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Turbulence measurements in the centerline region of a turbulent round jet using a software-driven laser doppler system

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ABSTRACT – This paper demonstrates turbulence measurements of a turbulent round jet. It is aimed to map the energy cascade and turbulent scales along the jet centerline, spanning from the developing region to the fully developed counterpart. Measurements were performed using a software-driven LDA system, which was tested and proven to deliver high accuracy measurements. The velocity static moments show a similar trend with previous jet studies, as expected. The spatial kinetic energy spectra and second-order structure functions have been compared to the Kolmogorov -5/3 and 2/3 power laws. Good agreement is only obtained in the fully developed region.

1. INTRODUCTION
An axisymmetric turbulent round jet has been considered as a classical flow problem since this in principle simple flow still exhibits many of the elementary physical behavior patterns of turbulent flow [1]. Experimental investigation on it will therefore be significant in solving different kinds of problems identified in various types of flow processes [2]. Measurement wise, the centerline region is considered less challenging compared to the shear region, where the velocity fluctuation and turbulence intensity are much higher [3]. Investigation on this region may therefore be not as central as across the shear layer but a higher resolution and rigorous measurement along the jet centerline can be of the great interest in mapping the energy cascade and turbulent scales in the centerline region. This even becomes more essential when the measurements are performed using a novel and sophisticated laser Doppler system [4], which has been proven to function robustly even in the more difficult regions of the jet [5]. In fact, a significantly higher data rate is also expected from the measurements in the centerline region, which allows us to compute more accurately and obtain meaningful plots of the higher order turbulence statistics.

2. METHODOLOGY
Measurements were performed along the jet centerline (exit diameter, D=10 mm) to investigate the centerline profiles of the mean streamwise velocity and its higher order statistics. The measurement points range from x/D=10 up to x/D=37, with 10 mm increments between each point (see Figure 1), which should cover both the non-equilibrium (developing) and equilibrium (fully developed) regions of the jet. The exit velocity was set to nearly 40 m/s that corresponds to a jet exit Reynolds number, Re=25000. The data was then transferred to a computer for signal processing and data interpretation using our in-house LDA processing software, which has been thoroughly described in [4,5].

![Figure 1 Distribution of measurement points along the jet centerline.](image1)

3. RESULTS AND DISCUSSION
The mean streamwise velocity, velocity variance and turbulence intensity profiles with downstream distance along the centerline are displayed in Figure 2. The first two of these decay approximately inversely proportionally with the downstream distance, as expected, with a faster decay in the developing region [6][7]. The turbulence intensity builds up more gradually in the developing region and asymptotes to a nominal value of around 24% in fully developed counterpart.

![Figure 2 The downstream profiles of mean streamwise velocity, velocity variance and turbulence intensity, with 3rd-order polynomial fit.](image2)
Further, the energy spectra were also computed, which describe the distribution of turbulent kinetic energy, $E$ across different wavenumbers, $k$ of the flow (see Figure 3). Each spectrum is deliberately normalized in the low wave number asymptote for a better comparison in shapes. The shape of the spectrum corresponding the fully developed region ($x/D=25$) appears to nearly follow the $-5/3$ slope as postulated by the Kolmogorov $-5/3$ law \[8\][9]. The spectra obtained in the non-equilibrium counterpart revealed a symptom of invalidity of the law.

![Figure 3 Downstream development of spatial turbulent kinetic energy spectra. Following arrow direction: $x/D=10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36$.](image)

The second order structure functions, $S_2(\ell)$ are plotted in Figure 4 to show the development of turbulent scales, $\ell$ across the jet centerline. The large scales are seen to grow, and more large-scale activity is relatively noticed in the downstream direction. The tendency to follow the $2/3$ slope is again higher in the equilibrium region compared to the non-equilibrium counterpart [10,11].

![Figure 4 Downstream development of spatial second order structure functions. Following arrow direction: $x/D=10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36$.](image)

4. CONCLUSION

Measurements have been successfully performed to map the energy cascade and turbulent scales along the jet centerline, while revealing different degree of validity of the Kolmogorov $-5/3$ and $2/3$ laws. The disagreement to the laws found in the developing region open doors to work on deeper statistical analysis, which can be useful for numerical turbulence modelers.

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