Aerodynamics Laboratory (AE 312)

Planar Jet

Performed by
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February 2024

1. Objectives

1. Examining the traits of the planar jet
2. Assessing the average velocity along its streamwise direction
3. Describing the longitudinal changes in both centerline velocity and the width of the jet
4. Confirming the presence of self-similarity
5. Validating the preservation of streamwise momentum flux
6. Confirming the suggested alterations in streamwise mass and energy flux

2. Apparatus

Experimental Setup:
The experiment utilised a wind tunnel with a flat nozzle, generating an air jet through a converging nozzle. This nozzle, with a width(w) of 44m and a height(d) of 18mm, produced a thin and elongated jet.

Flow Control:
A blower, linked to a motor, propelled the flow through the converging nozzle, ensuring controlled and directed airflow.

Measurement Tools:
Wind velocity at various streamwise stations was determined using a pitot tube and an electronic manometer. These instruments, along with a pitot tube mounted on a movable mechanism, measured stagnation pressure, aiding velocity profile analysis.

Positioning and Tracking:
Vertical and horizontal traverse scales, along with a table equipped with scales and screws, facilitated precise probe movement in streamwise and lateral directions.

Apparatus List:
1. Wind tunnel
2. Motor speed controller
3. Converging nozzle
4. Blower
5. Pitot tube with movable mechanism
6. Electronic manometer
7. Vertical and horizontal traverse scales
8. Table with scales and screws
9. Connecting pipe

Fig(i): experiment apparatus

3. Theory

Free shear flows:
These flows, characterised by high Reynolds numbers, operate without confinement from boundaries and are directly exposed to the ambient environment. Consequently, the pressure throughout these flows is nearly atmospheric. The term "shear" denotes the dominance of velocity gradients between the jet and ambient air. Free shear flows primarily manifest as jets and wakes:

- Jets: A jet represents a high-speed stream of fluid projected into a stationary surrounding medium, typically emanating from a nozzle, aperture, or orifice. The velocity gradients arise due to the differing speeds between the jet and ambient air, making these flows shear-dominated. The primary phenomenon results from the contrast in velocities.

- Wakes: The wake is the region of disturbed flow, often turbulent, downstream of a solid body moving through a fluid. This disturbance is caused by the fluid's flow around the body and forms behind it when the flow crosses over. While the flow inside a wake is predominantly turbulent, it can also exhibit laminar characteristics.

In both cases, there exists a characteristic velocity scale,U, and a characteristic shear layer width(d). As these flows are free, the pressure remains approximately constant, except within the turbulent shear layer. This experiment focuses on a detailed study of turbulent jets.

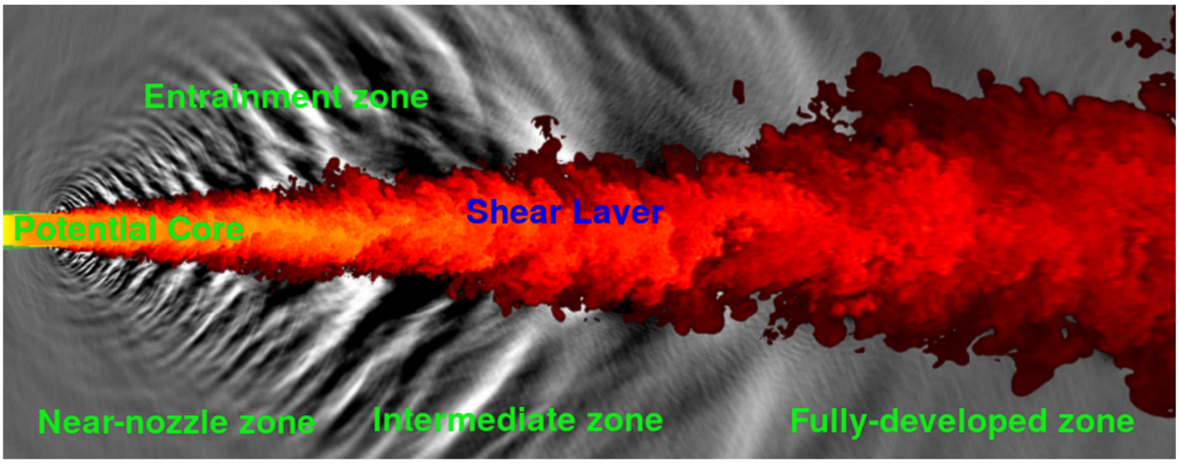
Planar Jet:
The planar jet, emerging through a nozzle with a significantly larger length than its width, exhibits negligible variation in the span-wise direction. Flow properties vary predominantly in the axial and transverse directions, ensuring a genuinely two-dimensional flow. The flow field can be characterised into distinct regions:

- Potential Core: In this zone, the exit velocity prevails, and viscous effects are negligible. The region, just outside the nozzle opening, remains unaffected by shear effects. The mean velocity stays constant and close to the jet exit velocity. The flow here is uniform, irrotational, and devoid of velocity gradients.

- Shear Layer: This region marks the mixing of two streams, where the dynamic interaction leads to velocity gradients.

- Entrainment Zone: The shear layer, formed during mixing, drags the surrounding stationary fluid inward due to velocity gradients. This region, known as the entrainment zone, is characterised by predominantly radially inward flow.

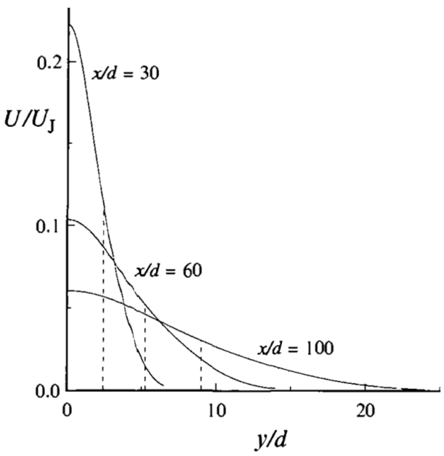
- Fully Developed Zone: As the flow progresses away from the nozzle, the potential core diminishes, and a fully developed flow is established downstream. In this zone, the flow reaches statistical equilibrium, resulting in self-similar velocity profiles. Consequently, the flow becomes independent of initial parameters in the fully developed zone.



Fig(ii): planar jet development

Velocity Profile in fully developed zone:

- Study time-averaged (mean) streamwise velocity, denoted U(x, y)
- Velocity decays on centerline, but grows at outer regions
- Jet widens as it slows down
- Profiles appear to be similar (just scaled differently)



U: Mean streamwise velocity (also denoted by U)

U_j: Nozzle exit velocity

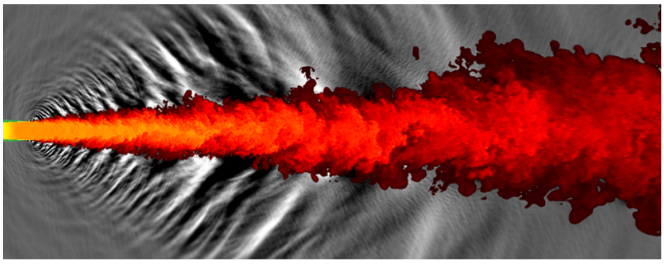
d: Nozzle exit thickness

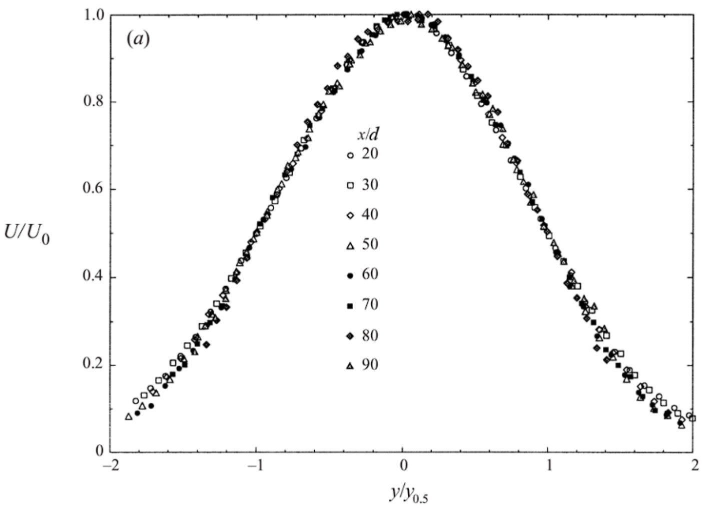
Fig(iii): velocity profile

Concept of Self-Similarity:

- In fully-developed region, initial (near-nozzle) condition is ‘forgotten’
- Thus, there is no characteristic dimension in the streamwise direction
- Another way of seeing this is that the flow is in ‘equilibrium’
- In such a situation, it is natural to expect the flow to be self-similar
- I.e., if the velocity and lateral coordinate are properly scaled, then the profiles should ‘collapse’ irrespective of the actual streamwise position
- A natural choice for normalising y is the jet half-width $y_{0.5}(x)$,

  $U(x, y = y_{0.5}) = 1/2\, U(x, y = 0)$
- Velocity is to be normalised by centerline velocity $U0(x) := U(x, y = 0)$





Fig(iv): self similarity plot in fully developed zone

Variation of streamwise Fluxes:

$$\text{Mass flux:} \quad \dot{m}(x) := \int_{-\infty}^{\infty} \rho U dy \sim x^{0.5},$$

$$\text{Energy flux:} \quad \dot{E}(x) := \int_{-\infty}^{\infty} \rho U^3 dy \sim x^{-0.5}.$$

while the streamwise momentum flux remains unchanged as there is no external force acting and shear stresses don’t impact the momentum. This is consistent with the theoretical predictions.

4. Procedure

1. Measure ambient temperature and pressure to calculate air density using the ideal gas law.
2. Initiate the wind tunnel, configuring the jet velocity at the nozzle throat to 53 m/s. Adjust the velocity through dynamic pressure calculations and verification with a manometer. Position the pitot probe at the planar jet's midpoint to minimise inaccuracies.
3. Obtain air velocity measurements at various streamwise locations by vertically moving the pitot tube until the manometer reading approaches zero, signifying the jet stream's boundary.
4. While measuring pressure, account for potential oscillations in the digital manometer's readout. Employ the average of two bounding values to mitigate dynamic pressure variations for subsequent calculations.
5. Repeat steps 3 and 4 for different stations along the x-axis (streamwise direction).

5. Ambient data and Test section velocity

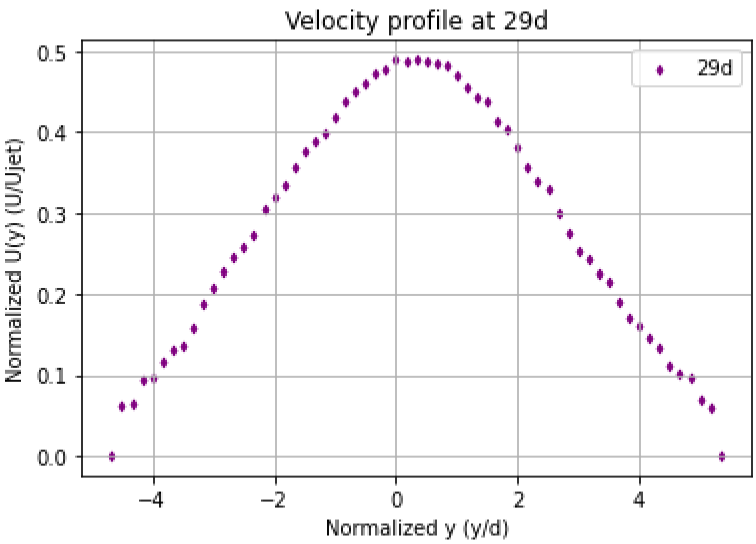
Parameters	Measured value for day 1	Measured value for day 2
Temperature (T∞)	301.15 k	300.15 k
Density (ρ∞)	1.17 kg/m^3	1.16 kg/m^3
Pressure (P∞)	100920 Pa	100680 Pa
Nozzle Velocity (V∞)	53 m/s	53 m/s

Table(a): ambient data

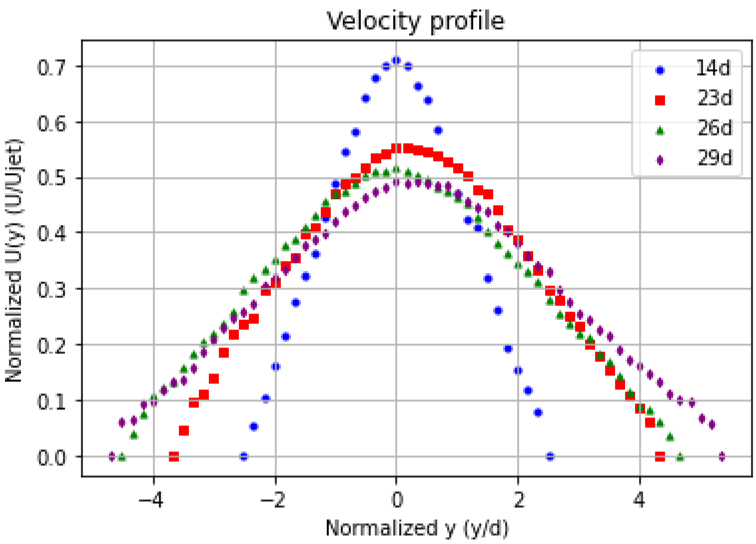
6.Plots

Velocity profile:
In the planar jet experiment, we choose different x-locations, and at each of these x-locations, we measure the dynamic pressure (using a pitot probe) at various y-locations across the jet. Flow velocity at these locations is then calculated from the equation for dynamic pressure, $\Delta p = \rho V^2/2$. The measured dynamic pressure and the corresponding calculated velocities usually display a scatter owing to uncertainties in experimental measurements

For reference:



Fig(v): velocity profile at x=29d for reference



Fig(vi): velocity profile for each station

Gaussian fit:
It can be seen from above figures that the scattered data makes estimation of the peak velocity as well as the jet half-width difficult. However, we note that the velocity profile appears similar to a Gaussian function. Thus, we suggest that you fit the velocity profile data at each x-location (i.e., U(x=constant,y)) to a Gaussian function as given below, as long as you are past the end of the potential core:

$$U(y) = U_0 \exp(-\ln 2 \frac{(y-y_0)^2}{b^2}) \quad \text{.... (2)}$$

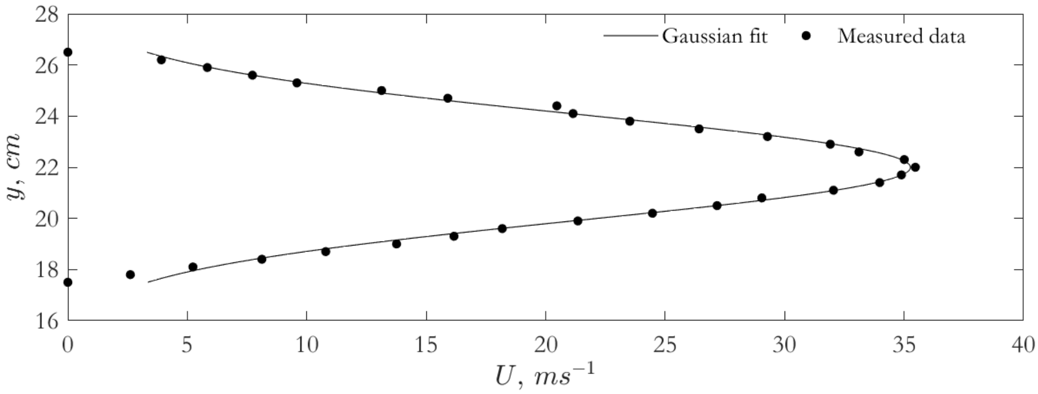
Here, U_0 is the centerline velocity, b is the jet half-width (see that this works out by putting U = $U_0/2$ in the above expression), and y_0 is the position of the centerline. Note that you will obtain different values of these three parameters at each x-location. Although you may expect y_0 to be constant throughout x, it may not be so due to slight non-parallelism between the x-traverse axis and the jet axis.
The actual curve fitting can be done using the MATLAB function fit as follows
f = fit(y, U, 'gauss1')

which leads to the following relation between U and y:

$$U(y) = a_1 \exp\left\{-\left(\frac{y-b_1}{c_1}\right)^2\right\}$$

Gaussian fits:

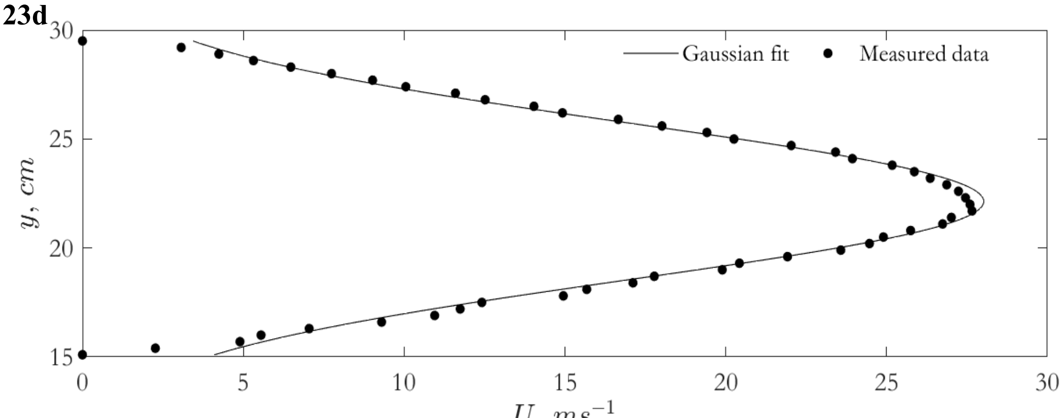
At x=14d



Fig(vii): gaussian fit at x=14d

The centerline velocity at 14d is 35.271, the half-width at 14d is 2.4369, and the centerline at 14d is at y = 21.9947

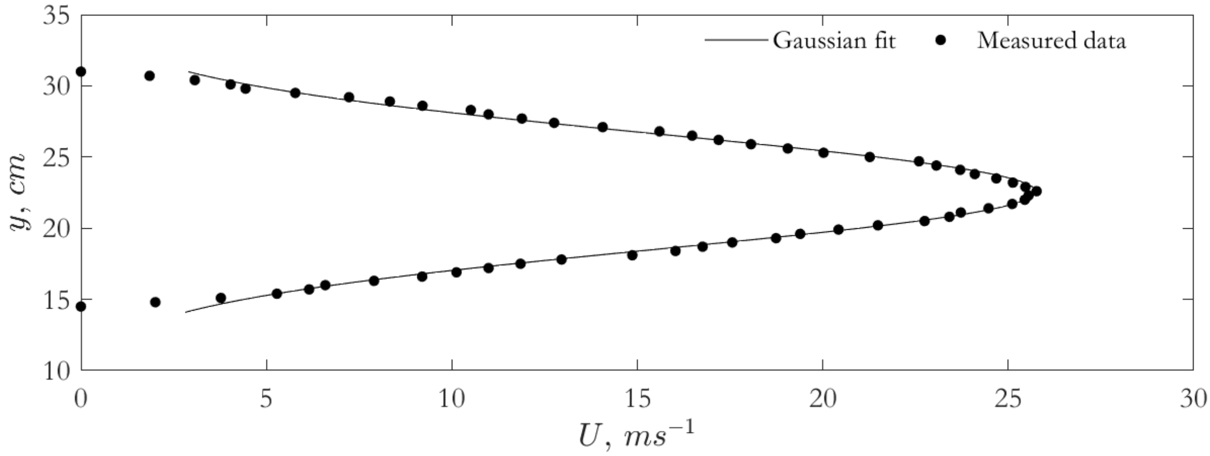
At x= 23d



Fig(viii): gaussian fit at x=23d

The centerline velocity at 23d is 28.0199, the half-width at 23d is 4.2296, and the centerline at 23d is at y = 22.138

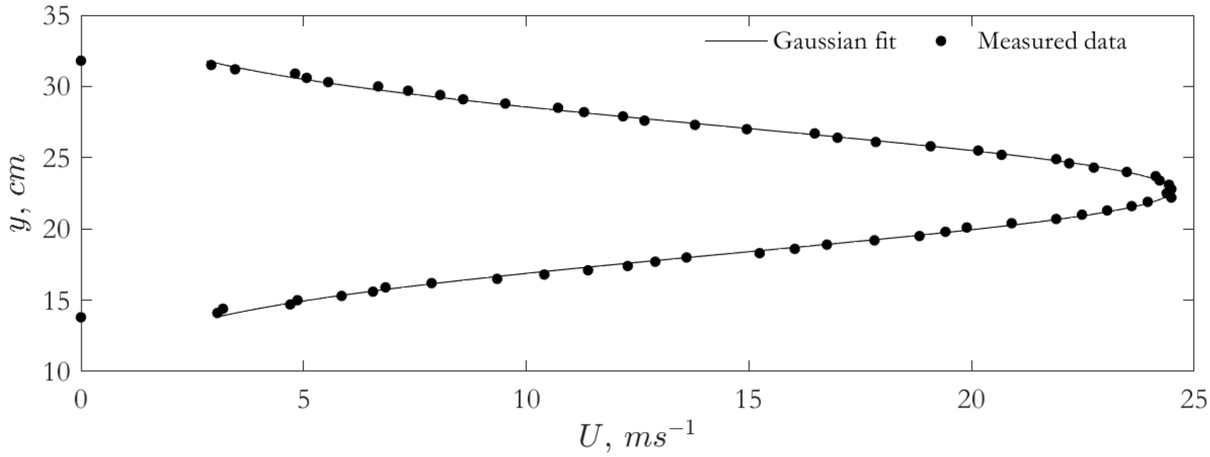
At x=26d



Fig(ix): gaussian fit at x=23d

The centerline velocity at 26d is 25.7332, the half-width at 26d is 4.7429, and the centerline at 26d is at y = 22.5702

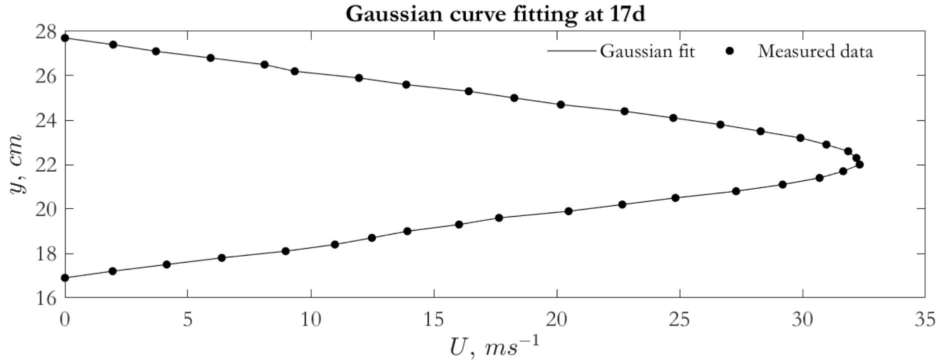
At x=29d



Fig(x): gaussian fit at x=29d

The centerline velocity at 29d is 24.4986, the half-width at 29d is 5.1359, and the centerline at 29d is at y = 22.7213

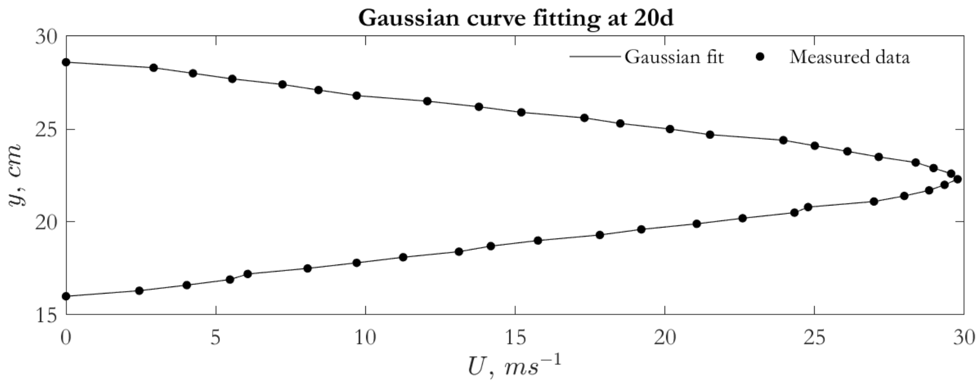
At x=17d



Fig(xi): gaussian fit at x=17d

At 17d, centerline velocity is 32.4859, half-width is 2.9086, and centerline is at y = 22.2743

At x=20d



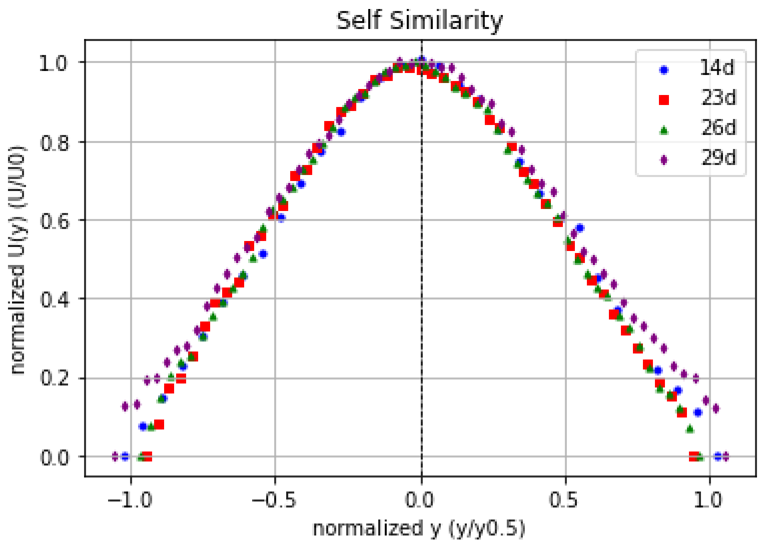
Fig(xii): gaussian fit at x=20d

At 20d, centerline velocity is 29.6796, half-width is 3.4891, and centerline is at y = 22.3734

Self Similarity:

Self-similarity plots are vital tools in fluid mechanics, enabling the normalisation of velocity data for diverse axial positions. By doing so, these plots facilitate the identification of universal flow patterns and the assessment of turbulence characteristics. They play a pivotal role in recognizing fully developed regions within turbulent systems, aiding us in extracting meaningful insights and validating theoretical models with efficiency and accuracy.

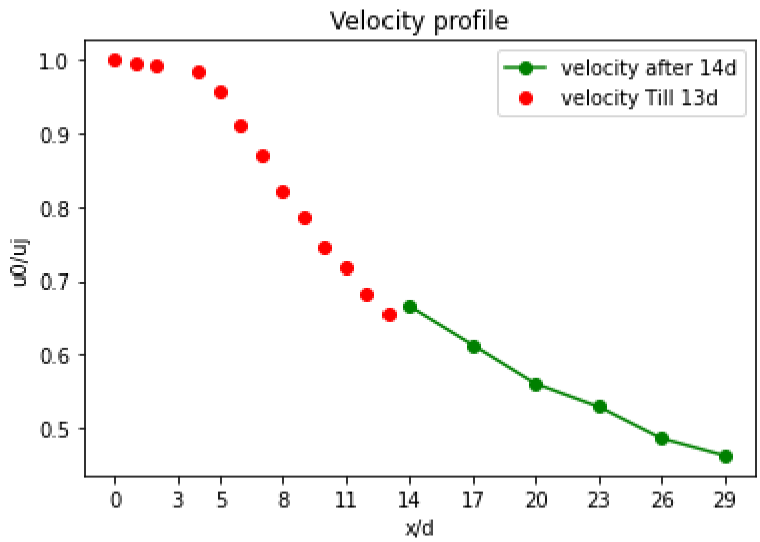
In the context of self-similarity plots, the velocity profiles at different axial positions are normalised by the respective centerline velocity, denoted as $U(y)/U_0$. Simultaneously, the lateral coordinate y is normalised using the corresponding jet half-width, denoted as $y/y_{0.5}$. The Gaussian fits, as explained earlier, were utilised for calculating $y_{0.5}$. In the fully-developed region, where the flow becomes independent of initial parameters, there is no characteristic dimension in the streamwise direction. This characteristic allows for the anticipation of self-similarity in the flow—normalised velocity and lateral coordinate should result in overlapping profiles, regardless of their streamwise position. The jet half-width, $y_{0.5}$, serves as a natural choice for normalising the lateral coordinate y, while the mean streamwise velocity is normalised by U0. Self-similarity plots were constructed for various station positions, revealing that beyond x=10d, the profiles exhibit overlap. This observation supports the logical inference that stations on and after x=14d (specifically, x=14d, 23d, 26d, and 29d) lie within the fully developed zone. The accompanying figure visually validates the similarity of profiles at all axial stations in the fully developed region of the flow field.



Fig(xiii): Self similarity plot

Potential Core Length:

The potential core is identified as the region where the centerline velocity (U0) approaches the jet exit velocity (Uj). To determine the potential core length, we systematically vary the ratio U0/Uj across different station locations and observe the resulting variations. In this context, the centerline velocity decreases along axial locations due to the interaction between high-momentum fluid particles at the jet exit and the free stream particles outside the jet. This diffusion of momentum, known as entrainment, leads to the progressive reduction of centerline velocity with increasing axial distances.



Fig(xiv): normalised velocity vs normalised distance

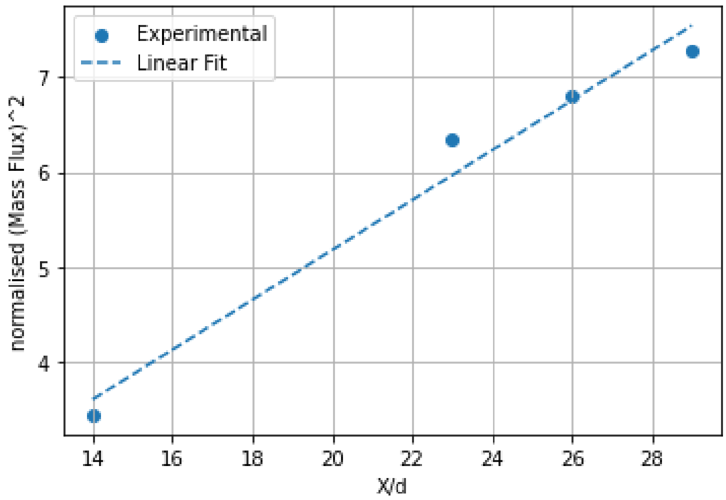
From the plot, it can be seen that the centerline velocity up to x=4d is nearly invariant. Thus, we can claim confidently that the potential core ends at approximately x=4d. Further,we notice non uniform variation of the plot between x=4d and x=13d. It is also observed for x/d ≥ 13, the plot is smoothly decreasing, thus this in addition to the self-similarity trends further verifies this domain should denote the fully developed region

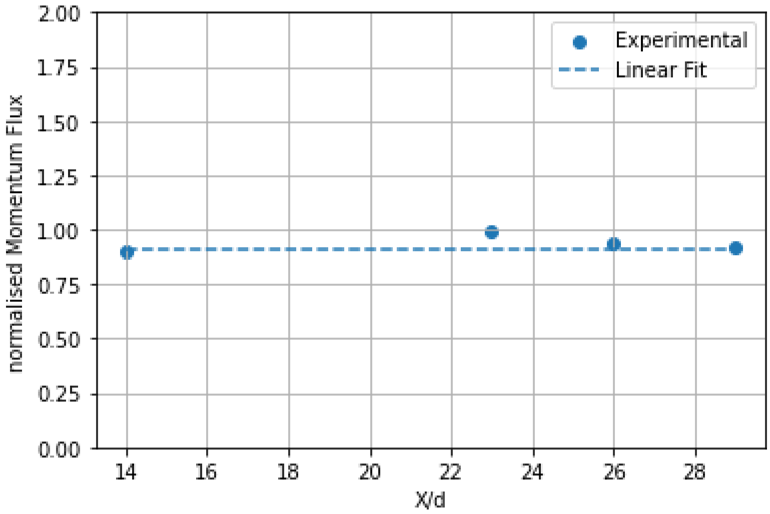
Flux:

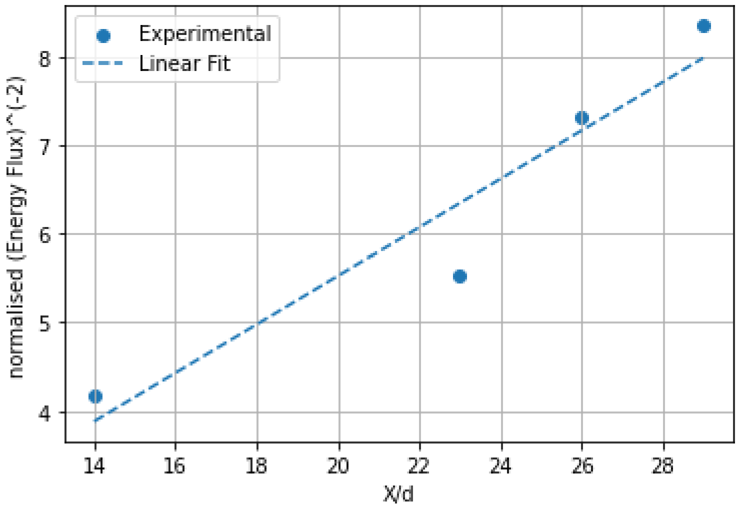
Momentum flux

$$\dot{P}(x) := \int_{-\infty}^{+\infty} \rho U^2 \, dy$$

x/d	Normalised momentum flux	(Normalised energy flux)^-2	(Normalised mass flux)^2
14	0.90	4.17	3.44
26	0.93	5.53	6.34
26	0.93	7.32	6.79
29	0.91	8.35	7.27



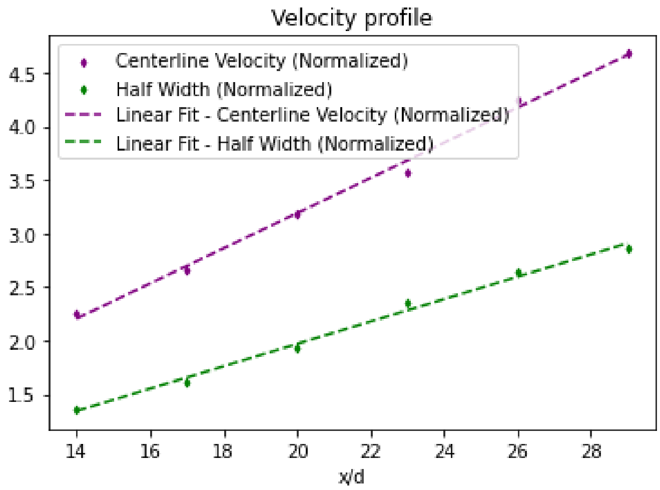




Axial variation:

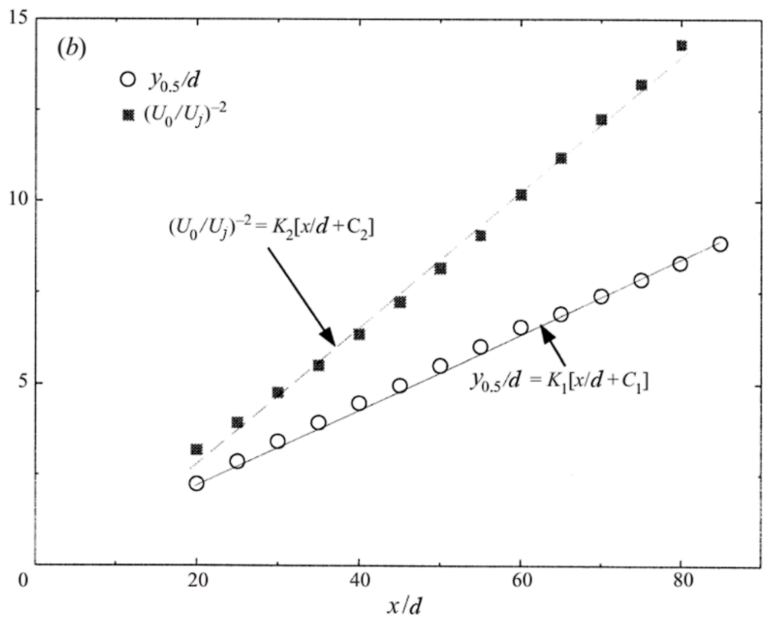
In Gordeyev and Thomas, 2000 it is mentioned that the local centerline velocity varies with square root of the distance from the nozzle and the jet half width varies linearly with distance from the nozzle as given below:

$$\frac{y_{0.5}}{d} = k_1[\frac{x}{d} + c_1]$$
$$\frac{U_j}{U_0}^2 = k_2[\frac{x}{d} + c_2]$$



Fig(xv): Variation of the experimental data for (U0/Uj)^-2 and y0.5/d with x/d

We compare our plot with the plot obtained by Gordeyev and Thomas, wherein their data was plotted for nozzle exit velocity Uj = 35m/s with a corresponding Reynolds number of 28,000 based on slot width of 12.7mm.



Fig(xvi)

In contrast to Fig(xvi), our plot aligns with the documented pattern outlined by Gordeyev and Thomas in the fully developed zone, as observed. Thus, the plot presented in Fig(xv), featuring a mean velocity decay rate (k_2 = 0.1344) and widening rate (k_1 = 0.093), corresponds to the relationships defined by Gordeyev and Thomas. This concordance underscores the reliability of your results and their accordance with established insights in the field.

9. Conclusion

1. The presence of self-similarity has been affirmed at stations x=14d, 23d, 26d, and 29d, indicating their location within the fully developed region.

2. The observed self-similar jet velocity profiles within the fully developed zone of the planar jet field align with the findings reported by Gordeyev and Thomas in 2000.

3. Experimental verification supports a Potential Core length of approximately 4d.

4. The mean normalised mass flux increases with streamwise distance due to jet mixing in the entrainment zone, displaying a direct proportionality to $x^{1/2}$ in the fully developed region.

5. In the fully developed region, the mean normalised momentum flux remains conserved along the streamwise direction.

6. The mean normalised energy flux experiences a decrease in the streamwise direction due to viscous dissipation, with a direct proportionality to $x^{-1/2}$ in the fully developed region.

7. The normalised half jet width exhibits a linear trend with x/d, consistent with the $y_{0.5}/d$ versus x/d plot provided by Gordeyev and Thomas in 2000.

8. The relationship U_0/U_j^{-2} demonstrates linear variation concerning x/d, aligning with the U_0/U_j^{-2} versus x/d plot provided by Gordeyev and Thomas in 2000.

9. Mean velocity decay rate and spread rate values obtained from experimental data mirror those validated by the values reported by Gordeyev and Thomas in 2000.

8. References

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