Some experimental results on jet turbulence

Abstract

To examine about the effect of Reynolds number on velocity spectra and turbulence properties along the centerline at selected points. The measurements were taken for Reynolds number ranging from 20K to 160K based on the nozzle diameter and jet mean exit velocity, using Hot-wire anemometer with an objective to investigate the change in coherent structures and behavior of the velocity spectra around the potential core point and along the lipline at the nozzle exit.

Introduction

Turbulence jets are used in propulsion system of an aircraft, rockets and missiles, the studies in jet turbulence also have a potential of reducing the jet noise of an aircraft. The study of jets is done with the help of pitot tube, hot wire and with the help of latest lesser based methods of velocity measurement giving a pure view of Direct numerical simulations and larges eddies simulations, controlling the turbulence rather than having just an idea of the flow.
Jet evaluation: jets is developed from the circular nozzle exit, which interacts with steady outside environment. The jet flow gets diffused out in a radial direction downstream, and the radial directional diffusion of the velocity take place until the initial momentum decreases enough that viscous forces become dominant and dissipates the energy making the jet flow to end. The flow issuing from the nozzle exit depends on the boundary and initial condition as the jet flow proceeds in the downstream direction.

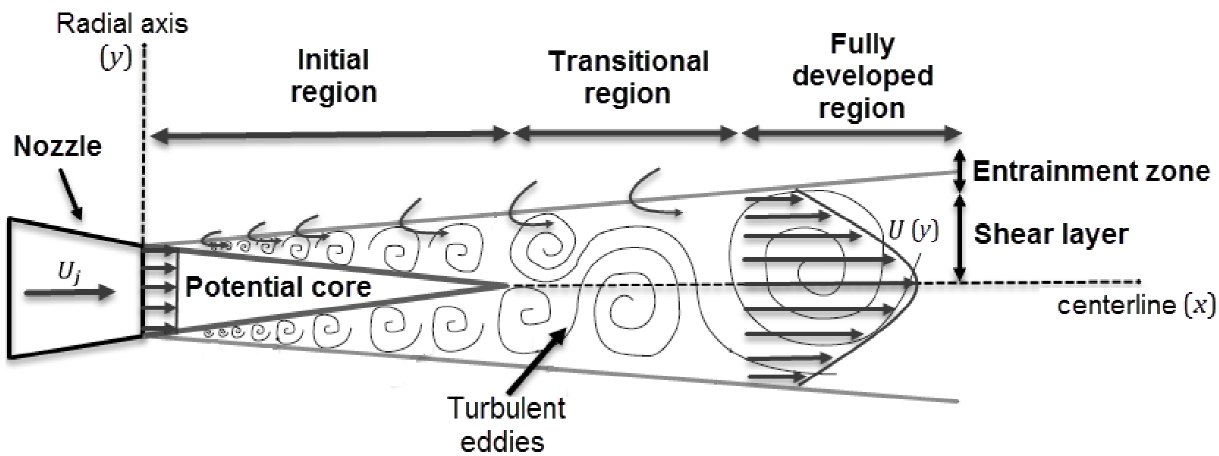


Fig. 1. Jet issuing from a contraction nozzle

Defining the coordinates for the jet flow, a convention used for measurements of different parameters. As shown in the fig. 1. The centerline axis along the nozzle axis is in downstream direction of the flow, following the polar coordinate system. the velocity components along the nozzle axis, along the radial axis and the tangential direction (along θ) are U, V & W respectively. The Reynolds decomposition denoted as $u = U + u'$, $v = V + v'$,& $w = W + w'$, the instantaneous velocity consist of mean velocity (U) + fluctuation part(u'). The nozzle outlet diameter of D flowing fluid with characteristic velocity Uj and the centerline velocity is Uc. A characteristic length, jet half width is defined as $U_{r/2} = U_c / 2$, the half of the centerline velocity. There is a generation of shear layer because of the velocity of the flow from nozzle interact with the quiescent environment, as shown in the figure the jet stream diffuses in radial direction, due to the share layer, the air from the ambient environment enters, resulting in increased mass flux, but the momentum remains conserved, as it should be.

The Jet stream is defined in regions: near field the initial region, intermediate zone the transition region and far field the fully developed region. For the initial region, it is defined from the length of the potential core, it appears only for the contraction nozzle; the intermediate zone is generally under the range of $0 \leq X/D \leq 7$, {where x is the downstream distance measured from the nozzle exit and D is the diameter of the nozzle} at the far field location the flow is fully developed, where the thin shear layer approximation holds making the flow to be self-similar, this region is located approximately from $X/D \geq 70$. The transition region from near to far field, in this region the flow forms highly anisotropic turbulent structures and evolves within few nozzles' diameter.

Methodology

Experimental setup and procedure

The velocity data was measured using hot wire majorly along centerline at $X/D \leq 30$, only the streamwise component of the instantaneous velocity was taken by single hot-wire probe operated at constant temperature, the frequency response of the hot wire and anemometer, from the square-wave technique, was about 10 kHz, and the temporal response of the wire was approximately 30-60 s. The hot wire and the pitot were set side by side for calibration to avoid any aerodynamic interference, the hot wire calibrations were conducted, prior to and after each set of measurements, at the nozzle exit the velocity having a top-hat profile which means the velocity variation at pitot tube and at the hot-wire sensor are negligible. The celebration of hot wire is carried out by measuring the flow velocity from pitot tube by manometer and storing that velocity value to the corresponding voltage value at that instance. The calibration was done for the velocities ranging from 0 to 100m/s and 0 to 140m/s by the step of 10m/s, the curve also contains some intermediate points as 5m/s to 35 m/s with step of 5m/s. The pitot tube is then removed after the calibration is done, obtaining the calibration curve as shown in figure 2. Using the traverse system, the position of hot wire is set accordingly to get the centerline and radial velocity data for the single-point measurements. Taking 60 points along centerline with the step of 0.4D, 0.2D and 1D and 35 to 40 points along radial axis with the step of 0.01D and 0.05D.

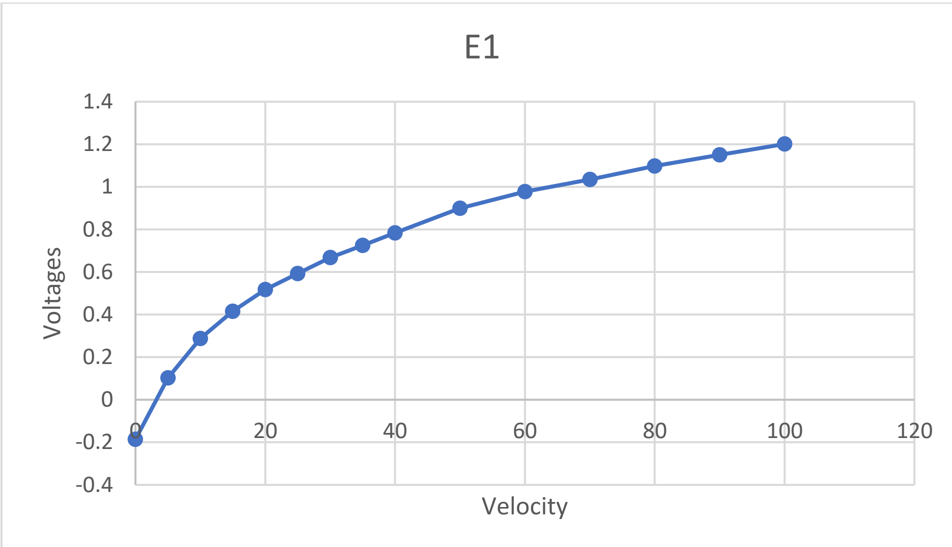


Fig. 2. Calibration curve for velocity range of 0 to 100m/s

The lipline and at the potential core location obtained from the turbulence intensity graph for centerline and radial velocities. The potential core can be located when the ratio of nozzle exits velocity U_j to centerline velocity U_c start to increase, which is the centerline decay of mean velocity U_j/U_c vs X/D as shown in figure. 3. It generally lies around $X/D \approx 5$. The lipline corresponds to the location in radial direction where the turbulent intensity is maximum, it generally lies around $Y/D \approx 0.5$. Shown in figure 4.

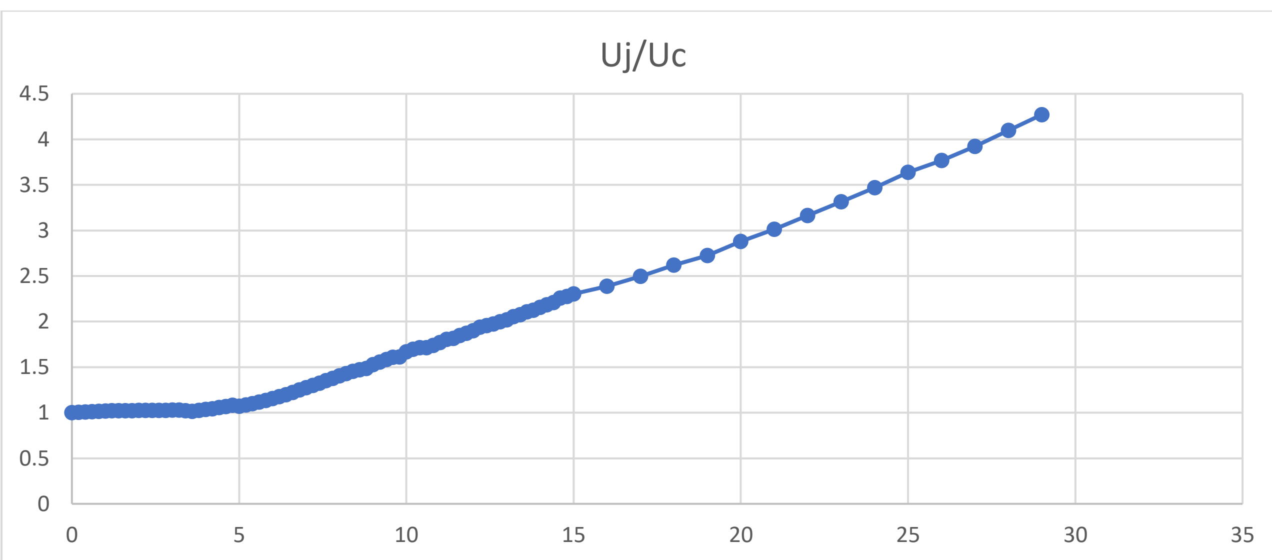


Fig. 3. Axial decay of centerline mean velocity for 48m/s (Potential core ends at X/D = 5)

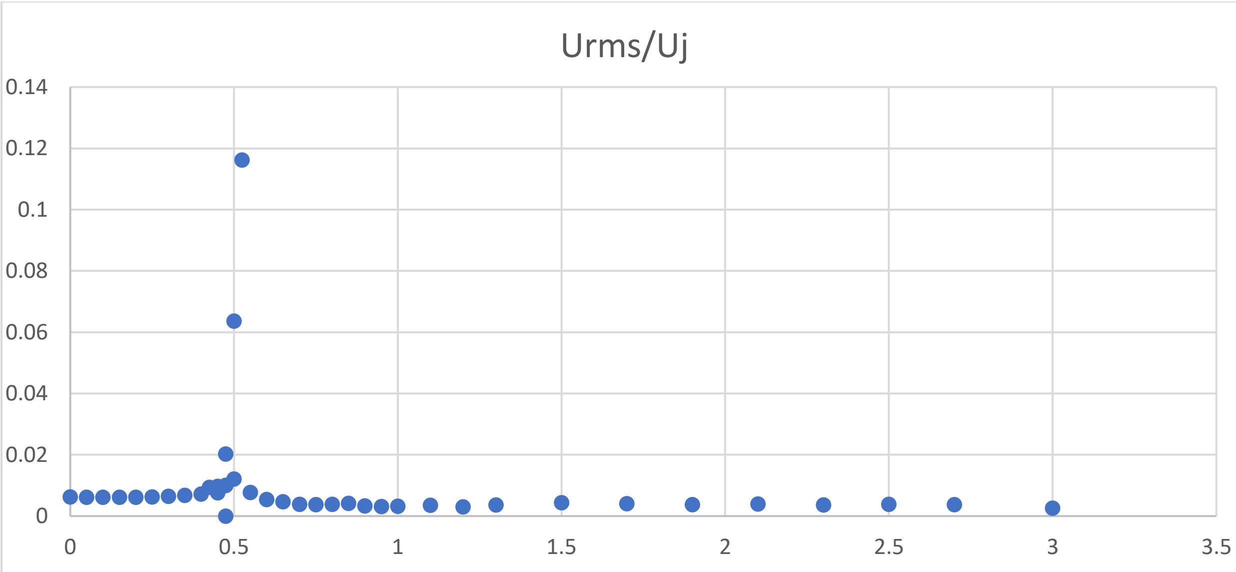


Fig. 4. Turbulence intensity VS y/D for 48m/s (lipline at 0.5y/D location)

Formulations and results

The power spectral density (PSD) and auto correlation function are Fourier pairs of each other, the velocity fluctuations in time and its square are required for modeling of the jet noise. The Cross-correlation function and cross spectral power density (CPSD) is defined as

$$R(y,\delta,\tau) = \frac{\overline{\acute{u}(y,t)\acute{v}(y+\delta,t+\tau)}}{\sqrt{\overline{\acute{u}^2}(y)\overline{\acute{v}^2}(y+\delta)}} \tag{1}$$

$$S(y,\delta,\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R(y,\delta,\tau)e^{-i\omega t}d\tau \tag{2}$$

For our purpose, only axial component velocity data in time scale was taken and is considered for the auto correlation and PSD at a single point. Giving auto correlation and PSD equations as follow:

$$r(\tau) = \overline{\acute{u}(t)\acute{u}(t+\tau)} \tag{3}$$

$$R(\tau) = \frac{\overline{\acute{u}(t)\acute{u}(t+\tau)}}{\overline{\acute{u}^2}} \quad \text{\{Normalized auto correlation function\}} \tag{4}$$

$$S(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} r(\tau)e^{-i\omega t}d\tau \tag{5}$$

The power spectrum density shows same amplitude information as root mean square of the velocity fluctuations.

The PSD at the lipline location at fixed axial location, in our case at nozzle exit, on increasing the jet velocity (U_j), the amplitude of PSD increases and extends the flat energy region to higher frequencies. On increasing the Reynolds number, the turbulence energy spectrum shifts to higher wavenumber. This is also consistent with points within the potential core where coherent structures are seen to move in higher frequencies (Fig.5). For a fixed jet exit velocity, the amplitude of PSD increases and the frequency at which the energy begins to decay decreases, due to the effect of shear layer growth down the stream.

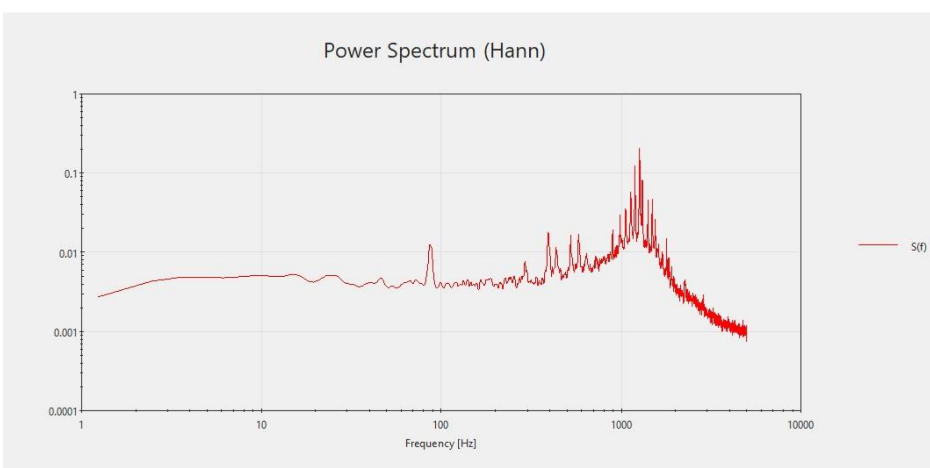
A non-dimensional parameter called Strouhal number for scaling the frequency and power spectral density amplitude, it is expressed as St

$$St = \frac{(F)(D)}{U_j} \tag{6}$$

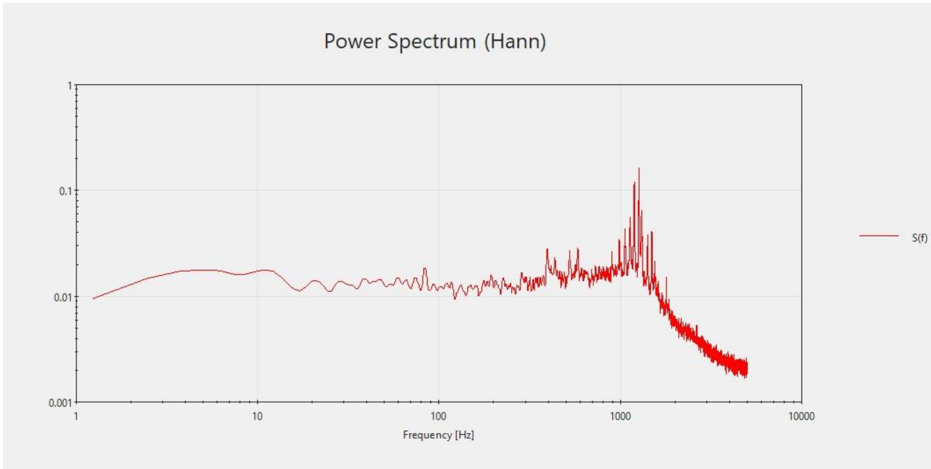
Where, F is the peak dominating frequency from PSD plot, D is the nozzle diameter, and U_j is nozzle exit velocity.

Velocity in m/s	X/D location of potential core	Strouhal number
15	4.4	0.40
48	5.2	0.341
60	4.4	0.466
80	5	0.45
100	4.6	0.40
120	4.8	0.416

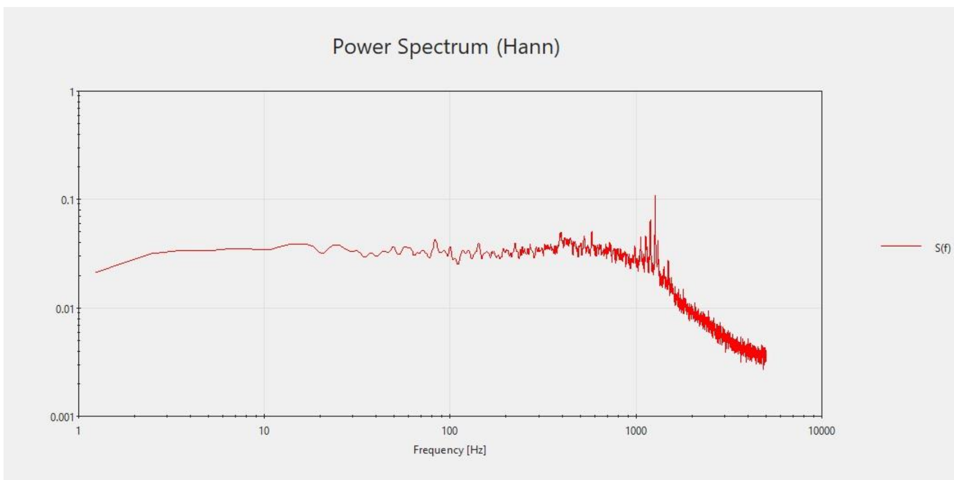
Table 1. Strouhal number at potential core for velocity range from 15 to 120 m/s



(a) X/D = 3.6 along centerline, upstream of potential core end, St = 0.466

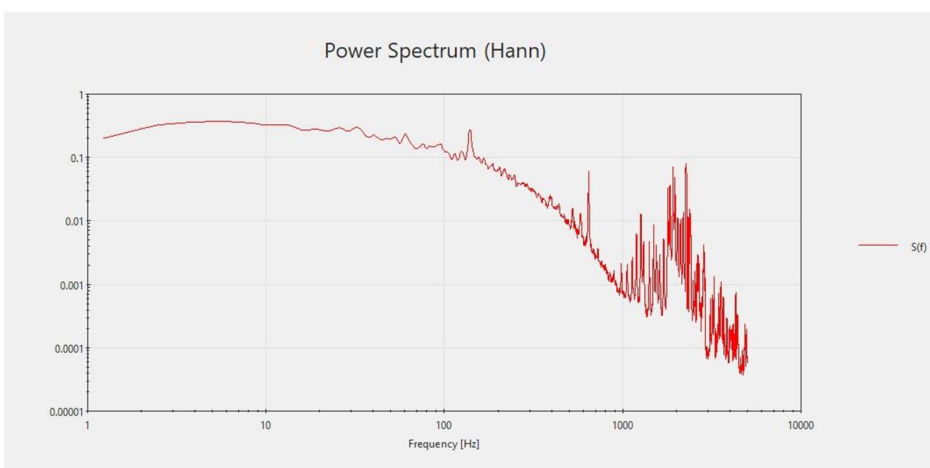


(b) X/D = 4.4 along centerline, at the end of potential core, St = 0.466

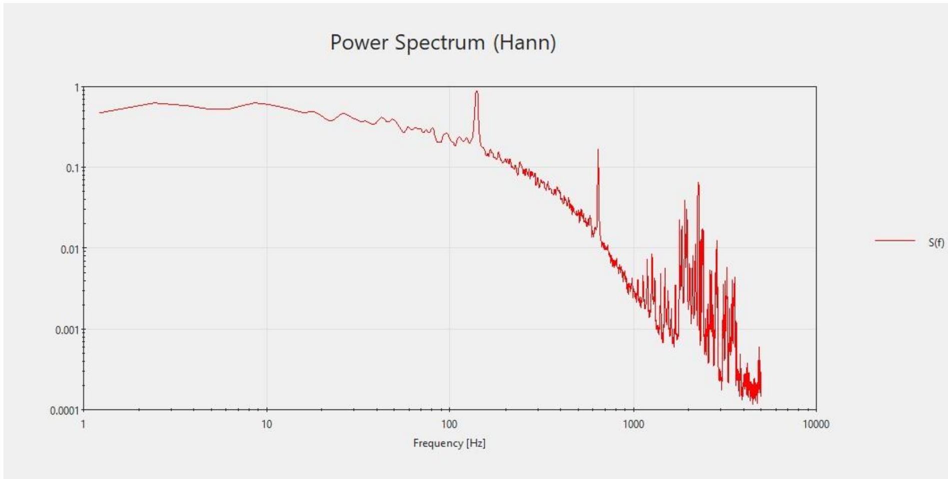


(c) X/D = 5.4 along centerline, downstream of the potential core, St = 0.460

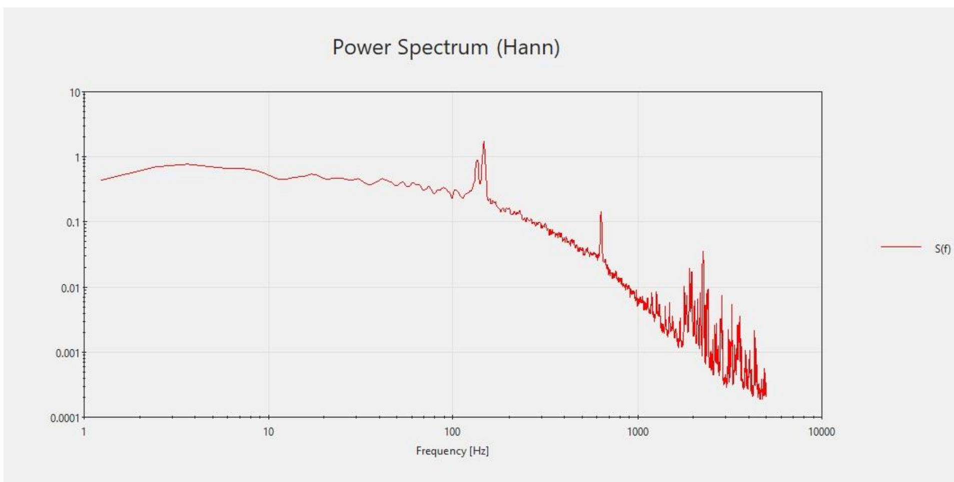
Fig. 5. Power spectral density at the potential core points at jet exit velocity of 60m/s (Re = 79.5k)



(a) Y/D = 0.44 and X/D = 0, along the lipline, Re = 79500 (60m/s)



(b) Y/D = 0.45 and X/D = 0, along the lipline, Re = 106000 (80m/s)



(c) Y/D = 0.46 and X/D = 0, along the lipline, Re = 133000 (100m/s)

Fig. 6. Power spectral density along the lipline axis at nozzle exit for increasing jet velocity

Conclusion

The Hot- wire measurements were carried out for circular jet contraction nozzle for the Reynolds number ranging from 20,000 to 160,000 to examine the mixing and transition of the jet flow. From the data of velocity spectra, on increasing the Reynolds number the range of velocity spectra increases. From *J. Mi* 2013 paper, the present Reynolds number range fall after the critical Reynolds number $Re_d \approx 10,000$ that have close agreement with independency of Reynolds number with mean centerline velocity decay and spread. The Strouhal number found to have very small variations with Reynolds number which agrees well with what is mentioned in (2009) *Andrew pollard*, giving no effect of Reynolds number on the number of vortices formed in the jet flow.

References

1. Anderson Proença1 (2019) /Measurements of the single-point and joint turbulence statistics of high subsonic jets using hot-wire anemometry.
2. Andrew pollard (2009) /The velocity spectra and turbulence length scale distributions in the near to intermediate regions of a round free turbulent jet.
3. J. Mi, M. Xu and T. Zhou (2013) /Reynolds number influence on statistical behaviors of turbulence in a circular free jet.
4. C.G. Ball, H. Fellouah, A. Pollard (2012) /The flow field in turbulent round free jets
5. Hamed Sadeghi, Philippe Lavoie & Andrew Pollard (2014) /The effect of Reynolds number on the scaling range along the centerline of a round turbulent jet