Studies on Circular Free Jet

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Abstract

In this experiment, the free shear layer characteristics of the jet stream were investigated by measuring the subsonic jet spread and velocity distribution. The velocity distribution was estimated by measuring stagnation pressures along and normal to the centerline with a Pitot tube at various distances. Non-dimensional velocity was shown by a horizontal distance along the nozzle's centerline and a vertical distance away from the centerline. The velocity of the stream was determined to decrease as horizontal and vertical distances increased. The experimental and theoretical results are compared to estimate the mass flow variation along the jet axis.

Nomenclature

D	Diameter of the nozzle, mm
g	Acceleration of gravity
h	Height measured in Manometer, cm
θ	Inclination angle of Manometer
V	Velocity, m/s^{-1}
R	Universal gas constant
T	Temperature ° C or K
ρ	Density
P_{atm}	Atmospheric Pressure
P_{st}	Stagnation Pressure
ρ_{air}	Density of air
ρ_{eth}	Density of Ethanol

Introduction

A jet is a free shear layer formed as a result of a pressure differential across a nozzle or opening. Since low-speed jet flows are employed in numerous technical applications such as fluid amplifiers, liquid inflow and vapor impingement in weightlessness, and the laminar gas jet diffusion flame, a thorough understanding of jet flow dynamics is essential.

When compared to the surrounding fluid medium, jet fluid has more momentum. As a fluid boundary cannot sustain a pressure differential across it, the subsonic jet boundary is a free shear layer with constant static pressure. The boundary layer at the device's outflow emerges as a free shear layer, mixing with the ambient fluid and entraining it in the jet stream. As a result, the mass flow at any cross section of the jet gradually rises, and the jet extends downstream.

The jet centre line velocity decreases with downstream distance to conserve momentum. The centre line velocity decay divides a free jet shape into four major zones - convergent zone, transition zone, self similar zone, and termination zone. The potential core is a region in which the velocity remains constant in relation to the exit velocity. The jet slows down beyond the potential core due to mixing and momentum exchange with the outside flow: the jet's influence extends outwards, while the outside's impact is felt at the axis.

Moving normal to the streamline, the velocity near the jet will remain constant for a short distance and then rapidly decrease, whereas sufficiently enough from the jet, the change in velocity will be progressive. Furthermore, when going down the center line, the velocity remains constant for a short distance before progressively decreasing.

Experimental setup

The experiment was carried out in a subsonic blow down wind tunnel connected to a 10 mm diameter nozzle. A centrifugal blower, diverging duct, screens and mesh, converging duct, test-section, and a nozzle affixed at the end of the test-section comprise the setup. A Pitot tube, which could move in three translational directions, was mounted on an x-y traverse. The pitot tube was oriented toward the nozzle's output. The Pitot tube pressure was measured along and across the nozzle using a multi-tube variable inclination manometer.

Theory

The velocity field distribution of circular jet flow is seen in the image. Because of the disparity in velocity between the jet and the surrounding fluid, an unstable thin shear layer forms at the jet boundary. The shear layer renders the flow unstable, resulting in turbulence inside the flow. The shear layer continues to expand along the flow direction, causing the jet to spread outward and its velocity to decrease along the flow direction. The centre-line velocity decay divides a free jet shape into four major zones. They are as follows:

1. The Convergent Zone: The potential core of the jet is defined as the zone where the centre-line velocity equals the nozzle exit velocity. Normally, this zone extends up to 5D, where D is the diameter of the nozzle outlet. The shear layer that surrounds this zone is where the jet stream and the

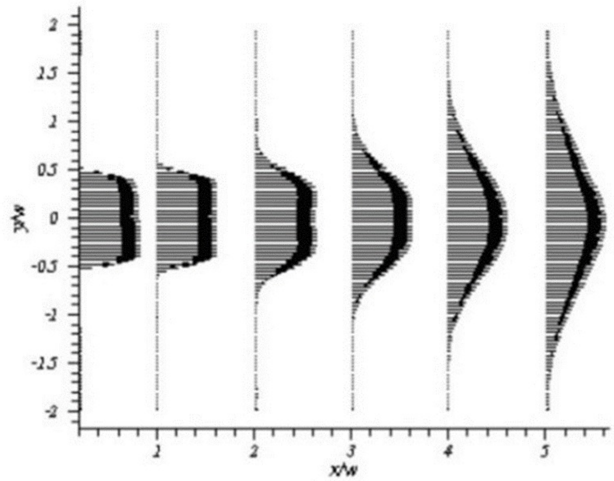
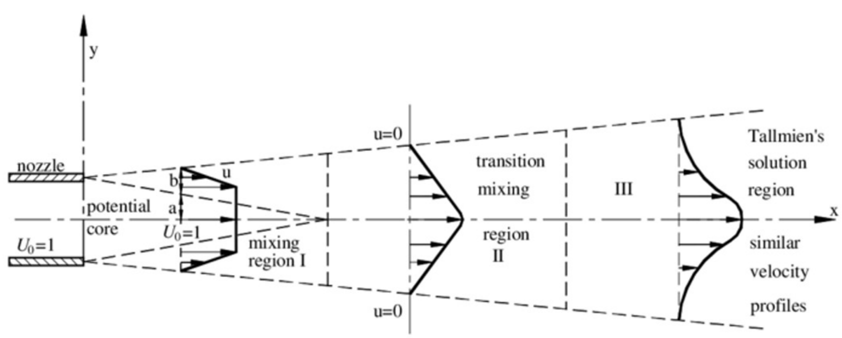


Figure 1: Jet flow field

ambient stream mingle. The spread of the shear layer reduces the breadth of the potential core.

2. The Transition Zone: This region begins after the convergence zone, that is, when x/D > 5. The beginning and transition zones are characterized as developing areas because continual momentum and energy transfer from the jet stream to the surrounding environment happens in these regions. The shear layer fills the whole width of the jet in this area, and the potential core is missing. The jet center-line velocity drops constantly throughout the flow direction. The transition zone shrinks as the Reynolds number increases, and the drop in velocity in this zone is proportional to $\sqrt{x}$



3. The Self Similar Zone : This region starts after the convergent zone, i.e.

it starts approximately when x/D > 50. The jet velocity profile becomes self-similar in this area. The flow is well developed in this zone. In this region transverse velocity profiles are similar at different values of x and the centre-line velocity decay is approximately proportional to 1/x

4. The Termination Zone: The centreline velocity quickly decays in this region. Despite the fact that this zone has been researched by various scholars, the real mechanisms in this zone are not well known. The free shear layer formed here differs from the typical boundary layers associated with solid borders, which expand to the end of the solid.

The Pitot Tube measured the stagnation pressure, which is given by

$$P_{\mathrm{st}} = P_{\mathrm{atm}} + 1/2 * \rho * V^2 \tag{1}$$

$$P_{\mathrm{st}} = P_{\mathrm{ref}} + \rho_{\mathrm{eth}} * g * h * sin(\theta) \tag{2}$$

Here the static pressure is constant and is equal to the atmospheric pressure. Thus the velocity of the jet can derived using these equations and bernoulli's equation

$$V = \sqrt{\frac{2(P_{\mathrm{st}} - P_{\mathrm{atm}})}{\rho_{\mathrm{a}}}} \tag{3}$$

Procedure

- Establish the set up.
- Measure the inclination of multitube manometer and atmospheric pressure.
- Note down the room temperature.
- Note the diameter of the nozzle
- Turn on the blower and set an RPM of 1600.
- Set the pitot tube such that it is at the center of the jet
- Move the pitot probe fixed on the traverse in away from the jet along the central line in axial direction.
- Measure and note the pressure readings from the multitube manometer for every 2mm.
- Repeat this experiment to axial distance of 20 D.
- Now fix the pitot probe at 0.1D and move it in the transverse direction.

- Note down the readings from multitube manometer until the reference level (atmosphere).
- Repeat the experiment for axial distance of 3D and 6D.

Sample Calculations

Atmospheric Pressure, h = 760 mm of Hg
Density of mercury, ρ_m = 13600 kg/m3
P_a = ρmgh = 101396.16 Pa
Ambient Temperature, T = 29°C= 300.15 K
Density of air,ρ_a

$$\rho_a = \frac{P_a}{RT} = 1.177\ \frac{kg}{m^3}$$

Velocity in test section

Density of ethanol, ρ_e = 789 kg/m3
Manometric Inclination Angle, θ = 30°
Manometric Reference Height, h_ref = 27.3 cm
Calculation of velocity of flow in Test Section:

$$\mathrm{V} = \sqrt{\frac{2(\rho_{\mathrm{eth}}*g*(h_t-h_s)*sin(\theta))}{\rho\mathrm{a}}}$$

Pitot probe moving along the centre line

Density of ethanol, ρ_e = 789 kg/m3
Manometric Inclination Angle, θ = 30°
Manometric Reference Height, h_ref = 27.3 cm
Pitot head at a distance dx = 60mm along x-axis from the nozzle, $h_{stag,60}$ = 10.9 cm
Calculation of velocity of flow in Test Section:

$$V_x = \sqrt{\frac{2(\rho_{\mathrm{eth}}*g*(h_{ref}-h_{stag})*sin(\theta))}{\rho\mathrm{a}}}$$

$V_{x,60}$ = 38.33 m/s

Pitot probe at 0.1D moving across the centre line

Density of ethanol, ρ_e = 789 kg/m3
Manometric Inclination Angle, θ = 30°
Manometric Reference Height, h_ref = 27.3 cm
Pitot head at a distance r = 5 mm along y-axis at x/D = 0.1 from the nozzle, $h_{stag,4}$ = 20.9 cm
Calculation of velocity of flow in Test Section:

$$V_y = \sqrt{\frac{2(\rho_{\text{eth}} * g * (h_{ref} - h_{stag}) * sin(\theta))}{\rho \text{a}}}$$

$V_{y,5}$ = 14.9 m/s

Pitot probe at 3D moving across the centre line

Density of ethanol, ρ_e = 789 kg/m3
Manometric Inclination Angle, θ = 30°
Manometric Reference Height, $h_r ef$ = 27.3 cm
Pitot head at a distance r = 7 mm along y-axis at x/D = 3 from the nozzle, $h_{stag,}$ = 23.7 cm
Calculation of velocity of flow in Test Section:

$$V_y = \sqrt{\frac{2(\rho_{\text{eth}} * g * (h_{ref} - h_{stag}) * sin(\theta))}{\rho \text{a}}}$$

$V_{y,}$ = 8.42 m/s

Pitot probe at 6D moving across the centre line

Density of ethanol, ρ_e = 789 kg/m3
Manometric Inclination Angle, θ = 30°
Manometric Reference Height, $h_r ef$ = 27.3 cm
Pitot head at a distance r = 10 mm along y-axis at x/D = 6 from the nozzle, $h_{stag,10}$ = 25.4 cm
Calculation of velocity of flow in Test Section:

$$V_y = \sqrt{\frac{2(\rho_{\text{eth}} * g * (h_{ref} - h_{stag}) * sin(\theta))}{\rho \text{a}}}$$

$V_{y,10}$ = 4.44 m/s

Theoretical Prediction of Turbulent Jets

$\frac{V_{Centerline}}{V_0} = \frac{6.4 D_0}{x}$

where x is the axial distance along the jet. [1]

Mass Flux along the jet axis

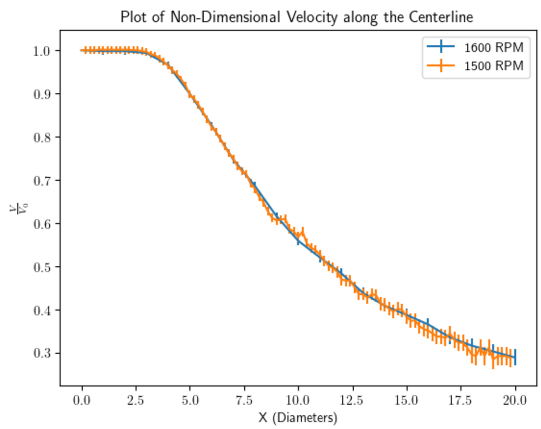
Density of air, ρ_a = 1.177 kg/m3
Kinematic viscosity ν = 15.7e-6 m2/s
According to Bickley jet similarity solution;
Theoretical Mass Flow Rate,

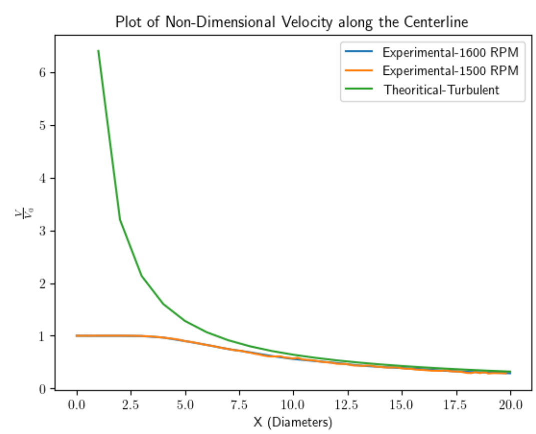
$$\text{Q} = 2\rho_a \cdot \int_0^\infty u\, dy = 3.3019(\text{M}\nu^3 \rho_a x)^{1/3}$$

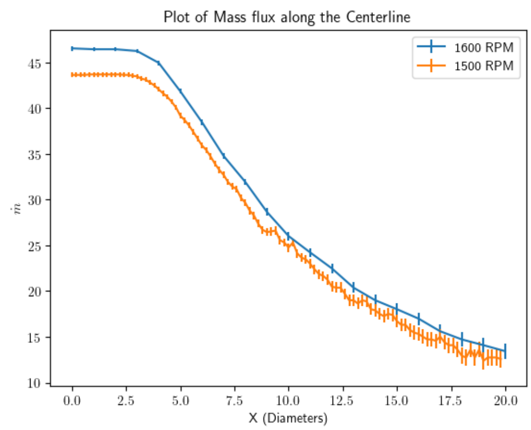
Discussions and Conclusions

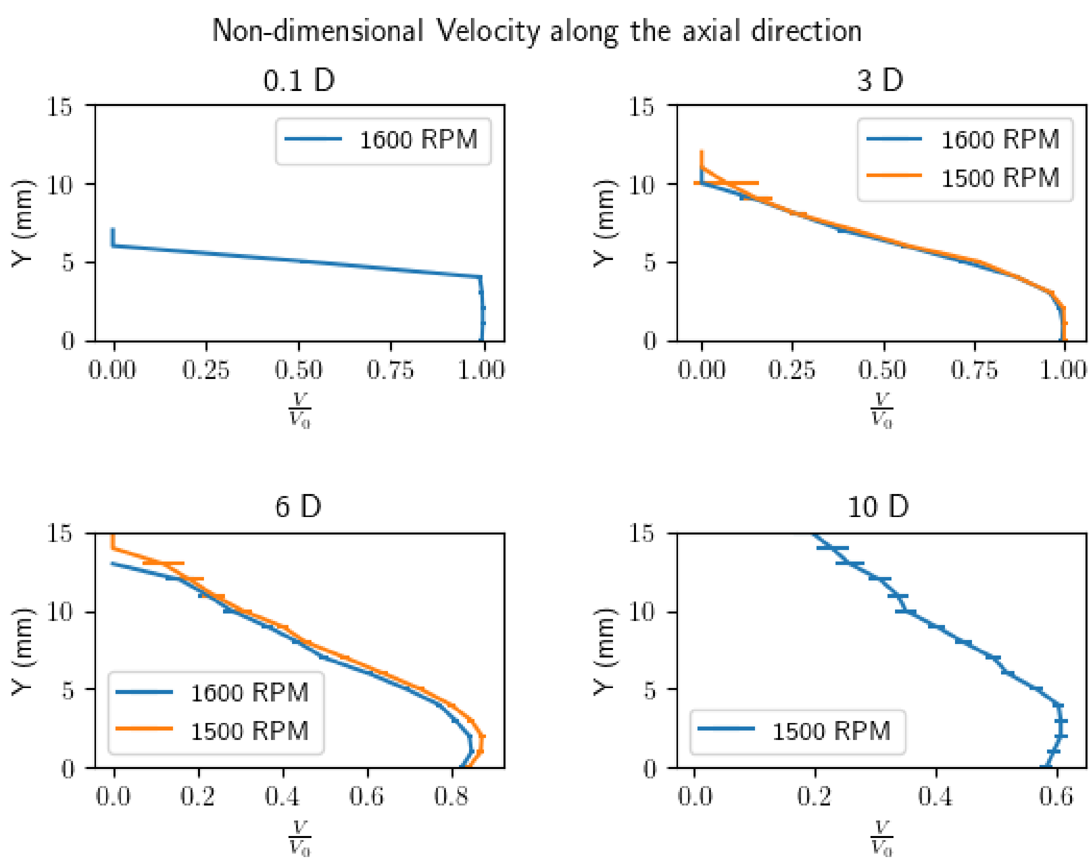
The jet boundary expands, causing a diffused velocity profile. Turbulence far downstream causes deviation from laminar solution and increased velocity radially outward. The mass flow rate differs by one order from experimental results due to high Reynolds numbers and also distance from origin.from the velocity plot. Developing region for the free jet can be deduced near to 40-45 mm as the velocity is almost constant here.

The following plots show us the required velocity profiles and mass flow rate. Error deviations are observed as bars in the graphs









Limitations

Theoretical analysis considers flow as 2D. Deviations from theoretical are due to 3D flow.

References

[1] Seo, Il Won, *Advanced Environmental Hydlaulics(River Mixing Theory)*