower as well. The effects of multi-scale grid turbulence generation on the premixed turbulent regimes are discussed

INTRODUCTION
In the context of "clean" energy production, the potential of power generation in a gas turbine fuelled with syngas (CO/H2) obtained from biomass or coal gasification, is an attractive solution. Heat release in a chemical energy conversion device depends on the quantity of fuel which can be burnt by unit of time. Turbulence is a key parameter to influence the heat release rate and flame/turbulence interactions need to be well characterized to model this effect. In this context, several previous studies investigated such interactions numerically (Bray, 1979 ; Poinsot et al., 1991) or experimentally by Lafay et al. (2008). However, these studies were limited to the flamelet regime (see the turbulent combustion diagram in figure 10, and Borghi (1985)) where the turbulence only affects the global structure of the flame but keeps unchanged the instantaneous laminar behaviour locally. Grid-generated turbulence has homogeneous and isotropic properties but it prohibits to reach high turbulence intensities: this restricts the exploration of turbulent combustion only to some regimes. To overcome this issue, the use of multi-scale grid generated turbulence has recently emerged (Makita, 1991 ; Hurst and Vassilicos, 2007 ; Mazellier et al., 2010 ; Marshall et al., 2011).
The aim of the present work is to set up and characterize the turbulence generated by a multi-scale turbulence generator under high pressure conditions to approach the gas turbine environment and to investigate the interactions between this turbulence and a premixed flame in such an environment. This paper is mainly devoted to the characterisation of the multi-grid turbulence at high pressures.

EXPERIMENTAL SET UP
The experiments are conducted at atmospheric pressure or in a combustion chamber of 300 mm inner diameter that has been developed to allow experiments up to 1 MPa. The chamber has two 600 mm high superposed vertical cylindrical sections with four 100 mm diameter quartz windows for optical diagnostics. The centrally placed burner can move along the chamber vertical axis (denoted z hereafter) by a stepping motor with an accuracy of 0.1 mm. The laser light traverses the combustion chamber through two opposite windows. The internal pressure is set using a pressure regulator, while the temperature is monitored via a thermocouple. No pressure oscillations or any other confinement effects are observed. The burner, shown in Figure 1, is an axisymmetric Bunsen burner. The internal burner diameter D is 25 mm, and its length is 230 mm. The multi scale grid device is composed of three successive perforated plates of different blockage ratios

(1st = 0.46, 2nd = 0.57 and 3rd =0.67) and different holes diameters (1st = 1.55mm, 2nd = 3.44 mm and 3rd =7.5 mm). The third grid is located 60.5 mm upstream of the burner exit, the second is placed 17 mm below the third and the first one is 7 mm below the second. These locations have been set following the rules defined by Mazellier et al. (2010). The multi-scale grid is designed to mimic the turbulence cascade process. The grids are set such that first small scales then intermediate and finally large scales are produced. A schematic of the turbulence generator is given in Figure 1.

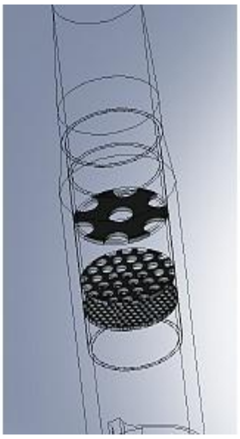

Figure 1: Schematic of the multi scale turbulence generator

The cold flow field issuing from the burner nozzle is investigated with a 2-component Laser Doppler Velocimetry. The measurements are restricted to the potential core where we intend to investigate the interactions between the flame and the nearly homogenous and isotropic turbulence. Results that will be shown in the next section have been obtained for pressures ranging between 0.1 and 0.5 MPa. In the following the results obtained with the multi-scale grids device are compared with results collected with a single-scale grid device on the same experimental facility shown in Lachaux et al. (2005). The single-scale grid was located 50 mm upstream the burner exit, the holes had a constant diameter of 2.5 mm and a mesh of 3.5 mm. The difference in inlet velocities was about 1 m/s.

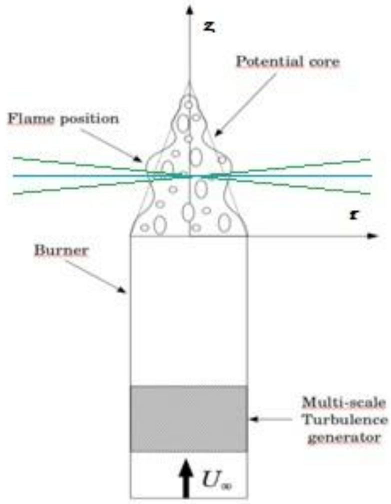

Figure 2: Schematic of the burner experimental set up with LDV

RESULTS AND ANALYSIS

Figures 3 and 4 show the radial and axial variations of the axial mean velocity. The mean bulk velocity for these measurements is 3.5 m/s. The mass flow rate is varied with a change of pressure to maintain the same bulk mean velocity.

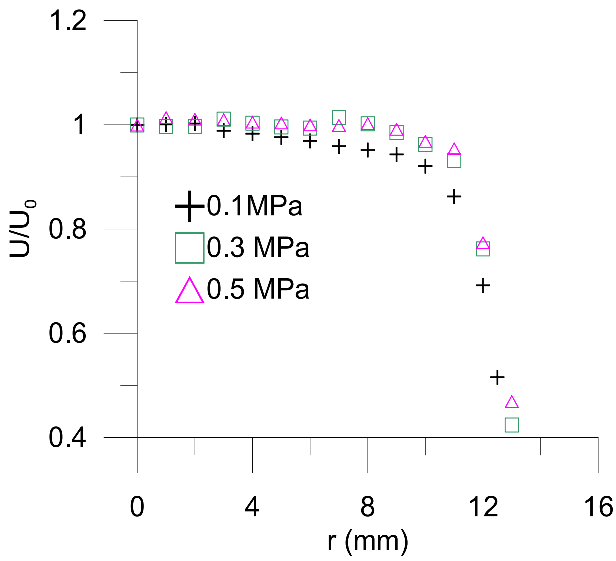

Figure 3 : Mean velocity profiles at 5 mm above the burner exit for 0.1, 0.3 and 0.5 MPa

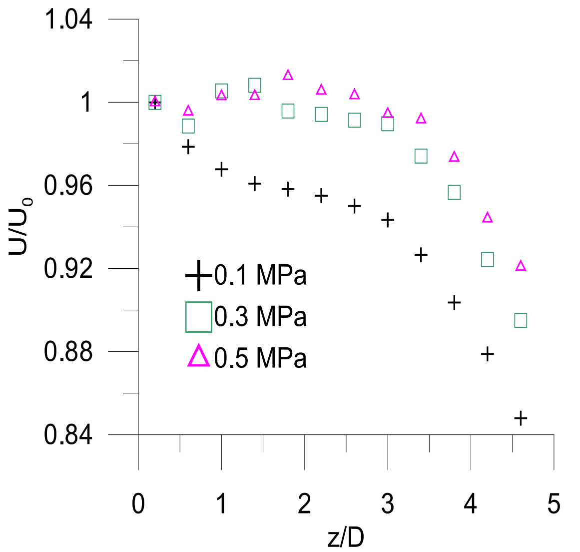

Figure 4: Axial mean velocity on the centerline along the burner axis

The impact of the pressure on the mean velocity profile is visible at 5mm above the burner (Figure 3). The mean velocity profile flattens with increasing pressure meaning that the boundary layers become thinner. This behaviour was also reported by Lachaux et al. (2005) and Soika et al. (2003). The centreline evolution of the mean velocity is strongly impacted by the pressure especially at 0.1 MPa which is characterized by an over-speed phenomenon close to the burner exit. This feature disappears at higher pressure. This results evidences that there exists a critical Reynolds number below which the small scale turbulence is not strong enough to enhance the turbulent diffusion which would smooth out the velocity gradients in the vicinity of the largest grid.

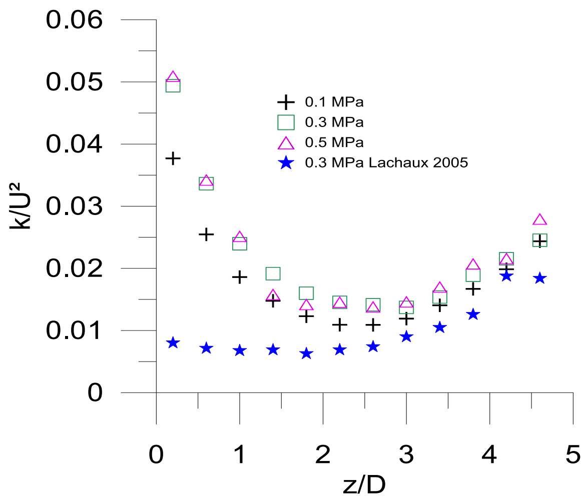

Figure 5: dimensionless turbulent kinetic energy along the burner centerline

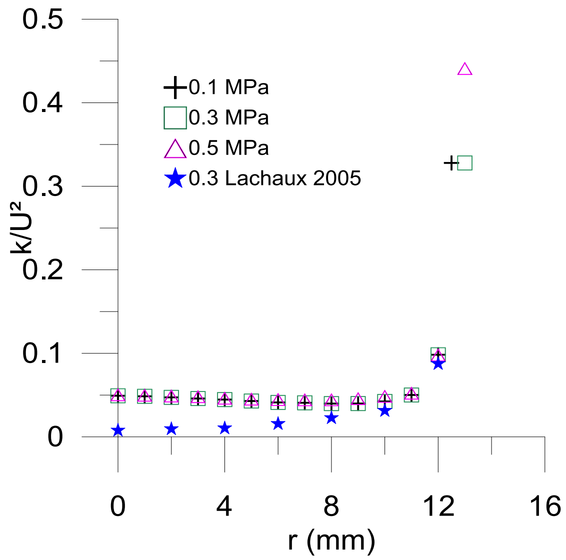

Figure 6: Dimensionless turbulent kinetic energy profiles at 5 mm above the burner exit

The axial decay rate is much reduced by the pressure and a reduced constant mean axial velocity is observed until the end of the potential core at about 80 mm. Downstream of this location, the decay rates are not influenced by the pressure increase.

The dimensionless turbulent kinetic energy normalized by the squared mean velocity k/U² where $k = \frac{1}{2}(u'^2 + 2v'^2)$ along the burner axis is displayed in figure 5. For comparison, results obtained with a single scale mono-grid with the same burner at the beginning of the homogeneous region (5mm above the burner exit for Lachaux et al. (2005) and 40 mm in this study) are also presented. One can observe that the turbulent kinetic energy generated by the multi scale turbulence grid is noticeably higher than that generated by the single scale grid. It can be seen that the turbulent kinetic energy is nearly homogeneous between 40 to 80mm. Furthermore, in the nearly homogenous region the turbulence intensity is increased by about 40% compared to the single-grid turbulence. The radial homogeneity is also improved as evidenced in Figure 6. The pressure has a small effect on the turbulent kinetic energy as shown in figures 5 and 6. Note that the nearly homogeneous region appears farther downstream compared to Lachaux et al. (2005). One can expect thereby that this region will not be disturbed by the pilot flame which is used to maintain the flame attached on the burner in combustion studies as it locally modifies the interactions between the flame and the turbulent flow field.

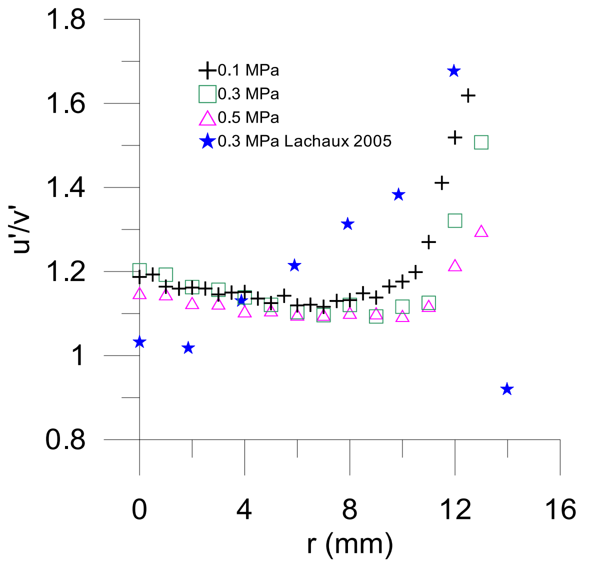

Figure 7 : u'/v' along the radius at 5mm above the burner

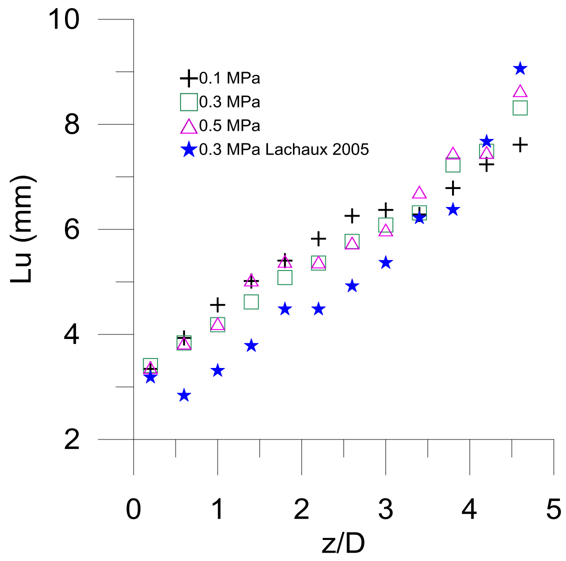

Figure 9: Axial integral length scale along the burner centreline

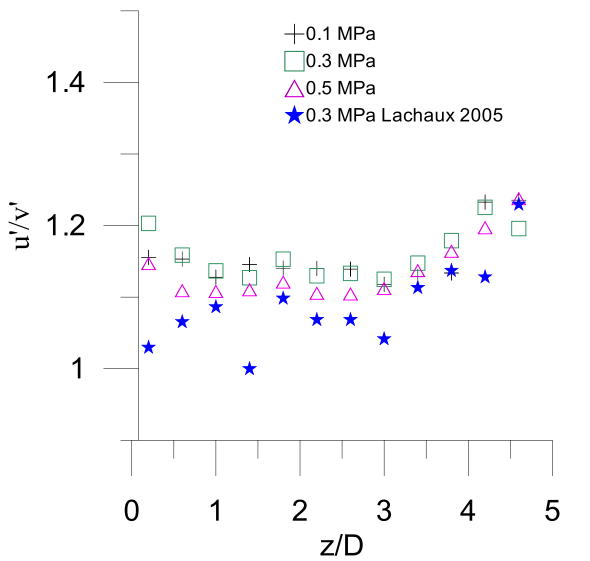

Figure 8: u'/v' profiles at 5 mm above the burner exit

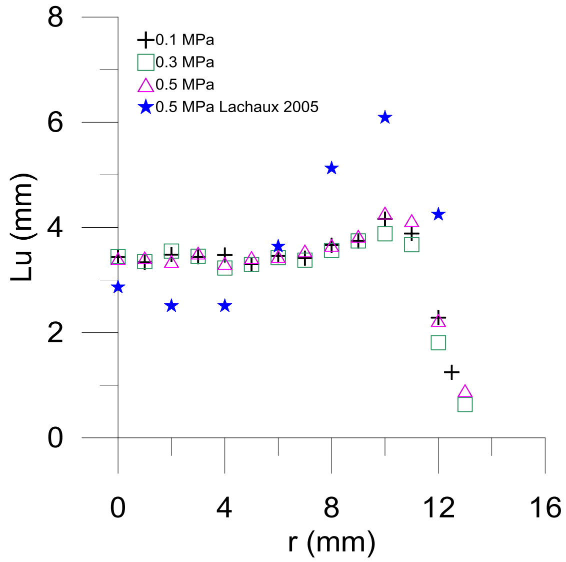

Figure 10: Radial variation of integral length scale at 5 mm above the burner exit

The radial and axial evolution of the isotropy is investigated by means of the ratio u'/v' (see figures 7 and 8). At 5 mm above the burner exit, the isotropy indicator is roughly constant (≈ 1.15) across the burner and then dramatically increases in the mixing layers. Even though the turbulence generated by the single-grid device is characterized by a better level of isotropy close to the centre of the burner, the average isotropy level across the burner is remarkably higher. Further downstream, for each pressure, the isotropy indicator slightly decreases until the end of the potential core where the mixing layers merge.

The integral length scales Lu are estimated (Figures 9 and 10) from the axial velocity autocorrelation following the procedure of George et al. (1979). Lu increases with increasing distance from the burner similarly to the results reported in Lachaux et al. (2005). The pressure is found to have little impact on the integral length scale in (Lachaux et al. (2005) and Soika et al. (2003) as well as in (Kobayashi et al. (1997). These results are verified in this study as the integral length scales do not vary when the pressure increases from atmospheric to 0.5 MPa. However, the integral length scale is almost constant across the burner in comparison with the single grid turbulence generator.

The small scale turbulence properties have been characterised by means of the dissipation rate ε which has been evaluated according to the turbulent kinetic energy budget equation. In decaying turbulence, this equation reduces to

$$\epsilon = -U\frac{\partial k}{\partial z} \qquad (1)$$

The right-hand side of equation (1) was estimated from the LDV measurements. The Kolmogorov length scale and the Taylor microscale have then been calculated assuming isotropy. Their values are reported in Table 1.

Table 1 shows the differences between the present work and the data from Lachaux et al. (2005) where the turbulence was promoted by a single grid in the same burner configuration. The comparison is made at the beginning of the homogeneous region which is 5 mm above the burner exit for Lachaux et al. (2005) and 35 mm above the burner exit for the present study.

For the multi-grid configuration, the values of u' are around two times higher than for the single grid turbulence generation. This result reflects the higher blockage ratio induced by the multi-scale grids device. Meanwhile, the isotropy factor u'/v' is comparable in both experiments. It is slightly lower than that reported in active grid turbulence (Mydlarski and Warhaft, 1996), fractal grids (Hurst and Vassilicos, 2007) or for (Shavit and Chigier, 1996) with transversal air injection in the main flow.

The integral length scale Lu is also larger compared to the single-grid case. In fact, the integral length scale is mainly related to the largest hole diameter for the multi-scale grids device which is 3 times larger than that of the single-grid device.

The Taylor micro scales λ and the Kolmogorov length scale η decrease with the use of multi grid turbulence generation. The small scales decrease with pressure as well which agrees with Lachaux et al. (2005) findings. The pressure increase reduces the kinematic viscosity and increases the turbulent Reynolds's number.

The impact of the new turbulence conditions on premixed turbulent flame regimes obtained with the same burner can be assessed using the diagram defined by Borghi (1985) (Figure 10 and Table 1). It is clearly observed that, especially at higher pressures, due to the increase of the turbulence intensity and turbulent Reynolds number, the decrease of small turbulence scales and the reduction of the laminar propagation velocity with pressure, the multi-grid turbulence promotion is expected to give rise to turbulent flame regimes well away from the classical wrinkled flame regime and closer to distributed reaction zone regimes, for classical fuels such as methane-air mixtures.

Table 1 : Cold flow and flame parameters for variouspressures for a methane-air mixture with an equivalent ratio of 0.6

	P (MPa)	U (m/s)	u' (m/s)	Lu (mm)	u'/v'	η (mm)	λg (mm)	S_L (m/s)	δL (mm)	u'/S_L	Ka	Da
Lachaux et al	0,1	2,54	0,17	3	1,1	0,21	1,99	0,113	0,197	1,49	0,9	9,4
This study	0,1	3,82	0,45	5,02	1,18	0,078	1,97	0,113	0,197	3,98	2,35	6,4
Lachaux et al	0,3	2,42	0,19	3,1	1,05	0,09	1,12	0,059	0,127	3,19	2	7,9
This study	0,3	3,78	0,46	5,09	1,13	0,039	1,02	0,059	0,127	7,8	6,75	5,14
Lachaux et al	0,5	2,37	0,18	2,9	1,07	0,06	0,86	0,042	0,106	4,22	3,1	6,2
This study	0,5	3,63	0,4	5,04	1,11	0,027	0,72	0,042	0,106	9,52	14,26	5

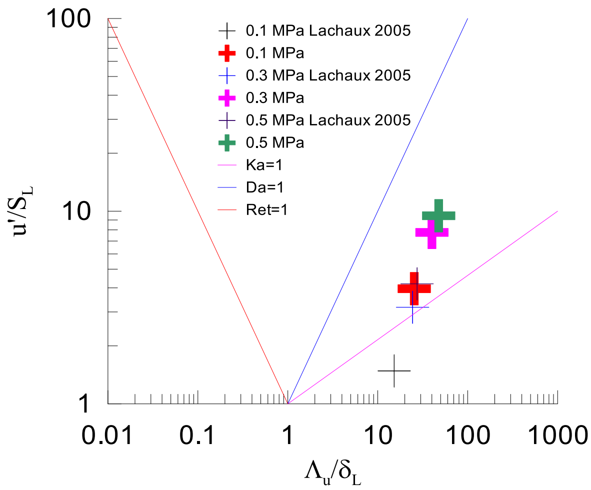

Figure 11: Turbulent combustion regimes of the investigated flames in Lachaux et al. (2005) compared to the ones calculated based on the data obtained in this work (ER = 0.6)

CONCLUSIONS

The results of this work show promising features for the multi scale turbulence generation in the framework of turbulent combustion investigations. It is shown that multi-scale turbulence grid arrangement used in this work is a good means to generate controlled turbulence. Compared to the turbulence intensities obtained by single grids (around 4%), the results from this study show that the turbulence intensity of the multi scale device reaches around 10% in the homogenous zone. In addition, small turbulent scales are both smaller and contain more energy which can lead to thickened premixed flame fronts when applied to turbulent premixed flame studies (Bédat and Cheng, 1995 ; Shepherd et al., 2002 ; Gülder, 2007). In the future, Rayleigh scattering technique will be used to investigate the effects of this type of turbulence generator on the instantaneous flame front thicknesses for CH4-Air and CO/H2-Air flames.

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