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by

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The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance of this thesis for the fulfillment of the requirements for the degree stated.

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EMISHAW DANDENA IFFA

A Thesis
Submitted to the Postgraduate Studies Programme
as a Requirement for the Degree of

DOCTOR OF PHILOSOPHY

MECHANICAL ENGINEERING DEPARTMENT

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR,

PERAK

May, 2011

DECLARATION OF THESIS

Title of thesis	QUANTITATIVE SCHLIEREN MEASUREMENT OF 3 DIMENSIONAL TEMPERATURE, CONCENTRATION AND VELOCITY FIELDS IN A GAS FLOW

I, ____________ EMISHAW DANDENA IFFA ____________

hereby declare that this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Teknologi PETRONAS or other institutions.

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ACKNOWLEDGEMENTS

I am eternally grateful for all the wonderful things God has given me and showed me during this study. He was my strength and hope during the difficult times.

I owe my deepest gratitude to my supervisor, AP. Dr. A. Rashid A. Aziz, whose encouragement, guidance and support from the initial to the final level of this research work. I am also very much thankful for his crucial comments and guidance in shaping and improving this dissertation.

I am heartily thankful to My Co- Supervisor, Dr. Aamir Saeed Malik, for making his support available throughout this research work.

I would like to thank Prof. Morgan R. Heikal of University of Brighton for his guidance at several stages of this project and during developing this dissertation.

It is my pleasure to thank members of Postgraduate Office and Department of Mechanical Engineering for their support by offering me Graduate Assistantship and providing laboratory facilities.

I am indebted to all of my colleagues in Center for Automotive Research (CAR) for their extended support while conducting experiments.

I extend my sincere thanks to Yohaness Tamirat, Ftwi Yohannes, Salahdin El-Sakin, Firmansyah, Benyam Seyoum, Mui' Nuddin Bin Moharun, Noraz Al-Khari Bin Noran, Dr. Umesh Deshanavar, Kahirul Anwar Ahmed, Janni Alang Ahmed and Zailan Alang Ahmed for their support and kind assistance.

Finally, special thanks are due to my family for all of the extended hours I spent for developing this project and writing the thesis instead of being with them, and to my parents, brother and sister for their encouragement and support.

ABSTRACT

Background Oriented Schlieren (BOS) estimates the flow behaviour that exists between the camera and background from the shift in the background image features due to the change in the transfer channel function. The current optical flow techniques used to find the deflection vectors of the change in background images rely on two main assumptions: global constant value of intensity and continuity of local motion. The global intensity invariance assumption hardly works for BOS technique when imaging a self luminous flow. In this thesis, an optical flow equation which takes the change in intensity into account and an estimation motion model that considers both translational and rotational deflections were developed. The results showed that for a transparent gas jet all the tested optical flow algorithms worked well. However the proposed model gave better results for BOS images taken through natural gas flames and smoke from a fog generator. The developed deflection vector estimation algorithm and optical tomography served as a tool to extract the index of refraction of the gaseous fields. The Gladstone-Dale relationship was used to show the direct correlation between the index of refraction and density of the flow. Three different types of axi-symmetric flows were used as gas sample media. These were a CNG injected fuel jet, an open methane flame and a hot air jet. Based on the measured index of refraction the species mole fractions of CNG injected jet and methane flame were measured. In addition, the three dimensional temperature fields of the methane flame and the hot air were also measured and displayed. The other main contribution of this research was the use of Background Oriented Schlieren (BOS) technique for the measurement of the velocity field of a variable density round jet. The density field was further exploited to extract the axial and radial velocity vectors for six different jet-exit temperature values with the aid of the continuity and energy equations. Results of the measured temperature and velocity vector fields were compared with thermocouples and hot wire anemometry readings respectively and showed good agreements.

ABSTRAK

Latar Belakang Berorientasikan Schlieren (Background Oriented Schlieren, BOS) menganggarkan kelakuan aliran yang muncul di antara kamera dan latar belakang dari pegalihan dalam ciri-ciri gambar latar belakang akibat perubahan fungsi saluran pemindahan. Teknik-teknik arus optik yang digunakan sekarang untuk mencari pembiasan vektor dari perubahan imej latar belakang bergantung pada dua andaian utama: pemalar nilai keamatan menyeluruh dan gerakan berterusan setempat. Dalam tesis ini, persamaan aliran optik yang mengambil kira perubahan keamatan dan anggaran gerakan model mempertimbangkan kedua-dua pelenturan penjelmaan dan putaran dibangunkan. Model yang dicadangkan memberikan hasil yang lebih baik untuk gambar-gambar BOS yang diambil melalui nyalaan gas asli dan asap dari generator kabut. Vektor pelenturan algoritma anggaran yang dibangunkan dan tomografi optik berperanan sebagai alat untuk mengekstrak indeks bias bidang gas. Hubungan Gladstone-Dale digunakan untuk menunjukkan hubungan langsung antara indeks biasan dan kepadatan aliran. Tiga jenis arus axi-simetri telah digunakan sebagai media sampel gas. Gas-gas tersebat adalah jet suntikan bahan bakar CNG, bukaan nyalaan metana dan jet udara panas. Berdasarkan kiraan indeks biasan, pecahan mol dari jet suntikan CNG dan nyalaan metana dihitung. Tambahan pula, medan suhu 3-dimensi dari nyalaan metana dan udara panas juga dihitung dan dipaparkan. Sumbangan utama yang lainnya dari kajian ini adalah penggunaan Latar Belakang Berorientasikan Schlieren (BOS) teknik untuk menghitung medan kelajuan jet pada pelbagai pembolehubah kepadatan. Medan kepadatan selanjutnya dimanfaatkan untuk mengekstrak vektor kelajuan paksi dan jejari untuk enam nilai suhu jet-keluar berbeza dengan bantuan daripada persamaan kesinambungan dan persamaan tenaga. Hasil keputusan dari perhitungan suhu dilandingkan dengan termokopel manakala vektor kelajuan dibandingkan dengan bacaan kawat panas anemometry dan masing-masing menunjukkan persamaan yang baik.

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NOMENCLATURE

Variable	**Description**	**Units**
a, b, c, d	Affine constants of rotation, dilation and shear	(-)
e, f	Affine units of translation	(-)
f_i	The oscillatory strength	(-)
l	The level of the wavelet transform	(-)
m	Molecular weight	(-)
m_e	The mass of an electron	(kg)
N	Index of refraction	(-)
R	Position vector	(m)
t	Instantaneous time where image is recorded	(sec)
u ,s	The shift and rescaling parameters of wavelet transform	(-) (-)
x, y, z	Cartesian coordinates	(-)
A, B	Constants incorporated to account intensity variation	(-)
C_1 and C_2	Standard deviations of images	(-)
E(S)	Fourier transform of deflection vector	(nm-sec)
G	Gladstone-Dale constant	(m^3/kg)
$G_{v_{\perp k} v_{\perp k}}$	Power Spectral density	(db)
I	Image intensity	(-)
$\overline{N}(k,l)$	2D Fourier transform of index of refraction	(-)
N'	Gradient of index of refraction	(-)
L^2	Domain of natural numbers	(-)
L	Optical path length	(m)
N	Number of pixels	(-)
P	Pressure	(kg/m^2)
$\overline{R}$	Universal gas constant	(J/(mol.K))

R	The radon transform matrix	(-)
S	Wave front arc length	(m)
T_o *and* T	Ambient and measured temperatures	(K)
U_i	Mean velocity	(m/sec)
V_i	Fluctuation component of velocity	(m/sec)
X_i	Species mole fraction	(-)
Z_{bm}	Distance between background and flow media	(m)
Z_{ml}	Distance between flow media and lens	(m)
Z_{bl}	The distance between background and lens	(m)
Z_f	The focal length of the camera	(m)

ρ	Gas density	(kg/m^3)
θ	Angle of refraction	(rads)
ε_x, εy	Light beam deflection angles	(rads)
α	Affine rotational coefficient	(-)
μ, ν	Translation terms along x and y axis	(m)
ψ	Wavelet function	(-)
ν and ν_i	Frequency and resonance frequency	(Hz)
δy_b	Imaginary deflection vector on the background	(m)
δy_i	The deflection recorded in the camera	(m)
μ_x and μ_y	Mean intensity images	(-)
σ_x, σ_y	Constants added to avoid zero denominators	(-)
		(-)

Abbreviations

BOS	Background Oriented Schlieren
CNG	Compressed natural gas
COV	Coefficient of variation
HWA	Hot wire annemometry
OF	Optical flow
OPL	Optical path length