THE CHARACTERISTICS OF AIR FREE JET FLOWS

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"I hereby verify that I have read this report and I found it sufficient in terms of quality and scope to be awarded with the Bachelor's Degree in Mechanical Engineering (Thermal-Fluid)."

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"I hereby declare that the work is my own except for quotations and summaries which have been duly acknowledged."

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ABSTRACT

The main purpose of this research is to determine the characteristics of free jet flow. This research is experiment based which focuses on the measurements method. The design of the nozzle is determined by calculation using the formula based on isentropic flow concept. In general, there are two types of nozzle with different size will be used in the experiment with diameter of 19 mm and 23.5 mm. At the end of the experiment, parameters such as velocity, pressure, temperature, speed of sound and Mach number are determined. Several relationships on velocity, pressure, temperature, speed of sound and Mach number are determined by using the data obtained in the experiment together with initial inlet pressure. Most of the graphs plotted have the common shapes of linear and polynomial. Through the graphs, the parameters determined are found to be related to one another. For overall view, this research noticed that the nozzle designed able to produce a subsonic flow.

ABSTRAK

Tujuan utama kajian ini adalah untuk mengkaji ciri-ciri aliran jet bebas. Kajian yang dilakukan lebih menumpu kepada kaedah pengukuran. Bagi menentukan ciri-ciri aliran muncung yang sesuai, beberapa siri ujikaji telah dijalankan. Rekabentuk saiz muncung ditentukan melalui pengiraan dari formula berasaskan konsep aliran isentropik. Secara umumnya, terdapat dua jenis muncung yang berlainan saiz yang digunakan iaitu berdiameter 19 mm dan 23.5 mm. Parameter seperti halaju, tekanan, suhu, kelajuan (*speed of sound*) dan nombor Mach telah ditentukan pada akhir ujikaji ini. Beberapa hubungan seperti halaju, tekanan, suhu, kelajuan bunyi (*speed of sound*) dan nombor Mach terhadap tekanan masukan ditentukan dengan menggunakan data yang diperolehi dari ujikaji . Melalui graf yang diperolehi, didapati kebanyakan hubungan berbentuk garis lurus dan polinomial. Selain itu, melalui graf didapati bahawa parameter-parameter tersebut berhubungkait di antara satu sama lain. Secara keseluruhanya, kajian ini telah mendapati bahawa muncung yang digunakan telah menghasilkan aliran subsonik.

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LIST OF SYMBOLS

Symbols	**Definition**
P	Pressure
P_{atm}	Pressure Atmosphere
P_0, P_{inlet}	Inlet Pressure
P_1, P_{throat}	Throat Pressure
P_2, P_{outlet}	Outlet Pressure
T	Temperature
T_{atm}	Temperature Atmosphere
T_0, T_{inlet}	Inlet Temperature
T_1, T_{throat}	Throat Temperature
T_2, T_{outlet}	Outlet Temperature
A	Area
A_0	Inlet Area
A_1, A^*	Throat Area, Critical Area
A_2	Outlet Area
D	Diameter
D_0	Inlet Diameter
D_1	Throat Diameter
D_2	Outlet Diameter
V	Velocity
V_{throat}	Throat Velocity
V_{outlet}	Outlet Velocity
a	Speed of Sound
a_{throat}	Speed of sound at Throat

a_{outlet}	Speed of sound at Outlet
M	Mach number

Greek	**Definition**
ρ	Density
$\dot{m}$	Mass Flow Rate
γ	Ratio of Specific Heats

Chapter 1

INTRODUCTION

The title "Characteristics of air free jet flows" of this research includes the design of nozzle and the experimental setup. The design of nozzle for compressible flow is examined, where two types of nozzles are designed using different diameters. Experiments are conducted to determine the performance for each of the two nozzle design. The experiment consists of the calculation of the Mach number in the jets from each nozzle. The performance test is conducted to make sure the air pressure sprayed meets the requirements at optimum level.

Each design of nozzle produced jets with specific parameters such as pressure (*P*), temperature (*T*), velocity (*V*), speed of sound (*a*) and Mach number (*M*). The parameters are used to determine the flow level whether it is subsonic, sonic or supersonic flow and also the characteristics of the flow.

In subsonic flow conditions occur for Mach numbers less than one, $M < 1$. The Mach number, (*M*) is defined as the ratio of the local flow speed (*V*) to the local speed of sound (*a*). For the lowest subsonic conditions, compressibility can be ignored.

As the speed of the object approaches the speed of sound, the Mach number is nearly equal to one, M = 1 and the flow is said to be transonic. At the some places on the object, the local speed exceeds the speed of sound. Compressibility effects are most important in transonic flows and lead to the early belief in a sound barrier. In fact, the sound barrier was only an increase in the drag near sonic conditions.

Supersonic conditions occur for Mach number greater than one, M > 1. Compressibility effects are important for supersonic aircraft and shock waves are generated by the surface of the object. It is thus a dimensionless quantity. In general, both V and a are functions of position and time, so that the Mach number is not just the flow speed made no dimensional by dividing by a constant. A flow for which the Mach number is greater than unity is termed as supersonic flow for which $V > a$. This means that the upstream flow remains unaffected by changes in conditions at a given point in a flow field. Normally the supersonic flow used at rocket engines, aircraft and etc.

There have been no in depth research that focuses on the characteristics mentioned above.

1.1 Background of Study

Free jet flows occur in a number of practical engineering systems and the operating conditions have a major influence on the jet mixing with the atmosphere. The geometry of the nozzles producing the jets is also of importance. This study covers the design of the nozzle, and speed limit for various nozzle diameters.

1.2 Problem of Statement

There have been no in depth research that focuses on the characteristics for air free jet flow. The main aim of this study is to determine the answer for the question arises during the execution of the experiment. The questions are as follows:

a) How to describe the flow in a nozzle for different diameter?
b) How to design nozzles to produce jets with specific characteristics such as pressure (*P*), temperature (*T*), velocity (*V*), Mach number (*M*) and speed of sound (*a*) ?
c) How to set up experimental facilities to investigate jets flows over a range of operating conditions?

1.3 Objective of Study

The main interest of this study is to collect of data and its analysis for a range of initial jet conditions. Experiments are conducted using the designated apparatus and to design of nozzle. The main objectives of the study are as follows:

a) To design nozzles to produce jets with specific characteristics.
b) To gain sufficient information to be able to predict jet flows.
c) To ensure the type of flow whether it is subsonic, sonic or supersonic flow for the nozzles.

1.4 Scope of Study

The scopes of this study are as follows:

a) Focusing on air parameters for free jet flows.
b) Experimental facilities are set up to investigate jet flows over a range of operating conditions.
c) Characteristics of jet flows are determined using the experimental methods in air free jet flows.

1.5 Benefit of Study

Nozzle is an important part in industry especially in manufacturing, aircraft and ship. Thus, the efficiency of the nozzle plays an important role in developing an industry. Below are the benefits gained from the research being carried out:

a) Through the research, the suitable diameter of the nozzle can be obtained for cutting smooth surface. This dimension can be used as a guideline in plasma arc cutting using supersonic under-expanded air plasma jet.
b) This research can also be used as a guideline to improve abrasive jet machining where which diameter is best suited to obtain smooth surface finish.

Chapter 2

LITERATURE REVIEW AND THEORY

2.1 Literature Review

Normally, we are mainly concerned with flows that are slow enough that they may be treated as incompressible. We now consider flows in which the velocity approaches or even exceeds the speed of sound and in which density changes along streamlines cannot be ignored. Such flows are common in aeronautics and astrophysics. For example, the motion of a rocket through the atmosphere is faster than the speed of sound in air. In other words, it is basic concept of supersonic study. Therefore, if we transform into the frame of the rocket, the flow of air past the rocket is also a type of free jet but in supersonic condition.

When the flow speed exceeds the speed of sound in some reference frame, it is not possible for a pressure pulse to travel upstream in that frame and change the direction of the flow. However, if there is a solid body in the way (e.g. a rocket or aircraft), the flow direction must change.

There have been many studies for the nozzle and characteristics of free jet flow. One of the studies had been conducted by A. Mohamad and A. Hamed (2003) to investigate on supersonic jets from convergent divergent nozzles with rectangular cross section experimentally. The purpose is to test the jet spread rate at different nozzle pressure ratio. From experiment, the results indicate that the rectangular supersonic jet spread rate is greater along the minor axis and increases with the nozzle pressure ratio.

Schlieren photographs are presented for over-expanded rectangular jets in quiescent atmosphere to show the effect of nozzle pressure ratio on the shock structure and jet mixing. The results indicate that the mixing rate is high along the jet's minor axis at the higher nozzle pressure ratios, but decreases as the nozzle pressure ratio is reduced. In over-expanded rectangular particle-laden jets, the shock strength was found to decrease as the nozzle pressure ratio was reduced.

Design and evaluation of high pressure fuel valve nozzles using the method of characteristics and CFD was studied by Sangwon, Charles and Allan (2003). The study is about the design fuel valve nozzles for natural gas engines that maximize the kinetic energy and momentum of the injected fuel and maintain a required mass flow rate. The nozzle design uses both the method of characteristics and computational fluid dynamics (CFD). Three types of nozzles were designed: a converging-diverging nozzle, three conical nozzles and an aero spike nozzle.

For the design and off-design conditions, the converging-diverging nozzle shows the best performance. The average axial momentum for the converging-diverging nozzle is about 24% higher than the straight shrouded valve under all conditions. For all nozzles mean momentum values are shifted upward about 3% for the start of injection condition relative to design and down about 3% at end of injection Computational results for the average axial momentum per unit fuel mass are summarized in Table 2.1, with performance evaluated relative to the straight shrouded valve.

	On-design		**SOI**		**EOI**	
	$\bar{V}_x$	%	$\bar{V}_x$	%	$\bar{V}_x$	%
Conv-div	776	24.5	792	23.3	755	25.2
conical	768	23.3	788	22.7	745	23.5
aerospike	737	18.3	755	17.6	716	18.7
shrouded	623	0	642	0	603	0
w/ retainer	607	-2.6	631	-1.7	579	-4.0

$\bar{V}_x$ (m/s)

Table 2.1 : Average axial momentum per unit fuel mass

Another study had been carried out by K. A. Phalnikar, F. S. Alvi, et.al (2001). on the behavior of free and impinging supersonic microjets including supersonic microjets in the range of 100 - 400 microns with exit velocities in the range of 400- 500 m/s. Such microjets are used to actively control larger supersonic impinging jets. The flow field was visualized using a Micro-Schlieren system with effective magnifications greater than 100x Schlieren images, which to the best of our knowledge have never been obtained at this scale, clearly show the characteristic shock cell structure can be observed in large-scale jets. Based on these images, the jet is clearly supersonic as far as 10-12 diameters downstream. Quantitative measurements providing jet decay and spreading rates as well as shock cell spacing are also obtained via pressure surveys using micro-pitot probes.

Flow visualization was mainly carried out to provide a global view of the overall flow field and to allow for a comparison of the microjet flow field to macroscale supersonic under expanded jets. A summary of the flow visualization test cases is provided in Table 2.2 for the 200 and 400 mm nozzles. Due to viscous losses between the plenum and the nozzle exit, the total pressures at the nozzle exit are necessarily lower than the plenum pressures. The total pressures at the nozzle exit corresponding to each plenum pressure are shown in the table. Also listed in this table is the corresponding Nozzle Pressure Ratio, NPR, the ratio of total pressure at the nozzle exit to ambient pressure: $P_o / P_{ambient}$, M_j, the fully expanded jet Mach number and the Reynolds number based on the nozzle exit diameter.

Nozzle Size (μm)	P_{plenum} (psia)	$P_{0,exit}$ (psia)	NPR	M_j	Re_d
200	60	56.4	3.83	1.53	11750
200	80	76.9	5.23	1.74	15700
200	100	92.2	6.27	1.86	19600
200	120	107.4	7.3	1.96	23500
400	60	50.4	3.42	1.45	23500
400	80	67.2	4.57	1.65	31000
400	100	83.8	5.7	1.8	40000
400	120	97.5	6.63	1.89	47000

Table 2.2 : Test cases for microjet characterization

The study of under expanded sonic jet by K. Bulent Yuceil, et.al (2001). is about the near field velocity structure by using a digital PIV technique. The two main motivations were to investigate the applicability of the PIV technique to supersonic jet flows and to provide some basic velocity information on the near field of these jets. The PIV technique along with the particles used in this study can indeed provide important information on the general structure of these jets and allow for some comparisons. However, particularly in the case of highly-under expanded jets, the sudden and essentially discontinuous change in velocity across shock waves cannot be qualitatively measured by the PIV or, for that matter, any laser technique that relies on large particle (Mie) scattering.

Velocity measurements in the initial jet region covering a stream-wise distance of up to x/D=8 are presented. The measurements were made for 5 different chamber pressures with the same sonic nozzle. The conditions for each jet studied are summarized in Table 2.3.

	P_o (kPa)	T_o (K)	P_e (kPa)	T_e (K)	P_o/P_a	P_e/P_a	M_j
Jet 1	191.50	282	101.33	235	1.89	1	1
Jet 2	483.32	282	255.73	235	4.77	2.52	1.68
Jet 3	1444.90	282	764.50	235	14.26	7.55	2.28
Jet 4	2974.90	282	1574.02	235	29.36	15.53	2.85
Jet 5	3891.89	282	2059.20	235	38.41	20.32	3.03

Table 2.3 : Summary of experimental conditions

A supersonic gas injector for fueling and diagnostic application on the National Spherical Torus Experiment was studied by V.A. Soukhanovskii, H.W.Kugel, et.al (2004). The purpose was to explore the compatibility of the supersonic gas jet fueling with the H-mode plasma edge, edge localized mode control, edge magneto hydrodynamic stability, radio frequency heating scenarios, and start-up scenarios with a fast plasma density ramp up. Calculation for nozzle design will be emphasized for the following part. The supersonic jet velocity is $u=Mc=M\sqrt{\gamma KT/m}$ where M is a Mach number, c is a local speed of sound, and γ is the specific heat ratio. The static temperature T in a compressible flow, however, is reduced according to $T/To = \left(1+(\gamma-1)M^2/2\right)^{-1}$, where T_0 is the stagnation temperature, so that the terminal velocity is $u_{\max} = \sqrt{2\gamma kT_0/(m(\gamma-1))}$.

As a summary, a prototype pulsed supersonic gas injector is developed for fueling and diagnostic applications on NSTX. The prototype SGI is built for off-line optimization work. The goal of the characterization experiments is to measure the gas injection velocity. A local Mach number is obtained under the assumption of isentropicity from the Rayleigh-pitot law using the pressure measurements upstream and downstream the shock formed at the transducer immersed in the flow. The impact (stagnation) pressure P_i is measured on axis and the flow static pressure P_o is measured in the SGI plenum. The SGI ultilizes a contoured Laval nozzle with the measured Mach number 4 for a range of plenum pressures, a well defined density profile and the divergence half angle of 6^oC. The prototype SGI rate is up 120 Torr l/s. Based on the high density and collimation of the supersonic jet and the expected higher penctration into the plasma edge, several plasma diagnostic applications that ultilize conventional gas injectors can be much improved.