SCHOOL OF MECHANICAL ENGINEERING

THE EVOLUTION OF THE NEAR FIELD OF A PRECESSING JET FLOW

Kimberley Christina Clayfield

PhD Thesis

2004

Dedicated to my parents

Rita & Peter Ewen and Jim Clayfield,

for their love and support,

and to my sister Jennie,

whose fearlessness inspires me.

It is never wise to turn aside from knowing,

however the knowing comes.

“The Hollow Hills”

Mary Stewart

Contents

Table of Contents

Abbreviations

Acronym	*Description*
FPJ	Fluidic precessing jet
JICF	Jet in cross-flow
LDA	Laser Doppler anemometry
MPJ	Mechanical precessing jet
PIV	Particle image velocimetry
PLIF	Planar laser-induced fluorescence

Roman Symbols

Symbol	*Description*	*Units*
C_{cl}	Centreline concentration	
C_0	Exit concentration	
D	Nozzle diameter	mm
D_m	Molecular diffusivity	
d_τ	Diffraction limited particle image diameter	m
d_{diff}	Diffraction limited minimum image diameter	m
d_p	Particle diameter	m
e_{bias}	Vorticity bias error	
e_{random}	Vorticity random error	
$f_\#$	Camera f-number	
f_p, f	Frequency of precession	Hz
K_c	Concentration decay coefficient	
K_v	Velocity decay coefficient	
M	Magnification	
ND	Neutral density level	
R	Ratio of jet velocity to cross-flow velocity	
Re	Reynolds number	

Symbol	*Description*	*Units*
R_C	Distance between vortex cores	
r	Radial component	
r*	Spanwise component perpendicular to direction of α	
Sc	Schmidt number	
St	Strouhal number of precession	
s	Total streamwise arc length	
T	Transmittance	
t	Time	s
U_{cf}	Cross-flow velocity	ms^{-1}
U_{cl}	Centreline velocity	ms^{-1}
U_{conv}	Vortex convection velocity	ms^{-1}
U_{rx}	Total velocity in r-x plane	ms^{-1}
U_0	Exit velocity	ms^{-1}
U_Φ	Tangential velocity	ms^{-1}
x	Axial component	
x*	Streamwise component in direction of α	
x_0	Distance from jet virtual origin to nozzle exit	
x_{PC}	Distance from nozzle exit to end of potential core	

Greek Symbols

Symbol	*Description*	*Units*
α	MPJ jet exit angle (angle from vertical)	degrees
Γ_1	Circulation of one vortex of a counter-rotating vortex pair	
Δ	Velocity sampling separation	
δ	Characteristic length scale of flow	m
δ_z	Depth of field	m
ε	Strain	

Symbol	*Description*	*Units*
λ	Wavelength	m
λ_0	Ratio of random vorticity error to random velocity error	
λ_B	Batchelor scale	m
λ_K	Kolmogorov scale	m
ν	Kinematic viscosity	m^2s^{-1}
Φ	Phase angle	degrees
	Azimuthal (tangential) component	
χ	Scalar dissipation rate	
ω	Angular velocity	$rad.s^{-1}$
ω_z	Vorticity	s^{-1}

Figures

Tables

Abstract

Research into the fluidic precessing jet, used in industrial burners, has been carried out within the School of Mechanical Engineering at the University of Adelaide for over a decade. The flow field generated by the fluidic precessing jet (FPJ) is extremely complex, and there are many questions yet to be answered about the mechanisms by which precession influences the mixing of the jet and ambient fluid, and hence combustion. Some may be answered by studying a non-reacting precessing jet. The mechanical precessing jet (MPJ) nozzle generates a precessing jet for which the exit conditions are well known, unlike the fluidic precessing jet. The non-reacting flow from this ‘mechanical analogue’ of the FPJ forms the basis of the current study.

The MPJ provides a means of controlling and changing the structure of turbulence in a precessing jet by varying its precessional frequency. The characteristics of the MPJ flow are primarily determined by a Strouhal number of precession, and may be categorised as belonging to either a ‘low Strouhal number’ or ‘high Strouhal number’ regime of behaviour.

The fundamental aim of studying the mechanical precessing jet flow is to determine the influence of the structure of turbulent motions, and in particular the large scale motions, on jet mixing. The analyses presented in this thesis lead to a better understanding of the underlying mechanisms of precession-enhanced turbulent mixing and combustion.

Simultaneously collected phase-averaged velocity and concentration fields of the MPJ flow are presented, and correlations between the fields analysed, for one low and one high Strouhal number. Additionally, because the turbulent flow produced by the MPJ nozzle is unsteady in nature and instantaneous realisations of the flow may differ significantly from the mean flow patterns, planar velocity and concentration measurements which show instantaneous flow structure over the entire field are presented.

The phase-averaged velocity and concentration field data have enabled new analytical models of the MPJ trajectory to be developed, and the behaviour of the major flow features, including the stability of the counter-rotating vortex pair, to be studied. The strong entrainment and mixing characteristics of the MPJ flow are also illustrated.

The data and analysis strongly suggest that the initial trajectory of the jet is essentially radial, during which the jet experiences axial compression. At larger radius the jet experiences axial stretching. A counter-rotating vortex pair is seen to form approximately two potential core lengths from the jet exit, where the jet appears to bend sharply towards the axis of rotation. These vortices dominate the jet motion in the near field and eventually merge in the transition region of the flow. The inner vortex of the counter-rotating vortex pair mixes at approximately half the rate of the outer vortex, thus delivering a rich fuel mixture to the transition region when the MPJ is used as a burner. This may explain in part earlier observations of highly radiant, fuel-rich flames in the transition region.

This study also outlines the development of an experimental technique for the simultaneous measurement of velocity and concentration in a plane. The medium is air, and the technique combines Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) of acetone vapour in a unique manner.

Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

Kimberley Christina Clayfield

Acknowledgments

My most heartfelt thanks to

Dr Richard Kelso
who was always there when it mattered;

Dr Gerald Schneider
for his guidance, advice, compassion and support; and for giving me the gift of the AIAA Student Branch – the beginning of a fantastic journey;

Chong Yau Wong
my partner in crime, who taught me, encouraged me, and kept me going when I wanted to stop. I couldn't have done it without you!

Julie-Ann Reppel, Paul Medwell, Karel Meeuwissen and Owen Lucas
my fellow lab-users, for giving their time and assistance so generously and willingly;

Dr Zeyad 'Are You Lucky?' Alwahabi and A/Prof Graham 'Gus' Nathan
for their invaluable advice and technical support;

Rachael Matthews and Matthew Tetlow
for keeping me sane. You were the best friends a postgraduate student could hope for!

Billy Constantine
computing officer and saviour – where would I be without you?

and finally
the magicians known as the workshop staff and electronics technicians in the Schools of Mechanical and Chemical Engineering, and the members of the Turbulence, Energy and Combustion research group, for the support provided throughout my time as a postgraduate student.