Experimental study on scalar transfer in regular and fractal grid turbulence: scalar mixing layer and axisymmetric CO$_2$ Jet

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Background of This Study

Classical grid turbulence using a biplane, square mesh grid ¹)

To generate stronger isotropic turbulence

The active grid²) has been investigated

Fractal grid turbulence³,⁴,⁵)

The fractal grids generate turbulent flows with higher turbulence intensities and Reynolds numbers than can be achieved with higher blockage ratio classical grids in similar wind tunnels and wind speeds $U$.

Refs.
Characteristics of the Fractal Grid Turbulence$^{3,4,5}$)

In the decaying region, $L_{11}$ is constant (Taylor microscale is also constant)

(Graphs from Hurst & Vassilicos $^3$)

Refs.
Contents

CO$_2$ jet diffusion in regular and fractal grid turbulence

Scalar mixing layer in regular and fractal grid turbulence

CO$_2$ release pipe
($d=3\text{mm}$)
CO$_2$ Jet Diffusion in Regular and Fractal Grid Turbulence

1. Grid turbulence
Fractal Grid

\( N \): fractal iteration
\( \sigma \): solidity
\( t_r \): thickness ratio of largest to smallest bars
\( M_{\text{eff}} \): Effective mesh size

\[
M_{\text{eff}} = \frac{4T^2}{P_M} \sqrt{1-\sigma}
\]

\( T^2 \): cross-sectional area of wind tunnel
\( P_M \): perimeter length of the grid

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Regular grid</th>
<th>Fractal grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N )</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>0.36</td>
<td>0.25</td>
</tr>
<tr>
<td>( t_r )</td>
<td>1</td>
<td>13.0</td>
</tr>
<tr>
<td>( M_{\text{eff}} )</td>
<td>15.0 mm</td>
<td>18.77 mm</td>
</tr>
</tbody>
</table>
Wind Tunnel and Flow Conditions

Mesh Reynolds number: \( \text{Re}_M = \frac{U_0 M_{\text{eff}}}{\nu_{\text{air}}} = 6,000 \)
Jet Reynolds number: \( \text{Re}_J = \frac{(U_J - U_0)d}{\nu_{\text{CO}_2}} = 5,000 \)

Measurements of grid turbulence (without a jet)
I- and X-type hot wire
\((X, Y, Z)\) coordinate

Measurements of jet diffusion field
dual hot-wire probe
\((x, r)\) coordinate
Sampling frequency: 10 kHz
Sampling number: 262,144
Rms Velocities (without the jet)

### Present

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>Mazellier &amp; Vassilicos (2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>$t_r$</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>$M_{eff}$ (mm)</td>
<td>18.77</td>
<td>26.3</td>
</tr>
<tr>
<td>$U_\infty$ (m/s)</td>
<td>4.8</td>
<td>5.2</td>
</tr>
<tr>
<td>$Re_M$</td>
<td>6,000</td>
<td>9,100</td>
</tr>
</tbody>
</table>

Fractal grid vs. Regular grid

- $u'^2/U_\infty^2$ vs. $X/M_{eff}$
- $u'/U_\infty$ vs. $Y/M_{eff}$

Mazellier & Vassilicos (2010)
Length Scales (without the jet)

Integral scale

Taylor micro scale

\[ \frac{L_{\text{ux}}}{M_{\text{eff}}} \]

\[ \frac{\lambda}{M_{\text{eff}}} \]

- Regular grid
- Fractal grid
- Mazellier & Vassilicos (2010)

Slope = 1/2
Turbulent Reynolds Number $R_{\lambda} = \frac{u'\lambda}{\nu}$ (without the jet)
Length Scale Ratio $L_{uX}/\lambda$ (without the jet)

$L_{uX}/\lambda$ is independent of $Re_\lambda$ in the decay region of fractal grids (as found by Vassilicos’ RG)
Skewness and Flatness Factors (without the jet)

![Graph showing skewness and flatness factors for regular and fractal grids compared to Mazellier & Vassilicos (2010).]
Power Spectra of $u$ (without the jet)

Fractal

Regular

$E_u(f) dt^2$

$X/M_{eff}$ increases

$f [Hz]$
CO$_2$ Jet Diffusion in Regular and Fractal Grid Turbulence

2. Jet Diffusion Field in Grid Turbulence
Experimental setup
Measurement of Velocity and CO$_2$ Concentration

Hot-wire 1 (low OHR)
- platinum wire
- OHR 0.4
- diameter 5 µm
- length 1 mm
- resistance 5.2 Ω

Hot-wire 2 (high OHR)
- platinum wire
- OHR 1.4
- diameter 5 µm
- length 1 mm
- resistance 5.2 Ω

two sensors with different overheat ratio (OHR)
Measurement of Velocity and CO$_2$ Concentration (2/2)

OHR dependence

Concentration dependence

Instantaneous velocity and concentration can be obtained from the output from two sensors with different OHR.
Axial Variations of Mean Velocity and Mean Concentration (on the centreline)

Mean velocity and mean concentration decay faster in the fractal grid turbulence
Axial Variations of the Half Width

Half widths increase faster in the fractal grid turbulence
Radial Variations of Mean Velocity and Mean Concentration (for fractal grid)

Axial velocity

Concentration
Axial Variations of rms Velocity and rms Concentration

Rms velocity and rms concentration decay faster in the regular grid turbulence
Axial Variations of Relative Intensities

Axial velocity

concentration

Regular grid
Fractal grid

\[ \frac{u'}{U_c - U_0} \]

\[ \frac{c'}{C_c} \]
Axial Variations of Axial Turbulent Mass Flux

Eddy diffusivity

<table>
<thead>
<tr>
<th>Type</th>
<th>Formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>$K = 3.73 \times 10^{-2} [\text{m}^2/\text{s}]$</td>
<td></td>
</tr>
<tr>
<td>Fractal</td>
<td>$K = 1.11 \times 10^{-1} [\text{m}^2/\text{s}]$</td>
<td></td>
</tr>
</tbody>
</table>
Cospectra of $u$ and $c$ (for fractal grid)

$$\frac{C_{0_{uc}}(f)}{\langle uc \rangle}$$

$x/d$ increases

-7/3
Conclusions of the First Part

**Grid turbulence**
- General agreements with Mazellier & Vassilicos’s data
- $\text{Re}_\lambda \sim 20$ in the regular grid turbulence, while $\text{Re}_\lambda = 80 \sim 150$ in the fractal grid turbulence

**CO$_2$ jet diffusion**
- Turbulent diffusion of momentum and scalar is faster in the fractal grid turbulence
Scalar Mixing Layer in Regular and Fractal Grid Turbulence
Measurement methods

- A time-resolved particle image velocimetry (PIV)
- A high-spatial resolution planar laser induced fluorescence (PLIF)

They are non-intrusive techniques for measuring.

They are developed and applied to the measurements of regular and fractal grid turbulence with high-Schmidt-number scalar transfer.
Fractal grid

The grid parameters of the fractal grid are as follows.

- \( N \) : The number of fractal iterations
- \( D_f \) : The fractal dimension
- \( \sigma \) : The blockage ratio
- \( t_r \) : The thickness ratio
- \( M_{eff} \) : The effective mesh size

\[
M_{eff} = \frac{4T^2}{P_M} \sqrt{1-\sigma}
\]

- \( T^2 \) : The area of the tunnel’s cross section
- \( P_M \) : The fractal perimeter’s length

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<td>4</td>
</tr>
<tr>
<td>( D_f )</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>( t_r )</td>
<td>1</td>
<td>9.76</td>
</tr>
<tr>
<td>( M_{eff} )</td>
<td>10[mm]</td>
<td>5.68[mm]</td>
</tr>
</tbody>
</table>
Experimental apparatus

<table>
<thead>
<tr>
<th>Sampling frequency</th>
<th>500 Hz</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling number</td>
<td>2048</td>
<td>~1024</td>
</tr>
<tr>
<td>$L_x \times L_y$ [mm$^2$]</td>
<td>7.5 × 40</td>
<td>25 × 100</td>
</tr>
<tr>
<td>$N_x \times N_y$</td>
<td>12 × 64</td>
<td>256 × 1024</td>
</tr>
<tr>
<td>Spatial resolution [mm$^2$]</td>
<td>0.6 × 0.6</td>
<td>0.1 × 0.1</td>
</tr>
</tbody>
</table>

$Re_M$ 2,500

Sc $\sim$ 2,100
PIV system

• Image capturing
  – Camera       High-speed camera, 8bit
  – Particles    polyacrylic ester
    mean diameter; 32 µm,
    specific gravity; 1.1

• Algorithm
  1. Digitizing
  2. Cosine interpolation
  3. Recursive cross-correlation analysis\(^{(1)}\)
  4. Offset cross-correlation analysis\(^{(2)}\)
  5. Error vector removal
  6. Sub-pixel analysis by gradient method\(^{(3)}\)

• Accuracy validation
  – Dantec LDV
  – PIV Standard Project\(^{(4)}\)

\[ \text{Comparison spectrum with Dantec LDV} \]

\[ \text{Regular grid turbulence} \]
\[ \text{Re}_M = 2500 \]
\[ x/M = 20 \]

\[ \text{present PIV} \quad \text{Dantec LDV} \]

ref.

\(^{(1)}\) Hart, D. P., Super-resolution PIV by Recursive Local-correlation, *Journal of Visualization*, 2000, 3


PLIF system

- **Image capturing**
  - Camera: Digital single-lens reflex camera (which has full-size image sensor)
    14 bit depth

- **Algorithm**
  1. Digitalization by Open CV
  2. Use a background image
  3. Self-developed method

- **Accuracy validation**
  - Single-point, time-resolved LIF\(^{(1)}\)

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\[ \begin{array}{c|c|c}
\text{Re}_M & 2500 & (M = 20\text{mm}) \\
\hline
x/M & 18 & \text{Regular grid turbulence} \\
\end{array} \]

\[(1)\] Ito, Y., et al., The effects of high-frequency ultrasound on turbulent liquid mixing with a rapid chemical reaction, *Physics of fluids*, 2002, 14
Image processing of PLIF

Our PLIF algorithm corrects the following errors

- Spatiotemporal variation of local excitation intensity due to an inhomogeneous concentration field on the light path
- Time variation of fluorescence quantum yield
- Spatiotemporal variation of incident laser intensity

ref.

Instantaneous fluctuating velocity vector fields

Fluctuating velocities in the fractal grid turbulence are much larger than in the regular grid turbulence.

\[ |V| 0.15 \quad 0.0 \]

\[ Re_\lambda \approx 10 \]

\[ Re_\lambda = \frac{u'\lambda}{v} \]

\[ Re_\lambda \approx 110 \]
Instantaneous scalar fields

\[ \frac{\partial C}{\partial y} \] at the center of the mixing layer \((y/M_{eff} = 0)\) in the fractal grid turbulence is smaller than in the regular grid turbulence.

This is notable in downstream region \((x/M_{eff} = 80)\).
Instantaneous fluctuating scalar fields

The half-width of fluctuating concentration are larger in the fractal grid turbulence than in the regular grid turbulence.
Conclusions (second part)

- Turbulence is much stronger in the fractal grid turbulence compared with the regular grid turbulence at the same mesh Reynolds number. (same results as wind tunnel exp.)
- Turbulent mixing is more enhanced in the fractal grid turbulence.

**In the future study**

- 3D3C+concentration measurement
- Structure functions of concentration fluctuation
- Derivative statistics on concentration fluctuation
- …
Fractal grid turbulence (square type)
Vortical field (the second invariant of the velocity gradient tensor) \((x/M_{\text{eff}} = 80 \sim 96)\)

\[
Q = \frac{1}{2} (-S_{ij}S_{ij} + W_{ij}W_{ij})
\]

Classical grid

Fractal square grid
Turbulent Mixing (DNS, Re_M=2,500, Pr=0.7)

(a) Regular grid

(b) Fractal grid (t_r=5.0)

(c) Fractal grid (t_r=8.5)
Turbulent Mixing (DNS, $Re_M=2,500$, $Pr=0.7$)

(a) Regular grid

(b) Fractal grid ($t_r=5.0$)

(c) Fractal grid ($t_r=8.5$)
This study was supported by the research cooperative program (April 2010 ~ March 2012) between Japan Society of Promotion of Science (JSPS) and The Royal Society (RS).

Thank you very much for your attention!