Flow field features of fractal jets

Giusy Castrillo*, Gerardo Paolillo, Mattia Contino, Gioacchino Cafiero and Tommaso Astarita
Dept. of Industrial Engineering, Università degli Studi di Napoli Federico II, Naples, Italy
* Correspondent author: giusy.castrillo@unina.it

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Abstract
The experimental investigation of the flow field generated by a round submerged water jet equipped with a square fractal grid (FG) and a single square grid (SG) is carried out by means of Time-Resolved Tomographic PIV (TR-Tomo PIV). The use of TR Tomo-PIV provides a leap forward in the understanding of the flow field organization and allows us to track the evolution of the coherent structures associated to the presence of the turbulent promoters. Furthermore, the role played by the large coherent structures in terms of volumetric flow rate of the jet is analyzed and discussed. Despite a similar macroscopic flow field, the strong differences in terms of turbulence lead to a higher effectiveness of the FG in terms of scalar transfer. Indeed, the capability of producing turbulence at multiple scales and the possibility of tuning the peak in the turbulence intensity profile as a function of the grid geometric parameters are both extremely beneficial for heat transfer enhancement purposes, as it shown via dedicated IR Thermography experiments when the jet impinges onto a flat plate.

1. Introduction
Over the years many studies have been devoted to the investigation of turbulent jet flows. On one hand the necessity of validating the numerical models with experimental results and, on the other, the appeal of using these devices for industrial purposes have been giving a strong burst to the research. Optical measurement techniques, such as Laser Doppler Velocimetry and Particle Image Velocimetry, have played an important role in the last decades.
Since the development and the evolution of coherent structures stimulate the entrainment process (Grinstein 2001), i.e. the mixing of the external air with the jet core, the understanding of the evolution of these energy-containing features is of paramount importance. This led to the study of several solutions to enhance the engulfment of air from outside the jet core towards the inside. Among the others, non-circular geometries like square (Gutmark and Grienstein 1999), tabbed (Gao et al 2003), daisy (El Hassan and Meslem 2010), cruciform (El Hassan et al 2011) or chevron nozzles (Violato et al 2012), which from one side stimulate the production of streamwise vortices and from the other avoid the generation of the annular structures typical of axisymmetric jets, are commonly applied solutions. The introduction of an upstream swirl
component to the main flow (Syred 2006, Ceglia et al 2014); the use of fluidic devices like naturally precessing jets (Cafiero et al 2014); synthetic jets (Greco et al 2013) have also been widely investigated.

The use of grids or mesh screens is a typical mean to enhance the turbulence production and, as a consequence, the efficiency of jets scalar transfer. The introduction of mesh screens (Zhou and Lee 2004, Zhou et al 2006) or perforated plates (Lee et al 2002) either in correspondence or in the vicinity of the nozzle exit, from one side interacts with the formation of the large structures of the flow field and from the other causes a strong turbulence enhancement.

Recently, Cafiero et al (2014) have demonstrated that fractal grids (i.e. obtained repeating several times the same shape progressively reducing its dimensions) can be used to generate turbulence in impinging jets, thus significantly enhancing the convective heat transfer rate. The interest in fractal-generated turbulence comes from its deeply different mechanism and behavior with respect to the turbulence generated by regular grids (Hurst & Vassilicos 2007). In fact, while the latter are characterized by a very intense peak immediately downstream the grid and then a quite fast decay, the former present a more complicated evolution of the turbulence intensity profile (see Fig. 1, left):

- An elongated production region where the turbulence builds up;
- A peak, located at a streamwise position which is found to be an only function of grid geometry (see Hurst & Vassilicos 2007);
- A fast decay region, where the turbulent energy dissipation rate is a function of the Reynolds number based on the Taylor lengthscale ($Re_\lambda$, see Gomes-Fernandes et al 2012).

The different evolution of fractal generated turbulence can be justified with the interaction between the wakes of the different iterations of the grid (see Fig. 1, right). In fact, the different size of the grid bars causes coalescence of the wakes at several streamwise locations; this brings to a progressive increment of the turbulence intensity profile as already mentioned.

On the other hand, for regular grids all the wakes merge at the same location right downstream of the grid, causing a strong enhancement of the turbulence intensity followed by a progressive decay, with a smaller rate than the one characterizing the fractal grids.

While the flow field behavior of grids in wind tunnel flows has been deeply investigated (see e.g. Hurst & Vassilicos 2007, Mazellier & Vassilicos 2010, Valente & Vassilicos 2011, Gomes-Fernandes et al 2012), a characterization of the interaction between fractal grid turbulence and shear layers (as in the case of a free or an impinging jet) is still lacking.
In this study, the investigation of the instantaneous and statistical features of the flow field of jets with fractal and single square grids is performed by means of Time Resolved Tomographic Particle Image Velocimetry (TR-TPIV).

![Graph](image)

**Fig. 1** (left) Axial velocity fluctuation as a function of the streamwise distance in the case of a wind tunnel experiments for 4 different fractal grids and a regular grid (from Hurst & Vassilicos 2007); (right) Wake interaction mechanism behind a fractal grid (from Mazellier & Vassilicos 2010).

The application of this experimental technique provides important information about the organization and the temporal evolution of the coherent structures in fractal generated turbulence. In Sec. 2 a description of the experimental apparatus is presented; the preliminary results regarding the instantaneous flow features along with the statistical features of the flow field are reported in Sec. 3. Finally, the main conclusions are drawn in Sec. 4.

2. Experiment outline

2.1 Experiment description

A schematic representation of the experimental apparatus used is provided in Fig 2. The jet is issued from a short-pipe nozzle (with diameter d=20mm and length 6.2d) installed on the bottom of a nine-sided water tank facility (internal diameter 600mm, height 700mm) made of Plexiglas in order to ensure full optical access, as described in Ceglia et al (2014). A terminating cap is used to locate eventually the grid insert in correspondence of the nozzle exit section.

A stabilized water flow rate of 0.20kg/s is provided upstream of the nozzle by a centrifugal pump and it is laminarized by passing through flow-conditioning grids and honeycombs installed into the plenum chamber (with diameter and length equal to 5d and 20d, respectively). The resulting Reynolds number, based on the nozzle exit section diameter d is about 30,000, thus the bulk velocity that will be used as reference velocity is \( V_j = 1.5 \text{ m/s} \).
The flow is seeded with neutrally buoyant polyamide particles with an average diameter of 56µm, dispersed homogeneously within the facility. Laser pulses are produced with a Dual Power PIV Nd:YLF laser system (527nm, 30mJ/pulse, 5ns pulse duration).

Fig 2 Experimental apparatus schematic representation.

The exit beam is adjusted in thickness using two spherical lenses such that the illuminated volume in the depth direction is about 30mm. The axial extent of the illuminated region is then set using two cylindrical lenses, in order to maximize the light intensity in the measurement region. Four SpeedSense M110 cameras (1280x800 pixels, 20µm pixel pitch) equipped with Tokina 100mm macro objectives are used to image the measurement region as schematically described in Fig 2. The resulting digital resolution is about 15 vox/mm. In order to ensure that the whole imaged volume is uniformly focused, home-made Scheimpflug mounts are adopted. An optical calibration is performed by taking images of a target plane mechanically translated along the depth of the measurement domain in the range ±20mm. A template-matching technique, with a cross-correlation based algorithm, is used to identify the location of the markers. The root mean square (rms) of the calibration error is about 0.35 pixels.

A sequence of 1000 double-exposure instantaneous realizations is captured at a frequency of 800Hz. The time delay is set to 625µs in order to get an effective acquisition frequency of 1.6Khz. The resulting displacement between subsequent snapshots is about 14 voxels: this value is slightly larger than the one recommended for a proper time-tracking of the flow field, but allows to get a larger dynamic range. A measurement domain of about (3 x 2 x 1.25)d is taken into account, starting from the axial distance equal to X=1.25d. The calibration is further corrected.
using the light scattered by the tracer particles via the Self calibration procedure (Wieneke 2008). This allows to reduce the rms of the calibration error down to 0.05 pixels.

The 3D volume is reconstructed at each time-step using the SMTE technique as proposed by Lynch and Scarano (2015). After 15 time-step, the ratio between the particles’ intensity and the noise associated to the ghost particles is larger than 3.5 as reported in Fig. 3.

![Intensity of the reconstructed particles within the volume](image)

Fig. 3 Intensity of the reconstructed particles within the volume.

The cross correlation is performed using an efficient algorithm, based on sparse matrices avoiding to repeat redundant calculation. The final dimension of the interrogation window is 48x48x48 voxels, with a grid distance of 8 voxels (vector pitch 0.5mm).

### 2.2 Grid Inserts description

![Grid insert description](image)

Fig. 4 Grid insert description.

A sketch of the grids used for the experiments is reported in Fig. 4. The fractal insert is made of a 0.5mm thick aluminum foil; the structure is shaped by laser cutting. The square pattern is repeated at three different scales (commonly referred to as iterations). The length $L_0$ and the thickness $t_0$ of the first iteration are equal to 9mm and 1mm, respectively. At each iteration $j$ the
length $L_j$ and the thickness $t_j$ are halved, i.e. $L_j = L_0R_j^j$ and $t_j = t_0R_j^j$, with $R_j = R = 1/2$. For this grid the ratio between the largest and the smallest bar thickness (i.e. the thickness ratio $t_r$, identified as a significant scaling parameter by Hurst & Vassilicos 2007) is equal to 4. The blockage ratio of the grid is equal to 0.32. The single square grid is obtained by removing the second and third iterations from the initial fractal grid. This results in an effective reduction of the grid blockage ratio of about 1/3 (where the effect of the four holding bars located along the corners is neglected).

### 3. Results

In order to describe the effect of the presence of the grid onto the flow field organization, the comparison of the fractal grid with a single square grid and the jet without turbulator is reported. **Error! Reference source not found.** addresses the differences in terms of time averaged velocity profiles and velocity fluctuations extracted along the $Z=0$ plane, aligned with grid bars, for the three investigated cases.

At short nozzle to plate distances ($X/d=1.5$), the effect of the FG reflects into a peculiar velocity profile with three peaks: two outer maxima associated to the contraction that the flow experiences through the holes between the grid and the external frame, and one associated to the central square of the grid. It is interesting to notice that, despite the absence of the secondary grid iterations, the SG behaves in a quite similar fashion with respect to the FG case. Indeed, the central peak is still visible, although less relevant. In addition to that, the presence of the grid also introduces a defect of mass in correspondence of the central square, similarly to the FG case.

It is also interesting to notice that, looking at the axial velocity component along the nozzle centerline (Fig. 6), the SG behavior is comparable to the one characteristics of the JWT, with a nearly constant velocity value up to $X/d=3.5$, whilst in the FG case the velocity rapidly drops as a function of the streamwise distance.

The axial velocity fluctuations at $X/d=1.5$ are also reported in **Error! Reference source not found.** The JWT case exhibits a peak in correspondence of the jet shear layer, thus $Y/d=0.5$ and nearly zero values in correspondence of the jet core, where the flow is potential. The grid strongly unsettles this behavior: in the SG case, in addition to the effect of the jet shear layer, another local peak can be detected at $Y/d =0.25$. This peak must be addressed to the wake developing from the grid bar. A similar effect can be also detected in the FG case, where the velocity fluctuations are more intense due to mutual interaction of the wakes shed by the different fractal iterations.
As the distance from the nozzle exit section increases, the effect of turbulence diffusion is such that the external peaks in the axial velocity profiles are progressively smeared out. In terms of velocity fluctuations, in the FG and SG cases the spreading wake and the progressively growing shear layer interact, causing the presence of a unique peak. Once again in the FG case the effect is more intense with respect to the SG one. The progressive shear layer penetration can be also detected in the JWT case at larger streamwise distances, where the axial velocity profile is attaining a bell-shaped profile and also on the centerline, where the velocity fluctuations are increasing.
**Fig 5** Mean axial velocity (left) and axial velocity fluctuations (right) at three axial separations from the nozzle exit, namely $X/d=1.5, 2.5, 3.5$ for the FG and SG cases. The JWT is also reported as reference. (Markers are plotted each 5 vectors).

Fig 6b reports the axial velocity fluctuations in the three cases (FG, SG and JWT) along the nozzle centerline. The FG always outperforms the SG case, as can be also envisaged being the SG blockage ratio nearly one third of the FG. The nearly constant profile is corresponding to the
region where the effect of the turbulence produced by the different fractal iterations is decaying but balanced by the penetrating shear layer (see Cafiero et al 2015).

A sequence of three instantaneous realizations of the flow field in the FG and SG cases is reported in Fig 7. The top row refers to the FG case; the iso-surface of axial velocity $V/V_j = 1$ is representative of the jet core issuing through the fractal grid iterations’ holes. In green the iso-surface of second invariant of the velocity gradient tensor $Q_{vv} > 0$ indicates the presence of azimuthally coherent structures. It is interesting to notice that, as a consequence of the perturbation induced by the fractal grid onto the jet shear layer, this coherent structure result to be distorted. This leads to the induction of streamwise vortices, indicated in figure as SW, between two subsequent structures. Thus, in addition to the already exploited streamwise structures associated to the local curvature of the jet shear layer (see Cafiero et al 2015), these vortices associated to the self-induction of the KH structures are also responsible for the increment in the entrainment rate (and scalar transfer efficiency) of such devices. As the axial distance increases, the azimuthally coherent structures break down.

In the SG case the flow topology is quite similar, as showed in Fig 7; indeed, also in this case the jet shear layer generates azimuthally coherent structures with a non-uniform curvature. In turn, these structures induce streamwise vortices as a consequence of their non-uniform curvature. The large scale flow organization is then mainly dominated by the interaction of the cross-shaped jet issuing through the nozzle with the quiescent ambient air. However, as already shown in Fig 6, in terms of turbulent velocity fluctuations the behavior is influenced by the secondary grid iterations. It must also be explicitly noticed that, due to the lack of volumetric resolution, the fine scale structures that can be present in the FG case are filtered by the PIV process.
Fig 6 Axial velocity (left) and axial velocity fluctuations (right) for the FG and SG cases. The JWT case is also reported as reference. (Markers are plotted each 5 vectors).

Fig 7 Instantaneous realizations of the flow field at two subsequent time steps in the FG case (top) and SG (bottom). Iso-surface of axial velocity U/Vj=1 along with the Q<0iso-surface (in green).
Despite the rather similar behavior in terms of large scale structures dynamics, in terms of convective heat transfer capabilities there is a significant difference between the two presented cases. In order to exploit this point, a comparison in terms of convective heat transfer capabilities of a round jet impinging onto a flat plate equipped with a SG and a FG via IR Thermography is reported. In order to carry out a fair comparison, which takes into account the difference in terms of grid blockage ratio between the two cases, the experiments are performed under the same power input, i.e. keeping the product of the volumetric flow rate times the pressure drop associated to the grid as constant. This leads to an effective Reynolds number for the SG case that is larger than the FG case (see Tab. 1 for the detailed values).

**Tab. 1** IR Thermography experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>Re</th>
<th>(\dot{m}[g/s])</th>
<th>(\Delta p_0[Pa])</th>
</tr>
</thead>
<tbody>
<tr>
<td>FG</td>
<td>15,000</td>
<td>5.1</td>
<td>320</td>
</tr>
<tr>
<td>SG</td>
<td>18,800</td>
<td>6.2</td>
<td>260</td>
</tr>
</tbody>
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Fig. 8 reports the Nusselt number \((Nu = \frac{hd}{k}\) being \(h\) the convective heat transfer coefficient, \(d\) the nozzle diameter and \(k\) the air thermal conductivity) distribution for the SG and FG cases at three different nozzle exit section to plate distances. It can be seen how, at short distances from the impinging plate, the FG significantly outperforms the SG. However, this increment is progressively smeared out as the axial distance increases. This significant increment is related from one side to the different capabilities in terms of turbulence intensity of the FG with respect to the SG. Another element can be related to the larger entrainment rate of the FG with respect to the SG case. Fig 9 shows the volumetric flow rate non-dimensionalized with respect to its value at \(X/d=1.33\) \((Q/Q_0)\) as a function of the axial distance for the FG and SG case. It is clear that the FG is characterized by a larger value of the volumetric flow rate. This element must be addressed to the effect that the fractal shape has in terms of streamwise vortices generation.
Fig. 8 Nusselt number distribution in the SG and FG cases at three nozzle to plate distances X/d={2, 4, 7}

Fig. 9 Volumetric flow rate as a function of the axial distance in the FG and SG cases. (Markers are plotted each 5 vectors).

4. Conclusions
In this paper the experimental investigation of a submerged water jet equipped with a fractal grid (FG) and a square grid (SG) is carried out by means of Time resolved Tomographic PIV. Both the statistical and instantaneous features are addressed: in particular, the large coherent structures organization suggests that there is no strong difference between the two presented cases. Indeed, in both cases the presence of azimuthally coherent structures that are generated as a consequence of the jet shear layer instability is evidenced. These structures embrace the jet core, which is cross-shaped, thus are not characterized by uniform curvature. This leads to the induction of secondary streamwise vortices.
However, it is shown that when impinging onto a flat plate, the FG significantly outperforms the SG case in terms of convective heat transfer rate, as demonstrated via dedicated IR Thermography experiments. This difference is addressed to the larger turbulence intensity level associated to the FG case with respect to the SG one from one side. From the other, the FG is more efficient in producing streamwise vortices, which is directly related to the entrainment rate of the jet and, as consequence, to its scalar transfer capabilities.

REFERENCES