Experimental Study of Mixing at the External Boundary of a Submerged Turbulent Jet

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Motivation and objectives

- An important property of mixing is a sharp increase of mixing rates (Konrad, 1976) attributed to the onset of small-scale turbulence within large-scale coherent motions. Studies of this effect have demonstrated complex nonlinear dynamics of this phenomenon (Hussain & Zaman, 1980; Huang & Ho, 1990; Moser & Rogers, 1991; Dimotakis, 2000; Meyer, Dutton & Lucht, 2006).

- However, it is not clear how such mixing states are attained. The uncertainty is strengthened by the differences in experimental results obtained in gaseous and liquid flows (Miller and Dimotakis, 1991). The difference in behavior is attributed to a Schmidt number effect that is high in liquid and low in gaseous flows.

- We investigate the mixing in the submerged air jet using the incense smoke characterized by a significantly larger Schmidt numbers than employed in the previous studies of gas flow mixing. In the present study we focus on the internal structure of the fluid mixing before the molecular effect predominates.

- In our analysis we use the approach suggested by Hazak et al. (2006) based on the measured phase function (Drew, 1983) and determination of its characteristics.
define a characteristic scale $\lambda_n$, where $n$ is a number of a statistical moment, and a property

$$\frac{\lambda_n}{n} = \text{const}$$

was used for the determination of the PDF parameters.
Experimental setup

1 – Nd-YAG laser, 2 – trajectory of the laser beam, 3 – light sheet optics, 4 – CCD camera, 5 – system computer.
1 – channel with transparent walls, 2 – tube with a jet nozzle, 3 – submerged jet, 4 – light sheet optics, 5 – laser light sheet, 6 – image area, 7 – CCD camera.
Jet velocity field

### Parameters

| Parameter | Value 1 | Value 2 |
|-----------|---------|---------|
| Re        | 10080   | 8430    |
| $U_o$, m/s| 15.1    | 12.6    |
| Re$_t$    | 1840    | 1370    |
| u, m/s    | 2.76    | 2.06    |
| Re$_\lambda$ | 166    | 144    |
| $\lambda$, mm | 0.9   | 1.0   |
| $\varepsilon$, m$^2$/s$^3$ | 2100 | 870 |
| $\eta$, $\mu$m | 36 | 44 |
| $u_k$, m/s | 0.42 | 0.34 |
Determination of a jet boundary

- Normalization of images in order to eliminate fluctuations of an initial concentration of particles.

- Defining of a threshold for image binarization with histograms of light distributions in a jet and in an external fluid.

- Images conversion into a binary form.

- Ensemble averaging of 50 binary images.

- Determination of a jet boundary and of an angle of the jet expansion with a threshold 0.5.
Blue line – in the jet. Red line in the surrounding fluid.
Measurements in a jet flow

Jet coordinates and a range of measurements

Binary jet image averaged over an ensemble
Determination of a phase function parameters

- Turn of binary images on different angles.
- Measurement of phase functions at an ensemble of images for each turn angle.
- Determination of a homogeneity range of the phase functions for all set of the angels.
- Construction of the histograms of the phase functions.
- Fit of the histograms of the phase functions with the Gamma function distribution.
Phase function

X(y/D)

α

y/D
Mean phase function across a jet

Circles: Re=10000  Triangles: Re=8400
Measured in a range centered at $y/D = 7.7$
Normalized histograms
(in log-log coordinates)

- $z/D = 0.36$
- $z/D = 0$
- $z/D = -0.36$
- $z/D = -0.91$
Fit of the phase function PDF

Blue circles: PDF of jet fluid,
Magenta circles: exponent part of PDF
Green circles: power part of PDF

\[ \propto \exp(-\xi) \]

Red circles: PDF approximation

\[ \propto \xi^{-r} \]
Ratios of moments

\[ \frac{\lambda_n}{nD} \]

\[ \Delta_m / D \]

\[ \frac{\lambda_1}{D}, \frac{\lambda_2}{2D}, \frac{\lambda_3}{3D}, \frac{\lambda_4}{4D} \]
Exponent $r$ vs. distance from the jet boundary

Circles: Re=10000

Triangles: Re=8430
Scale $\lambda$ vs. distance from the jet boundary

Circles: $Re=10000$  Triangles: $Re=8430$
Conclusions

- PDF of a phase function can be described with the Gamma distribution that is similar to the PDF of a phase function during mixing induced by Rayleigh-Taylor instability.

- The parameters of Gamma distribution can be determined using a least square fit of the measured histogram of the phase function, and not with a method of an equality of the PDF moments, if a range of measurements is shorter than $10\lambda_1$.

- The measured power $r$ is close to 1, and the scale parameter $\lambda_1$ increases from 0.05 to 1 D from a periphery to an internal part of a jet.

- There is no evident dependence of parameters on Re number at Re $\sim 10^4$, although the range of Re was not large.

- There is a difference in the parameters of Gamma distribution for mixing induced by Rayleigh-Taylor instability and for mixing at the external boundary of a turbulent jet caused, probably, by the different physical mechanisms of mixing in these two systems.