Experimental Investigations of The Influence of Reynolds Number and Boundary Conditions on a Plane Air Jet

by

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Originality Statement

I, Ravinesh C. DEO, hereby declare that this thesis, titled "Experimental Investigations of the Influence of Reynolds Number and Boundary Conditions on a Plane Air Jet", submitted for the award of a Doctor of Philosophy in Engineering at The University of Adelaide, is original in every respect. It contains no material which has been accepted for the award of any other degree or diploma in any university. Further to the best of my knowledge and belief, this Ph.D. thesis contains no material previously published or written by another person, except where due reference is made in the thesis.

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Abstract

A plane jet is a statistically two-dimensional flow, with the dominant flow in the streamwise (x) direction, spread in the lateral (y) direction and zero entrainment in the spanwise (z) direction respectively (see Figure 1). A plane jet has several industrial applications, mostly in engineering environments, although seldom is a jet issuing through a smooth contoured nozzle encountered in real life. Notably, the Reynolds number and boundary conditions between industrial and laboratory environments are different. In view of these, it is important to establish effects of nozzle boundary conditions as well as the influence of Reynolds number, on jet development. Such establishments are essential to gain an insight into their mixing field, particularly relevant to engineering applications. To satisfy this need, this thesis examines the influence of boundary conditions, especially those associated with the formation of the jet and jet exit Reynolds number, on the flow field of a turbulent plane air jet by measuring velocity with a hot wire anemometer. A systematic variation is performed, of the Reynolds number Re over the range $1{,}500 \leq Re \leq 16{,}500$, the inner-wall nozzle contraction profile r^* over the range $0 \leq r^* \leq 3.60$ and nozzle aspect ratio AR over the range $15 \leq AR \leq 72$ (see notation for symbols). An independent assessment of the effect of sidewalls on a plane jet is also performed. Key outcomes are as follows:

(1) *Effects of Reynolds number Re*

Both the mean and turbulence fields show significant dependence on Re. The normalized initial mean velocity and turbulence intensity profiles are Re-dependent. An increase in the thickness of boundary layer at the nozzle lip with a decrease in Re is evident. This dependence appears to become negligible for $Re \geq 10{,}000$. The centerline mean velocity decay and jet spreading rates are found to decrease as Re is increased. Furthermore, the mean velocity field appears to remain sensitive to Reynolds number at $Re = 16{,}500$. Unlike the mean velocity field, the turbulent velocity field has a negligible Re-dependence for $Re \geq 10{,}000$. An increase in Reynolds number leads to an increase in the entrainment rate in the near field but a reduced rate in the far field. The centerline skewness and the flatness factors show a systematic dependence on Reynolds number too.

(2) *Effects of the inner-wall nozzle exit contraction profile r^**

The inner-wall nozzle exit contraction profile r^* influences the initial velocity and turbulence intensity profiles. Saddle-backed mean velocity profiles are evident for the sharp-edged orifice configuration ($r^* \simeq 0$) and top hat profiles emerge when $r^* \geq 1.80$. As r^* is increased from 0 to 3.60, both the near and the far field decay and the spreading rates of the plane jet are found to decrease. Hence, the sharp-edged orifice-jet ($r^* \simeq 0$) decays and spreads more rapidly than the jet through a radially contoured configuration ($r^* \simeq 3.60$). The asymptotic values of the centerline turbulence intensity, skewness and flatness factors of the velocity fluctuations increase as r^* tends toward zero. The non-dimensional vortex shedding frequency of $St_H \simeq 0.39$, is higher for the sharp-edged orifice nozzle ($r^* \simeq 0$), than for the radially contoured ($r^* \simeq 3.60$) nozzle whose $St_H \simeq 0.24$. Thus, the vortex shedding should be strongly dependent on flow geometry and on nozzle boundary conditions.

(3) *Effects of nozzle aspect ratio AR*

The initial velocity and turbulence intensity profiles are slightly dependent on nozzle aspect ratio of the plane air jet. It is believed that a coupled influence of the nozzle aspect ratio and sidewalls produce changes in the initial flow field. The axial extent over which a statistically 'two-dimensional' flow is achieved, is found to depend upon nozzle aspect ratio. This could be possibly due to the influence of the evolving boundary layer on the sidewalls or due to increased three-dimensionality, whose influence becomes significantly larger as nozzle aspect ratio is reduced. A statistically two dimensional flow is only achieved over a very limited extent for $AR = 15$. In the self-similar region, the rates of centreline velocity decay, spreading of the mean velocity field and jet entrainment increase with an increase in nozzle aspect ratio. An estimate of the 'critical' jet aspect ratio, where three-dimensional effects first emerge and its axial location is made. Results show that the critical aspect ratio increases with nozzle aspect ratio up to $AR < 30$. For $AR \geq 30$, the critical aspect ratio based on jet half width, attains a constant value of about 0.15. Thus, it appears that when the width of the flow approximately equals the spacing between the sidewalls, the plane air jet undergoes a transition from 2-D to 3-D. A distinct hump of the locally normalized turbulence intensity at an axial distance between 10 to 12 nozzle widths downstream, characterizes the centerline turbulence intensity for all nozzle aspect ratios. This hump is smaller when nozzle aspect ratio is larger.

(4) *Effects of the sidewalls*

A jet issuing from a nozzle of $AR = 60$ and measured at $Re = 7{,}000$ is tested with sidewalls, i.e. plane-jet and without sidewalls, i.e. free-rectangular-jet. It is found that the entire flow field behaves differently for the two cases. The initial velocity profiles are top hat for both jets. The free rectangular jet decays and spreads more rapidly in both the near and far field. It is found that the free rectangular jet behaves statistically two-dimensional up to a shorter axial distance ($x/H = 70$) as opposed to the plane jet whose two-dimensional region extends up to $x/H = 160$. Also noted are that the axial extent of the two-dimensional region depends strongly on nozzle aspect ratio. Beyond the 2-D region, the free rectangular jet tends to behave, statistically, like a round jet. The locally normalized centerline turbulence intensity also depend on sidewalls. Turbulence intensity for the plane jet asymptotes closer to the nozzle (around $x/H = 30$) whereas for the free rectangular jet, turbulence intensity varies as far downstream as $x/H = 100$, and then asymptotes. A constant St_H of 0.36 is found for the free rectangular jet whereas an St_H of 0.22 is obtained for the plane jet.

It is noted that the effects of jet exit Reynolds number, inner-wall nozzle exit contraction profile, nozzle aspect ratio and sidewalls on the plane air jet are all non-negligible. The effect of viscosity is expected to weaken with increased Reynolds number and this may contribute to the downstream effects on the velocity field. Both the nozzle contraction profile and nozzle aspect ratio provide different exit boundaries for the jet. Such boundary conditions not only govern the formation of the initial jet but also its downstream flow properties. Hence, the initial growth of the shear layers and the structures within these layers are likely to evolve differently with different boundary conditions. Thus, the interaction of the large-scale structures with the surroundings seems to depend on nozzle boundary conditions and consequently, influences the downstream flow. In summary, the present study supports the notion that the near and far fields of the plane jet are strongly dependent on Reynolds number and boundary conditions. Therefore, the present thesis contains immensely useful information that will be helpful for laboratory-based engineers in selection of appropriate nozzle configurations for industrial applications.

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…Thankyou My Lord…

To

My Loving Parents

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For Their Blessings & Inheritance

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And

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For Her Love, Sacrifice & Encouragement

Towards my PhD

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On this landmark day, I acknowledge and remember three most important people in my life. Their contributions towards my Ph.D. are worthy of very special and humble thanks and remembrance. They are my loving **mum** and **dad** and my dear wife **Aruna**. My **parents**, **Mr and Mrs Bisun Deo**, deserve the highest level of respect for their benediction towards my achievement, endurance in educating me and for providing me the inheritance to be the first professional doctorate in our family. Indeed this Ph.D. is a dream they have visualized through me and I thank them for their sacrifice, prayers and blessings.

It is impossible for me to quantify the amount of support provided by my **wife**, **Aruna** on every stage of my career. Her words of encouragement, enthusiasm and advice still beeps in my ears, especially those which convinced me not to quit! The strength of her determination that I will be able to complete this huge task was a driving force behind my success. She sacrificed a large portion of her own career, luxury and indeed her invaluable time towards my doctorate. *It is to my parents and my wife that I dedicate my entire thesis.*

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Vita

Born in a remote village of Naleba in the township of Labasa, Fiji Islands, Ravinesh gained his primary education at Naleba Bhartiya School from Classes 1-6 and junior secondary education at Naleba College from Forms 1-4. He undertook high school education from Forms 5-7 at Labasa College. He was the High School 'Dux' (Best High School academic student) in 1995, for achieving the highest standards in Mathematics, Biology, Chemistry and Physics. During this year, he broke the *Year 13 National Examination* (Fiji Seventh Form Examination) **ALL-TIME** record, by scoring the highest mark of 360/400 for the *first* time in the Fiji. His exam results created a new record of 97 % in Physics and 96 % in Chemistry.

Ravinesh completed his BSc in 1998, with subject majors, Physics and Mathematics from University of the South Pacific in Fiji. He was awarded the University Gold Medal and Motibhai Prize for being the outstanding Physics student. Overall, his GPA was at the High Distinction level (4.4/4.5). He continued for further education, to pursue an MSc in Meteorological Physics at University of Canterbury, New Zealand. He completed his masters successfully in May 2001, with degree awarded (with Honors) in July 2001. From August 2001 - April 2005, Ravinesh worked on his PhD project, within the Turbulence, Energy and Combustion [TEC] Group, School of Mechanical Engineering, University of Adelaide.

This doctoral dissertation was officially submitted on 07 June 2005. The Adelaide Graduate Center officially confirmed the award of a PhD (subject to minor amendations satisfactory to the supervisors) on 22 August 2005. Ravinesh now works as an Associate

Lecturer in Physics at University of the South Pacific in Fiji. His interest in fluid mechanics continues, and he hopes to pursue a post-doctoral, subject to career opportunity.

Nomenclature

0.1 Acronyms

H	length of the short side of nozzle
w	length of the long side of the nozzle
r	contraction radius of the nozzle profile
AR	nozzle aspect ratio, where $AR = w/H$
r^*	contraction ratio of the nozzle profile, where $r^* = r/H$
l_w	length of the hot-wire sensor
d_w	diameter of the hot-wire sensor
$U_{o,b}$	bulk mean velocity
$U_{o,c}$	exit centerline mean velocity
U_c	local centerline mean velocity
$U_{m,c}$	centerline mean velocity maximum
$U_{ic,m}$	centerline instantaneous velocity maximum
U	mean velocity along lateral (y) direction
U_i	instantaneous velocity
U_n	normalized mean velocity, where $U_n = U/U_c$
$U_{n,c}$	normalized centerline mean velocity, where $U_{n,c} = U_c/U_{o,c}$
U_{co}	co-flow mean velocity
Re	Reynolds number defined by $Re = U_{o,c}\, H \;/\; \nu$
u	fluctuating component in the streamwise (x) direction, $u = U_i$ - U_c
$u^{'}$	root-mean-square (rms) of u, such that $u^{'} = (< u^2 >)^{1/2}$
$u^{'}_c$	centerline rms, such that $u^{'}_c = (< u^2_c >)^{1/2}$
$u^{'}_n$	normalized rms (turbulence intensity), where $u^{'}_n = u^{'}/U_c$
$u^{'}_{n,c}$	normalized centerline rms, (centerline turbulence intensity), where $u^{'}_{n,c} = u^{'}_c/U_c$
$u^{'}_{c,\infty}$	asymptotic value of centerline turbulence intensity
$u^{'}_{c,max}$	magnitude of the local maximum of turbulence intensity
S_u	centerline skewness factor, where $S_u = < u^3 > /(< u^2 >)^{3/2}$
F_u	centerline flatness factor, where $F_u = < u^4 > /(< u^2 >)^2$

$S_u^{c,\infty}$ asymptotic value of centerline skewness factor

S_u^{min} minimum value of centerline skewness factor

S_u^{max} maximum value of centerline skewness factor

$F_u^{c,\infty}$ asymptotic value of centerline flatness factor

F_u^{min} minimum value of centerline flatness factor

F_u^{max} maximum value of centerline flatness factor

x_p jet potential core length

$y_{0.5}$ velocity half-width of the jet, i.e. the y-location from the centerline, where $U = \frac{1}{2}U_c$

K_u decay rate of normalized centerline mean velocity

K_y jet spreading rate

d internal diameter of a round nozzle

x_{01} virtual origin from the normalized mean centerline velocity

x_{02} virtual origin from the normalized velocity half-widths

x_m downstream distance at which a hump in turbulence intensity occurs

$x_{m,\infty}$ downstream distance at which the asymptotic value of turbulence intensity occurs

$x_{p,\,\max}$ maximum downstream distance up to which the flow is planar

y'_{05}/w characteristic jet aspect ratio, where $y'_{0.5}$ is the velocity-half widths at $x_{p,\,\max}$.

R_o adjustable overheat resistance of the CTA

R_T total resistance of the sensor and cables

A_R laboratory room area in the same plane as the nozzle opening width H

A_n nozzle area

H_R height of room

H_j height from the bottom of room up to the nozzle

ΔT time constant of the CTA system

f_c optimum cut-off frequency of the CTA system

v fluctuating component in the spanwise (y) direction, $v = V_i$ - V_c

w fluctuating component in the transverse (z) direction, $w = W_i$ - W_c

q turbulence kinetic energy, defined by $q = \frac{1}{2}(u^2 + v^2 + w^2)$

$q_{c,\infty}$ far-field turbulent kinetic energy

St_H Strouhal number for a plane jet, defined by $St_H = f\,H/U_{o,b}$

St_p Strouhal number for a round jet, defined by $St_p = f_p\,D/U_{o,b}$

m mass flux at any axial distance downstream from the nozzle exit

D geometric diameter of a round nozzle

D_e equivalent diameter of a round nozzle with the same exit area as a rectangular nozzle, where $D_e \simeq 1.13\,AR^{0.5}\,H$

0.2 Greek Symbols

ν kinematic viscosity of air, $\nu \simeq 1.47 \times 10^{-5}\ m^3 s^{-1}$ at 25^o ambient conditions

α overheat ratio of CTA system, usually $\simeq 1.8$

δ thickness of the boundary layer at the nozzle lip, $\delta \simeq \int\limits_{y=0}^{y=\infty} (1 - {}^{U}/_{U_{o,c}})\ dy$

ϕ_u power spectrum of u where $\int \phi_u(f)\ df = \overline{u^2}$

ϵ kinetic energy dissipation term, $\varepsilon \simeq 15\upsilon \left\langle ({}^{du}/_{dx})^2 \right\rangle$

τ_w viscous stress term, $\left(\tau_w = \rho\nu \frac{\partial U}{\partial y}\right)$

ρ density of test medium, for air $\rho \simeq 1.2\ kg\, m^{-3}$ at 25^o ambient conditions

0.3 Some Special Terms

(1) Nozzle profile factor: denoted as r^* and defined by r/H.

(2) Plane jet: a jet which issues through a rectangular nozzle with sidewalls.

(3) Quasi-plane jet: a jet which issues through a large aspect ratio rectangular nozzle but no sidewalls.

(4) Round jet: a jet that issues through a round nozzle.

(5) Pipe jet: a jet through a long pipe.

0.4 Coordinate System

x axial (streamwise) coordinate

y lateral (transverse) coordinate

z spanwise coordinate

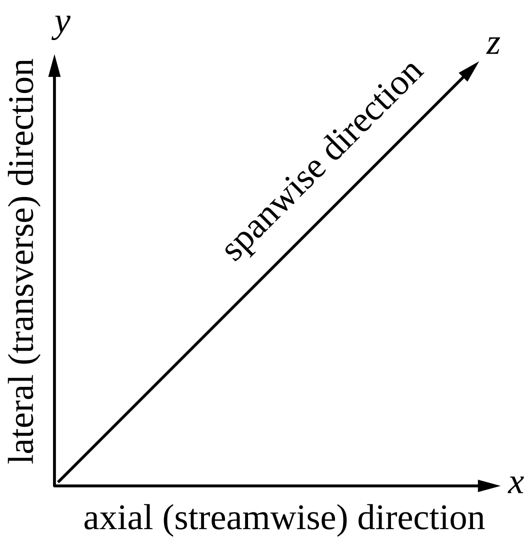

Figure 1: The coordinate system used in the present study.