2nd Fluids, Energy, and Turbomachinery Expo

11 July 2012
Imperial War Museum
Duxford, United Kingdom

Preface

Welcome to the second Fluids, Energy, and Turbomachinery Expo (FETE). This transferable skills graduate conference has been organised to provide graduate students with an opportunity to improve their research communication, as well as their personal and professional development skills. Furthermore, it is a chance for students and faculty members to learn about the wide range of research that takes place within Division A at the Department of Engineering.

This conference invites the graduate students working in Division A to present their and take part in the specially selected workshops. More than 60 graduate students from the three research groups in Division A are taking part in the conference. This year's conference will have several posters on display and 15 student presentations, for which there will be prizes for the top performances. The students will also receive informative feedback on their presentation skills, with an opportunity to discuss their performance in a 1-on-1 review session. In addition, well-known keynote speakers with a breadth of knowledge in academia and industry have been invited to give talks in their respective fields. There will also be three different workshops in which students will learn how to develop the skills necessary for success in research and industry.

We very much value your feedback on the presentations, posters, and on the day in general, via the forms provided.

The conference proceedings and presentations will be made available on the FETE 2012 website (`http://fete.eng.cam.ac.uk`) to Division A members only.

The Organising Committee of FETE-2012

Acknowledgements

The Organising Committee of FETE-2012 wishes to express their gratitude to the Department of Engineering transferable skills fund for financially supporting this event. We would like to thank the keynote and workshop speakers for their and for sharing their knowledge. The support from Sue Jackson and the Graduate Development Office is very much appreciated. We would like to thank all the participants for their valuable contributions to making this conference a success. We would also like to thank the faculty members attending this conference for their time and support. Finally, we would like to give our thanks to Susanne Horn of DLR Göttingen for providing the LaTeX code used to compile this abstract book.

The Organising Committee of FETE-2012

UNIVERSITY OF CAMBRIDGE

DEPARTMENT OF ENGINEERING

Contents

Organisation

Organising committee

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Conference Program

Wednesday, 11th July

Time			Item	Venue
9:00	–	9:15	Arrival & registration	Conservation hall
9:15	–	9:30	Opening address	Conservation hall
9:30	–	10:30	Student presentations I	Concorde suite
10:30	–	11:00	Coffee break	Conservation hall
11:00	–	12:00	Workshops I	Marshall auditorium/ Concorde suite
12:00	–	13:00	Keynote speech I	Marshall auditorium
13:00	–	14:00	Lunch break & poster session	Conservation hall
14:00	–	15:00	Student presentations II	Concorde suite
15:00	–	16:30	Workshop II	Marshall auditorium
16:30	–	17:00	Coffee break	Conservation hall
17:00	–	17:45	Keynote speech II	Marshall auditorium
17:45	–	18:00	Closing statements & prizes	Marshall auditorium
18:00	–	18:30	Departure	Not specified
18:30	–	20:00	Dinner & drinks	Engineering department

Student presentations I

9:30 – 10:30 Concorde suite rooms

Each talk is scheduled to last for 15 minutes, with three minutes for questions and two minutes for change of speaker. Feel free to switch rooms between presentations.

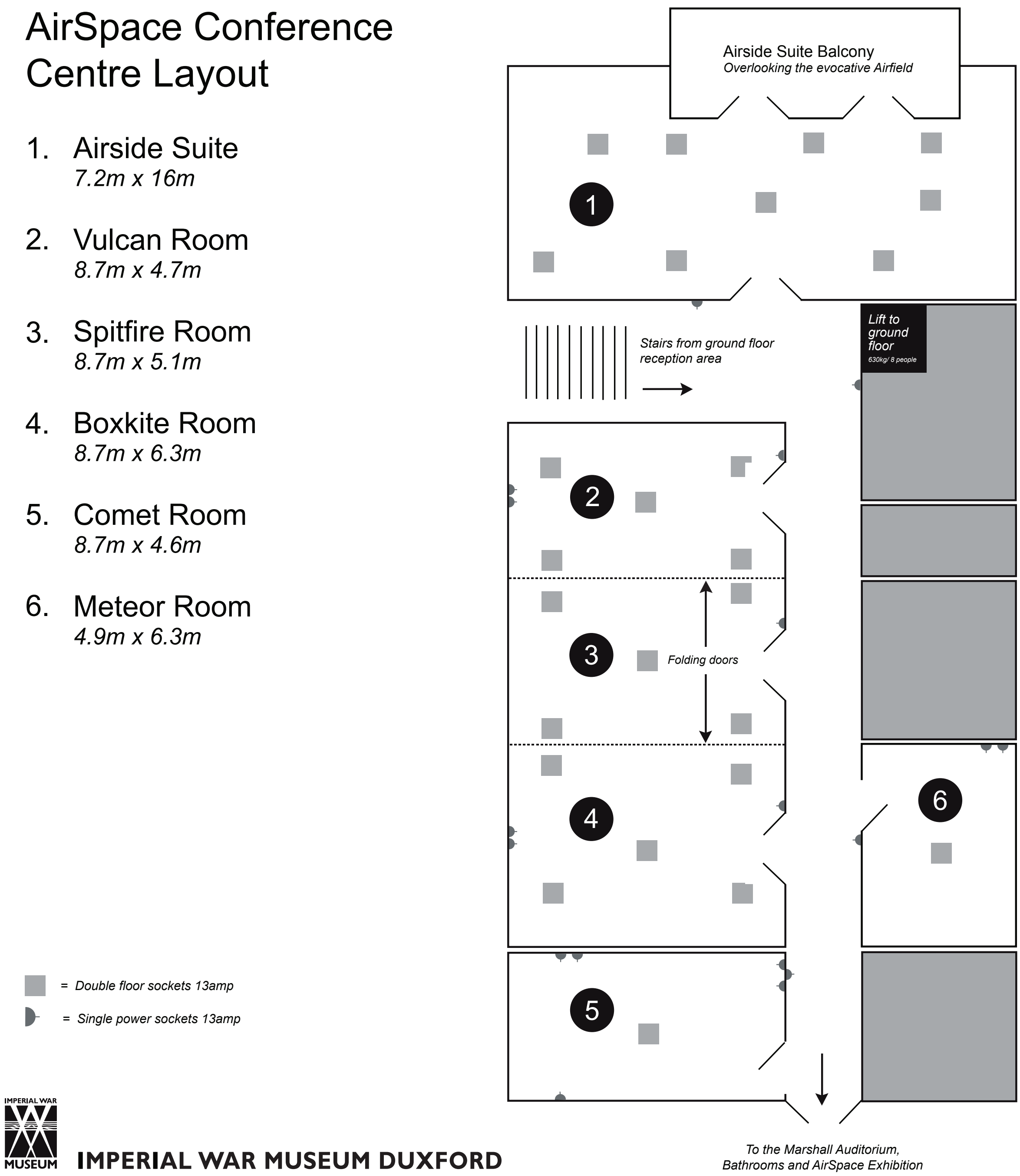
	Spitfire room Fluids	Boxkite room Energy	Vulcan room Energy
9:30–9:50	Towards a silent fan *Timothy Newman*	Limits of engine downsizing for reduced fuel consumption *Orian Welling*	Differential geometry as a paradigm for multidisciplinary design optimization *Craig Bakker*
9:50–10:10	On the formation of pancake eddies in stratified turbulent flows *Andrea Maffioli*	Fast EGR measurement using UEGO Sensors *Kieran Hegarty*	Developing a Dimensionless Evaluation Framework for Oil Extraction by In Situ Combustion *Michael Youtsos*
10:10–10:30	Vortex breakdown in swirling jets: origin and control *Ubaid Ali Qadri*	High Temperature Condensation Particle Counter *Kanchit Rongchai*	The benefits of multiple targets in accelerator driven subcritical reactors *Ali Ahmad*

Student presentations II

14:00 – 15:00 Concorde suite rooms

Each talk is scheduled to last for 15 minutes, with three minutes for questions and two minutes for change of speaker. Feel free to switch rooms between presentations.

	Spitfire room Fluids	**Boxkite room Energy**	**Vulcan room Turbo**
14:00–14:20	Linear stability analysis of complex turbulent flows *Vikrant Gupta*	Stabilisation and blow-off of turbulent flames *James Karuiki*	Turbine Rim Seal Aerodynamics *Martin Chilla*
14:20–14:40	Reduced-order Jet Noise Modelling for Chevrons *Karthik Depuru*	Uncertainties in Aircraft Engine Soot Emissions *Marc Stettler*	DNS of surface roughness effects on wall turbulence at low Reynolds number *Xiaoyu Yang*
14:40–15:00	Flow physics of a normal-hole bled supersonic turbulent boundary layer *Joseph Oorebeek*	Clocking in multistage axial turbines *Kathryn Evans*	Large eddy simulations in turbines *Vadlamani Nagabhushana Rao*



Floor plan of the Duxford IWM conference venue.

The aerodrome at Duxford was built during the First World War and was one of the earliest Royal Air Force stations. During 1917 the Royal Flying Corps expanded and Duxford was one of a number of new stations established to train RFC aircrew. In September 1918 RAF Duxford opened as a flying school, and after the war ended the airfield was used as a base for the disbandment of squadrons from the Continent. In 1924, under reorganised Home Defence arrangements, RAF Duxford became a fighter station, a role it was to carry out with distinction for 37 years.

By 1938 the reputation of RAF Duxford's No.19 Squadron was such that it became the first RAF squadron to re-equip with the new Supermarine Spitfire, and the first Spitfire was flown into RAF Duxford in August 1938.

In June 1940 Belgium, Holland and France fell to German forces and the conquest of Britain was Germany's next objective. RAF Duxford was placed in a high state of readiness. The period of intense air fighting that followed has become known as the Battle of Britain, and RAF Duxford played a vital role in Britain's air defence. On 15 September 1940, *Battle of Britain Day*, RAF Duxford's squadrons twice took to the air to repulse Luftwaffe attacks aimed at London. The threat of invasion passed and RAF Duxford's squadrons had played an important part in the victory.

In April 1943 the airfield was fully handed over to the United States 8th Air Force, which had begun to arrive in Britain the previous May. RAF Duxford now became Base 357 and the headquarters of the 78th Fighter Group. On D-Day, 6 June 1944, the long-awaited beginning of the Allied invasion of occupied Europe, every available 78th Fighter Group Thunderbolt provided air cover to the Allied invasion fleet as it crossed the Channel. RAF Duxford was officially handed back to the Royal Air Force on 1 December 1945.

Following the end of the Second World War, the station entered its last operational phase. The defence needs which had called RAF Duxford into being as a fighter station no longer applied; it was too far south and too far inland, and the costly improvements required for supersonic fighters could not be justified. In July 1961 the last operational flight was made from RAF Duxford, and for some 15 years the future of the airfield remained in the balance.

IWM had been looking for a suitable site for the storage, restoration and eventual display of exhibits too large for its headquarters in London and obtained permission to use the airfield for this purpose. Cambridgeshire County Council joined with IWM and the Duxford Aviation Society, and in 1977 bought the runway to give the abandoned aerodrome a new lease of life.

Today IWM Duxford is established as the European centre of aviation history. The historic site, outstanding collections of exhibits and regular world-renowned Air Shows combine to create a unique museum where history really is in the air.

Map of the Imperial War Museum: Duxford

Invited keynote speakers

Prof Nick Cumpsty

Department of Mechanical Engineering
Imperial College London
Exhibition Road
London, SW7 2AZ

12:00 – 13:00 Marshall auditorium

I obtained my PhD in the Cambridge University Engineering Department on three-dimensional turbulent boundary layers, but then used a research fellowship in Peterhouse to move over to a topic "hot" at the time, engine noise. At that time one could not join the teaching staff of the Engineering Department without industrial experience and I went to work for Rolls-Royce in Hucknall, near Derby, on engine noise. This was an exciting time with the RB211 in development and then in February 1971 the Company went bankrupt. I survived the bankruptcy, but John Horlock lured me to the newly opened laboratory in Cambridge (then called the SRC Turbomachinery Laboratory, later named the Whittle Lab) on the bottom rung of the academic ladder. I began on 1st January 1972 and stayed in Cambridge for the next 28 years (with some sabbaticals in Caltech and MIT) eventually becoming Professor of Aerothermal Technology and Director of the Whittle. I came to feel I needed a change, so from the beginning of 2000 I was Chief Technologist of Rolls-Royce. This was a dream job, with no budget and no staff to look after. Rolls-Royce make (or made) senior staff retire at 62, so I had to leave in 2005 and I went as Professor of Mechanical Engineering to Imperial College (where I had been an undergraduate). Within about four weeks I was acting as Head of Department, in which role I continued for two years. I retired from Imperial in 2008, though I am allowed to keep an office there and I am involved in the research, but not the teaching.

In my first employment by Rolls-Royce I was young and junior, whereas in my second employment I was old and quite senior, so I have seen industry from both sides. It has to be said, however, that industry and Rolls-Royce in particular, has changed a great deal in the time. I have also seen academia from the bottom rung to the top; again the university world has changed a lot in this time too. In the old days we worked very hard, but things were less bureaucratic and much less time was given to what might be denigrated as paper work.

My early research was on 3D boundary layers, then on noise. On returning to Cambridge in 1972 I began work on centrifugal compressors and endwall flows in axial compressors, and broadly these were my principal fields for most of my time in Cambridge. My remit in Rolls-Royce as Chief Technologist went across the whole product range. Now I am still interested in axial turbomachinery, particularly compressors, centrifugal compressors, unsteady flow in radial turbines, flutter of fans and anything else people talk to me about. I work with colleagues here in Imperial; I visit the Whittle and talk to those active in fields where I have some knowledge; I have recently started a similar relationship with the Oxford Osney Lab, going there about once per month; and I have a long-standing close relationship with the Gas Turbine Lab in MIT. Retirement can be very busy, but also interesting and rewarding.

In the late 1980's I wrote my first book, Compressor Aerodynamics. I gave a new undergraduate course in the late 1990's which formed the starting point for my second book Jet Propulsion. I never want to write a book again! However I do get satisfaction from these, particularly Jet Propulsion, which has sold over 10000 copies and has influenced teaching and learning of the subject. I get particular pleasure seeing copies on desks of people in Rolls-Royce.

Dr Neil McDougall

Frazer Nash Consultancy
Stonebridge House
Dorking Business Part
Dorking
Surrey, RH4 1HJ

12:00 – 13:00 Marshall auditorium

Neil McDougall joined Frazer-Nash Consultancy in 2005 as Engineering Director after a varied career in consultancy and automotive component design and manufacture. He served on the Board of Frazer-Nash for three years before being promoted to Managing Director, a post he has held ever since. In the time that Neil has been with Frazer-Nash he has been part of the management team that has overseen the successful growth of the business from £20m turnover and circa 200 employees to £45m turnover and 450 employees today. Frazer-Nash, a wholly owned subsidiary of Babcock International Group, acts as an independent engineering consultancy in the UK and international markets. Clients include government, energy companies, defence "primes" and businesses in the transport and general industrial domains.

Previously, Neil has held senior positions at Johnson Controls, where he was Engineering Director for Automotive Interiors for the Ford Business Unit, and served on the Board of Ricardo Vehicle Engineering as their Engineering Director.

Neil took his PhD at the Whittle Laboratory in Cambridge, is a Chartered Engineer and a Fellow of the Institution of Mechanical Engineers. He is married to Jacky, and they have two grown-up children. Now (very much) too old to play rugby, he is limited to offering coaching advice from the touchline.

Dr Tom Gibson

Airbus UK
Aerodynamics research
New Filton House
Filton, Bristol, BS99 7AR

17:00 – 17:45 Marshall auditorium

Tom was an engineering undergraduate at Cambridge from 1989-92. He went on to take an MSc in aerodynamics at Cranfield then returned to Cambridge to study passive control of shock/boundary-layer interaction for his PhD. Following a brief period as a research associate on the Euroshock 2 program, he joined the Aerodynamics Department at Airbus in 1998, working in the Wing Shape design team at Filton. His initial assignments at Airbus were in research, looking first at high Reynolds number design and wind tunnel testing techniques in support of the A380 program. He then led the cruise aerodynamics portion of the *Nexus* research project, which was set up to develop new design approaches and technologies for the next aircraft program. In 2003 he became the leader of the Wing Shape team, thus becoming responsible for all wing external shape design and development work at Airbus. As such he led the team through the design of the A350XWB wing, and was among the 6-person core team which won the Airbus *Top Award for Excellence* in 2009 in recognition of this achievement. In parallel, he led the design of the Sharklet wing tip device which will shortly be going into serial production for the Single Aisle family. He currently has two main roles at Airbus. One is as an Overall Aircraft Aerodynamic Design manager with responsibility for further developing Airbus' aerodynamic design capabilities for future programs; the other is to provide *Flight Physics* support, especially in the areas of aerodynamics and flight loads, to a current winglet retrofit project. He also acts as an Expert in Wing Aerodynamic Design as part of the *EADS Experts* scheme.

Workshop sessions and speakers

Workshop I: Applying for post-doctoral fellowships and research grants

11:00 – 12:00 Boxkite room

This session will provide you with an introduction to Research Fellowships. It will consider how they fit in to a longer-term academic career, provide an overview of the key schemes open to engineers, and offer some practical tips on how to write a good research proposal. It will also point to other sources of support within the University.

Ms Elizabeth Simmonds

LizSimmonds@careers.cam.ac.uk

Liz Simmonds is the Careers Adviser for Postdocs in Physical Sciences and Technology. She is based in the University Careers Service, where she delivers a tailored careers programme for postdocs in the Schools comprising one-to-one guidance, and a variety of careers-themed workshops and events.

Liz read Natural Sciences at Cambridge, specializing in Chemistry. She joined the Royal Society of Chemistry as an Assistant Editor for Chemistry in Britain Magazine, where she developed a strong interest in education, science policy and career issues. Liz then moved to SETNET, a Government-funded organization promoting science and engineering careers to school children. As a programme manager, she looked after a number of key Government projects, including the Science and Engineering Ambassadors Programme, developing a broad knowledge of science and science-related careers in both the public and private sector. Liz joined the University Careers Service in 2007.

Workshop I: Moving into business

11:00 – 12:00 Marshall auditorium

This workshop will consider the idea of setting up and running your own business ? or joining a newly established business venture. What are the different options for scientists and engineers and what is involved in entrepreneurship?

The workshop will address the key elements of setting up a new business venture, what you need to consider, what you need to do, where you will find funding for a new business venture and any of the other issues that may concern people thinking about this as a career option ? for now or for the future.

Mr Peter Hiscocks

ph253@cam.ac.uk

Peter Hiscocks teaches innovation management and entrepreneurship on the MBA and other programmes at Cambridge Judge Business School. He also teaches entrepreneurship and business finance for other Departments within the University.

Peter has founded new ventures which include Integral Inc - a $50 million consulting company; Ecurie25 Ltd - a supercar club; and Pod Point Ltd - an EV recharging business. He is the Chairman of a £20 million seed-fund that helps fund new business start-ups and is on the advisory board of a large venture capital company. He has advised several European governments and has chaired European Commission committees on matters of innovation strategy; commercialising university intellectual property; and improving the effective transfer of research programmes into commercial innovations. At the University of Cambridge Peter was Director of Cambridge Enterprise and prior to that was the first Director of the Cambridge Entrepreneurship Centre. Peter was Visiting Professor of Entrepreneurship at the University of Auckland from 2001 until 2006; he is a Visiting Fellow at IST, University of Lisbon, and also a Visiting Lecturer in Entrepreneurship at Technical University, Delft.

Workshop II: The art of negotiation and influence

15:00 – 16:30 Marshall auditorium

An interactive workshop for developing your communication skills, designed and delivered by ex hostage negotiators. Gain the knowledge and expertise to help you get the best result when communicating with others. Learn how to make the most of conversations you have, find the answers you need, and discover how to deal with difficult people.

- Develop a range of advanced communication skills that will enable you to build trust and rapport. Learn techniques that will increase your effectiveness every time you negotiate or talk to someone in all areas of your life.
- Develop powerful listening and language skills that will enable you to get a better understanding of the values and beliefs of the person communicating with you, and enable you to understand and persuade them more easily.
- Develop your day to day effectiveness in everything you do, including your academic, professional, and personal life.

Mr Richard Mullender

`richardmullender@googlemail.com`

Former Lead Trainer at the National Crisis and Hostage Negotiation Unit at Scotland Yard, Richard Mullender is an expert in elite-level listening skills - with a lifetime's experience tackling communication challenges at the sharp end and offers a unique opportunity to find new ways to master the communication challenges you face.

Richard has trained staff at the Metropolitan Police, the United Nations and the FBI as well as corporate sector clients such as Oracle, Accor Hotels and the BNP Paribas, helping them to develop their listening skills and use of language to build rapport, establish trust and exert influence in the workplace. He also specialises in helping people develop their assertiveness skills in order to handle difficult conversations more effectively. An in-demand trainer and keynote speaker on communication and listening skills across the world, Richard has worked with corporate and public sector teams in South Africa, Kenya, Kosovo, the United States, Estonia, France, Qatar and the United Arab Emirates.

Fluids group abstracts

Reduced-order Jet Noise Modelling for Chevrons

Karthik Depuru Mohan[1]

[1] Fluids group, Department of Engineering, University of Cambridge, Cambridge, United Kingdom

Abstract:
Jet noise has been a major community concern since the 1940s. Among noise-suppression devices, chevron nozzles are most effective as they significantly reduce low-frequency noise without appreciable thrust loss. The objective is to understand the noise-suppression mechanisms of chevron nozzles by identifying the noise sources and predicting the far-field noise for both chevron and round jets. To identify noise sources, the fourth-order space-time velocity cross-correlations are calculated based on an LES flow field. The Gaussian form fits axial, radial and azimuthal cross-correlations reasonably well. The axial length scales of the cross-correlations are 3-4 times the radial or azimuthal length scales for both chevron and round jets. For chevron jets, the cross-correlation lengths vary with azimuthal angle at axial positions within 6 jet diameters. Further downstream, both chevron and round jets behave similarly. Although for round and chevron nozzles R1111 the fourth-order cross-correlation of the axial velocity is the dominant component of the source, for chevron jets there is a significant contribution from other components such as R2222 and R3333. The cross-correlations decay rapidly with the axial distance for a chevron jet, whereas they remain constant for a round jet. Chevrons intensify R2222 and R3333 within 2 jet diameters downstream of the nozzle exit. The amplitude, length and time scales of the cross-correlations of the LES velocity field are investigated as functions of position and are found to be proportional to the turbulence amplitude, length and time scales determined from a RANS calculation. These proportionality constants are universal i.e. independent of nozzle geometry and position within the jet. The scales derived from RANS are used for source description and an acoustic analogy is used for sound propagation. At low-frequencies, chevrons drastically reduce noise by 5-6 dB at 300 to the jet axis and 2-3 dB at 900. There is excellent agreement between far-field noise predictions and NASA measurements.

On the formation of pancake eddies in stratified turbulent flows

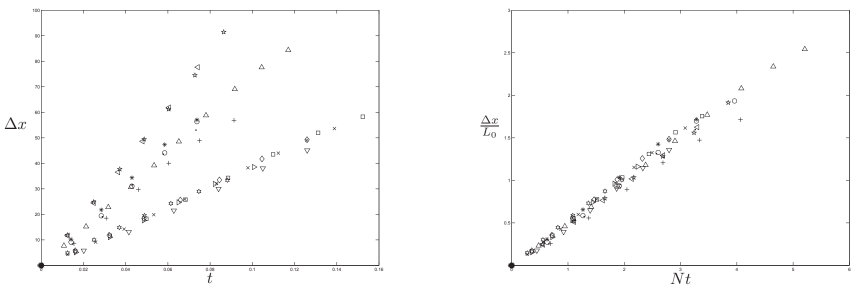
Andrea Maffioli[1], and Peter Davidson[1]

[1] Fluids group, Department of Engineering, University of Cambridge, Cambridge, UK

Abstract:
Turbulence in a fluid with a stable density stratification is highly anisotropic and contains flat "pancake eddies", which are squashed in the vertical direction along which the buoyancy force acts. The objective of this study is to clarify if internal gravity waves play a part in the formation of the anisotropic structures, in a similar way as inertial waves do in rotating turbulence [1].

Direct numerical simulations of a vertical slice of turbulence in a linearly stratified fluid were performed. By comparing isosurface plots of the materially conserved potential vorticity Π and the u_x velocity component, we found that pancake-like wavepackets travel out of the turbulent cloud. Simple laboratory experiments of a stratified cloud of turbulence confirm this picture.

The front propagation of individual wavepackets was tracked in the numerical simulations and the results are presented in Figure 1(a). The theoretical expression for the group velocity of horizontally-travelling internal gravity waves is $\mathbf{c}_g = (N/k_z)\mathbf{e}_x = (N\lambda_z/2\pi)\mathbf{e_x}$ (N is the Brunt-Väisälä frequency and λ_z is a vertical wavelength); Figure 1(b) shows the appropriately non-dimensionalized wavepacket propagation curves. The curves show a good collapse, which demonstrates that the waves are quasi-linear finite-amplitude internal gravity waves. We found that the wavepackets transport 18% of the total kinetic energy away from the cloud, highlighting the important role of the horizontal wave modes in meteorology.



(a) (b)

Figure 1: (a) Wavepacket front displacement against time. (b) Non-dimensional wavepacket propagation using N and the initial integral lengthscale in the cloud L_0.

References

[1] Davidson, P.A., Staplehurst, P.J. and Dalziel, S.B., (2006), On the evolution of eddies in a rapidly rotating system, *J. Fluid Mech., vol. 557, pp.135-144.*

Investigation of PIV accuracy for fine-scale turbulence measurements

Dhiren Mistry[1] and James Dawson[1]

[1] Fluids group, Department of Engineering, University of Cambridge, Cambridge, United Kingdom

Abstract:
2-dimensional Particle Image Velocimetry (PIV) is an experimental technique which measures the velocity of a fluid across a thin plane. However, the typical length-scales of fine-scales turbulence are sub-millimetre and are therefore very difficult to visualise and capture experimentally. The accuracy of PIV for fine-scales turbulence measurements is limited due to the effects of noise, particle seeding, and laser sheet thickness.

We used Direct Numerical Simulation (DNS) data of isotropic turbulence [1] to evaluate the effects of typical PIV errors on turbulence statistics. We performed this investigation by comparing isotropic DNS turbulence data with the same DNS data to which Gaussian noise was added, the spatial resolution was reduced, and adjacent vector-fields were averaged. We examined the joint-Probability Distribution Function (PDF) of the two 2-D velocity gradient invariants [2], $p = -tr(a)$ and $q = det(a)$ (a is the 2-D velocity gradient tensor), to compare the effects of these error sources. Examples of the p-q joint-PDF's are shown in figure 1, which compares experimental PIV measurements with the DNS data and the modified DNS turbulence data for which experimental errors are simulated. From the qualitative similarities of figures (i) and (iii), we conclude that the flattened joint-PDF shape of the experimental data is attributed to experimental noise and limited spatial resolution.

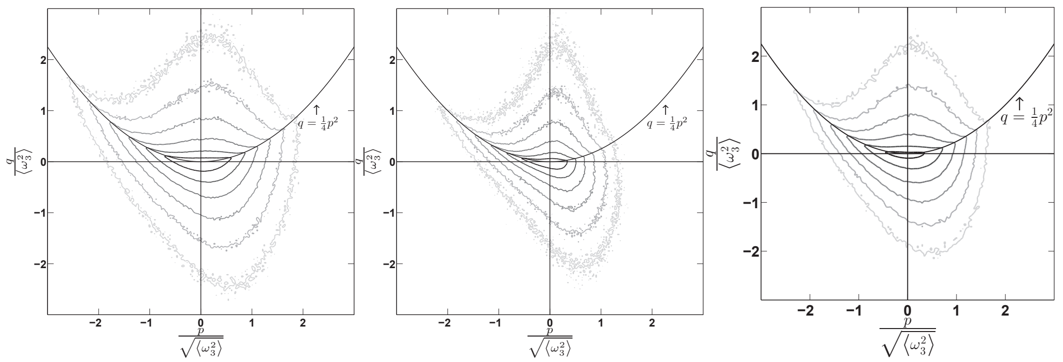


Figure 1: Comparison of joint-PDF's of (i) 2-D PIV data, (ii) DNS data from [1], and (iii) DNS data with added Gaussian noise and reduced spatial resolution.

References

[1] Data obtained from the JHU turbulence database cluster at `http://turbulence.pha.jhu.edu`

[2] Perry, A. E. and Chong, M. S., (1987), A description of eddying motions and flow patterns using critical-point concepts, *Annu. Rev. Fluid Mech., vol. 19, pp. 125-155.*

Flow physics of a normal-hole bled supersonic turbulent boundary layer

Joseph Oorebeek[1] and Holger Babinsky[1]

[1] Fluids group, Department of Engineering, University of Cambridge, Cambridge, United Kingdom

Abstract:
Understanding of the flow physics of bleed through a porous plate is essential for advanced supersonic inlet design. Although discrete suction has been studied for laminar flow control at subsonic speeds, very little detail has been visible at supersonic speeds until now.

Experiments performed at Mach numbers of 1.3, 1.5, 1.8 and 2.5 have currently been tested in the CUED Supersonic Wind Tunnel (SST). Laser Doppler Velocimetry (LDV), Schlieren and oil-flow visualization have been used to characterize the flow surrounding an array of normal bleed holes. In this way, flow features have been found which are unique to the supersonic regime, while other features are common to low speed incompressible tests.

Towards a silent fan

T.J. Newman[1], Dr A. Agarwal[1] and Prof Dame A.P. Dowling[1]

[1] Acoustics Lab, Department of Engineering, University of Cambridge, Cambridge, United Kingdom

Abstract:
The main objective of the work being presented is to develop low-order prediction models for fan noise and performance for fans operating at low Reynolds and Mach numbers. Compared to high Reynolds number fans, relatively little is known. The aims are to characterise, model and find ways to reduce the noise sources present in low-speed fans. Dyson's Air Multiplier desk fan is being used as the first test case for the project.

Figure 1: ***Dyson's Air Multiplier desk fan***

The initial focus is on the single-stage, mixed-flow compressor which draws in air through vents in the base of the Air Multiplier and delivers it to the hoop-like 'amplifier' which produces an annular jet. This annular jet entrains the surrounding air to produce an 'amplified' cooling airflow.

In order to understand contribution to the overall noise from the compressor, an experimental rig has been constructed as a platform for measurement of both aerodynamic and aeroacoustic compressor performance across the operating range. Principally, this consists of the compressor component housed in a long, cylindrical duct. The sound emitted into the duct at both the inlet and outlet of the compressor is measured. Since there are reflections at the open ends of the duct, a method has been developed to decompose the cut-on acoustic modes travelling up and down the duct. This method, an extension to the so-called two-sensor technique [1], allows separation of modal amplitudes of the sound travelling in both directions and includes the higher-order, azimuthal modes.

[1] A. F. Seybert, 'Two-sensor methods for the measurement of sound intensity and acoustic properties in ducts', *The Journal of the Acoustical Society of America*, vol. 83, no. 6, pp. 2233–2239, 1988.

Energy group abstracts

Photosynthetic measurement and kinetic modelling of microalgae

Victoria O. Adesanya *, Nicholas E. Ross, and Stuart A. Scott

Energy Group, Department of Engineering, University of Cambridge, Trumpington Street Cambridge, CB2 1PZ, United Kingdom.

Abstract

There is increasing interest in the use of algae feedstock in various industrial sectors, with applications ranging from nutrition and food products, high value products, pharmaceuticals to biofuel production. Algae biomass is also being employed in pollution control and waste water treatment as well as CO_2 mitigation and sequestration. Although algae have a great potential for various applications, large-scale production is limited. The bioproductivity of algae is affected by changing growth conditions (such as light, CO_2, temperature, nutrient, pH etc) which may lead to beneficial or harmful effects. Light is one of the most important growth factors affecting the rate of photsynthesis [1] and the intensity, spectral quality and duration of light controls algae biomass productivity [2]. It is therefore important to characterise the light distribution in a culture system in order to model photosynthetic growth rates as well as predict biomass productivity in photobioreactors.

This work examines the kinetic measurement of photosynthesis for algae culture grown under conditions of low light (~80 μmol/m^2/s) and high light (~800 μmol/m^2/s) using a Hansatech oxygen electrode. In particular, the effect of light intensity on photosynthetic rates was investigated. The algae strain studied were *Chlorella vulgaris* (CCAP 211/11B) and *Synechocystis sp.* (PCC 6803). Kinetic measurements in terms of oxygen evolution were performed under incident light intensities in the range of 0 - 1400 μmol/m^2/s. Results revealed that for low light grown algae cultures, photosynthetic rate increases linearly with photon flux density (PFD) up to ~200 μmol/m^2/s. Further increase in PFD leads to a deviation from linearity reaching a light saturation region with no change in the rate. Above ~800 μmol/m^2/s, a decrease in photosynthetic rate was observed, a phenomenon known as photoinhibition. On the contrary, photoinhibition was not observed in high light grown cultures however, at low PFDs, respiration overshadows photosynthesis. Photoacclimation and pigment loss was also established for algae cultures grown under high irradiance. In addition, a basic mathematical model was developed to describe the light distribution profile inside a tubular reactor and subsequently predict the rate of algal photosynthesis.

Keywords: Microalgae, photosynthesis, light, oxygen electrode and Oscillatory flow reactor.

[1] Hall, D. O., Rao, K. K. 1999. Photosynthesis, 6th edition. Cambridge University press, Cambridge.

[2] Park, K-H., Lee, C-G. 2001. Effectiveness of flashing light for increasing photosynthetic efficiency of microalgal cultures over a critical cell density. Biotechnol. Bioprocess Eng. 6, 189-193.

The benefits of multiple targets in accelerator driven subcritical reactors

Ali Ahmad[1], and Geoffrey Parks[1]

[1] Cambridge Nuclear Energy Centre, Department of Engineering, University of Cambridge, Cambridge, United Kingdom

Abstract:
The Accelerator Driven Subcritical Reactor (ADSR) is one of the reactor designs proposed for future nuclear energy production. Interest in the ADSR arises from its enhanced and intrinsic safety characteristics, as well as its potential ability to utilize the large global reserves of thorium and to burn legacy actinide waste from other reactors and decommissioned nuclear weapons[1]. The ADSR concept is based on the coupling of a particle accelerator to a subcritical reactor core by means of a neutron spallation target interface. This paper aims to investigate the benefits of multiple targets in ADSRs. The motivation behind this is, firstly, to improve the overall reliability of the accelerator-reactor system, and secondly, to evaluate other potential advantages such as lower beam power and improved fuel burn-up. Results showed that having two or three spallation targets, coupled to independent accelerators, offers better neutronic performance. This has been demonstrated through the increased effective multiplication factor (k_{eff}) in the two and three target configurations and a more uniform neutron flux distribution. Multiple target ADSR also proved effective in dealing with the pressing issue of frequent beam interruptions which needs to be addressed for the ADSR concept to move forward [2]. Assuming no simultaneous beam shutdowns, the two and three target configurations greatly mitigated the effects of thermal cyclic fatigue and therefore, limited the possibility of a fuel pin cladding failure. This is due to the reduced thermal shock of the system resulted from the availability of the other operating beam(s).

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Vortex breakdown in swirling jets: origin and control

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Abstract:
Fuel injectors have elaborate shapes and complex flow dynamics and play an important role in ensuring good mixing between the fuel and the air. My work represents the second stage in a wider project that aims to develop the capability to map out the sensitive areas in real fuel injectors and combustion chambers. This sensitivity information could significantly aid designers by providing information about the most influential parts of the design.

To a first approximation, a fuel injector can be modelled as a jet of fuel exiting into a space filled with air. In the previous stage, a numerical code was developed [1], which had the capability to study the sensitivity of low-density jets and flames such as a bunsen flame. In this project, we have extended the capabilities of this code to study the sensitivity of variable-density swirling flows and flames. This enables a much wider range of flows to be studied. Swirl is commonly employed in fuel injectors and combustion chambers because it improves mixing properties and because it leads to vortex breakdown, which helps to stabilize the flame.

Recent numerical studies have shown that the basic form of vortex breakdown is characterised by a steady axisymmetric breakdown bubble, and that an unsteady spiralling breakdown mode develops due to the self-sustained growth of helical perturbations on top of the breakdown bubble. We study the spiral mode of vortex breakdown in a laminar swirling jet and identify which regions of the flow are most influential in causing it and how it might be controlled. This allows us to understand the physical mechanisms that are important as we then go on to study low-density swirling jets (e.g. methane) and a swirling flame with vortex breakdown.

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Differential Geometry as a Paradigm for Multidisciplinary Design Optimization

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Abstract:
Multidisciplinary Design Optimization (MDO) is a methodology for optimizing large coupled systems. Over the years, a number of different MDO decomposition strategies, known as architectures, have been developed, and various pieces of analytical work have been done on MDO and its architectures [1]. However, MDO lacks an overarching paradigm which would unify the field and make its research more cumulative. We propose a differential geometry framework as such a paradigm: differential geometry comes with its own set of analysis tools and a long history of use in theoretical physics [2]. We begin by outlining some of the mathematics behind differential geometry and then translate MDO into that framework. This initial work gives new insight into how the architectures work while additionally producing a naturally arising measure of design coupling. The framework also suggests several new areas for exploration into and analysis of MDO systems. At this point, analogies with particle dynamics and systems of differential equations look particularly promising at this point for both the wealth of extant background theory that they have and the potential predictive and evaluative power that they hold.

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Effect of the initial conditions on the near field interactions of jet flow

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Abstract:
Jets have been the subject of investigation for many years as they are a fundamental flow that has many applications. Those of interest are the exhaust (thrust) jet from turbofan aero engines and combustion injector flows. Previous work has covered measurement of sound [1], self similarity [2], and modelling [3], although consensus on self similarity is not forthcoming [4]. This project has the long term aim of measuring two-point two-time correlations of a coaxial dual density jet, modelling the jet of a modern aero turbofan engine. Initially, basic measurements on more fundamental flows have been undertaken.

The objectives of this project is twofold: primarily it is to provide new, accurate experimental data for use in the verification of computational fluid dynamic (CFD), particularly large eddy simulation (LES) codes. Secondly, it is to investigate the science of coaxial dual density jets, the effect of initial conditions and the near field progression of vortices produced, in more detail than previously possible by using modern laser diagnostic techniques.

Initially hotwire constant temperature anemometry (CTA) has been used to study the initial conditions, and to undertake a preliminary study of the near field of the jet. Three antisymmetric initial conditions were used: an initially laminar top hat profile, produced by a smooth contracting nozzle; a top hat profile with turbulent boundary layer, produced using a contracting nozzle and a wire ring to create a turbulent boundary layer; and a turbulent pipe flow, created with a long pipe.

Further work will include planar laser induced fluorescence (PLIF) of acetone allowing two dimensional analysis of the density scalar in coaxial flow including two-point correlations. Additionally simultaneous particle image velocimetry (PIV) and PLIF will enable velocity and scalar to be measured simultaneously, giving further scope for the measurement of 2-point correlations.

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Development and performance of inexpensive oxygen carrier for chemical looping combustion of coal

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Abstract:

Chemical-looping combustion (CLC) has the intrinsic property of reducing CO_2 produced from burning of coal. An oxygen carrier, instead of air is usually used in the form of a metal oxide to provide oxygen for combustion of coal [1]. The current work focuses on the preparation and study of performance of a suitable Fe-based oxygen carrier for CLC of coal. Carriers were made from Fe_2O_3 and $Ca(NO_3)_2.4H_2O$ through a combination of mechanical mixing and wet impregnation methods under different molar loading. The activity of these solid particles was assessed by determining their reactivity in a reducing and oxidizing environments by reacting them with 5 vol% hydrogen followed by air in a thermogravimetric analyser (TGA). The particles were allowed to run over many cycles of reduction and oxidation at 800-900^{o}C.

The performance of particles varied with the molar loading and reaction temperature. A higher temperature gave better reduction, whilst a higher molar loading prevented complete re-oxidation . After 20 cycles, the wet impregnated carrier with molar loading of 0.01 and 800^{o}C can fully re-oxidized with air but at 900^{o}C re-oxidation capability was found as 95% in all molar loading. There was found a drastic drop (12%) of re-oxidation after 8 cycles at higher temperature.

This work shows that lower molar loading of CaO in Fe_2O_3 favors the CLC. Characterization of prepared particles is still under way. A series of study will be carried out using XRD, SEM and BET to determine the complete morphology of particles.

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LES of turbulent premixed combustion using SDR-reaction rate closure

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Abstract:
This project aims to develop a new, efficient and robust Scalar Dissipation Rate (SDR) model for the reaction rate closure of turbulent premixed flames in the context of Large Eddy Simulations (LES). The maximum temperature attained during combustion, and thus the thermal NOx formation, can be effectively controlled when the combustor operates in lean premixed conditions. However, the efficiency of the latter must be improved before premixed combustion can be implemented in practice. With the advancement of high-performing computers, LES is becoming more and more popular, especially to capture unsteady effects. In most of the engineering applications the combustor operates between the so called Corrugated Flamelet regime and the Thin Reaction Zone regime [1]. In these regimes the scalar variance transport equation reduces to a predominant balance between reaction rate and SDR. In LES context though, the progress variable may not be well approximated by a bi-modal PDF as in RANS [2], because of the partial resolution of the flame. Nonetheless, the processes associated with combustion occur at the small scales and thus the reaction rates need to be modelled. Moreover, in premixed flames the rate of micro-mixing, determined by the SDR, is intimately related to the chemical reaction rate and thus the mean reaction rate is proportional to the SDR. An algebraic model for LES [3], yet to be implemented in a CFD code, will be used in this work and the results will be validated using experimental data [4, 5]. As a first step towards this goal, a validation of scalar mixing case [6] is attempted and results from this calculation will be discussed.

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Sensitivity analysis of thermo-acoustic systems via a novel technique based on adjoint equations

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Abstract:
In a thermo-acoustic system, such as a flame in a tube, heat release oscillations couple with acoustic pressure oscillations. If the heat release is sufficiently in phase with the pressure, these oscillations grow, sometimes with catastrophic results. Control of these oscillations is one of the most challenging problems in the design of gas turbine and rocket engines. By means of adjoint sensitivity analysis, we aim to identify the most influential parts of a thermo-acoustic system and identify how to control them passively.

We apply adjoint-based sensitivity analysis to a time-delayed thermo-acoustic system: a Rijke tube containing a hot wire [1]. We calculate how the growth rate and frequency of small oscillations about a base state are affected either by a generic passive control element in the system (the structural sensitivity [2]-[3]) or by a generic change to its base state (the base-state sensitivity). We illustrate the structural sensitivity by calculating the effect of a second hot wire, with a small heat release parameter. We find the positions at which it has an optimal influence on the oscillations. We illustrate the base-state sensitivity by calculating the effects of tiny variations in the the damping factor, the heat-release time-delay coefficient, the heat-release parameter, and the hot wire location. Sensitivity analysis requires the direct governing equations (linearized about a base state) and the adjoints of these equations. We calculate these adjoints via two different approaches: (1) discretising the Continuous Adjoint equations (CA), (2) deriving the Discrete Adjoints (DA).

The successful application of this novel sensitivity analysis to thermo-acoustics opens up new possibilities for the passive control of thermo-acoustic oscillations, by providing gradient information that can be combined with constrained optimisation algorithms in order to reduce linear growth rates.

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DNS of laminar and turbulent premixed flames with inhomogeneous reactants

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Abstract:
Direct Numerical Simulation (DNS) of laminar and turbulent premixed combustion has been carried out in the presence of inhomogeneous fuel-air mixtures. The purpose of the study is to identify and to quantify flame stretch effects due to fluid-mechanical straining and also to differential propagation in the presence of gradients in fuel-air mixture strength. The in-house DNS code SENGA2 is used, and the simulations were performed on the UK national supercomputing facility HECToR. The chemistry is represented using a reduced methane-air reaction mechanism with 18 species and 68 steps, and the simulation domain is cuboidal in shape with a total of 250 million grid points.

Two competing effects, from the turbulent straining and from the composition gradient, influence the production of flame surface area and the overall flame consumption speed. Preliminary results have shown the existence of a correlation between flame surface area enhancement and the local transverse mixture gradient. This is in agreement with similar findings for two-dimensional laminar flame simulation[1].

Results are presented for the evolution of the inhomogeneous-mixture premixed flame in both laminar and turbulent flow fields. The effects of differential propagation are illustrated, and statistics are extracted to describe the development of the correlation between the turbulent strain rate and turbulent flame area enhancement, together with the associated consumption speed, displacement speed and heat release.

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DNS of turbulent MILD combustion

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Abstract:
MILD combustion is considered as an important combustion technique to achieve high combustion efficiency with low pollutant emissions [1-3]. In a MILD condition, the reactants are diluted with burnt gases so that the temperature rise is low compared to autoignition temperature for the given fuel. Also the diluted mixture is preheated higher than the autoignition temperature. From an experimental view point, there is no discerning flame front in direct photographs of MILD combustion [4, 5]. Reynolds averaged Navier-Stokes (RANS) simulations have been performed using a flamelet or eddy-dissipation based methods [6, 7] and the computed temperature field shows a trend consistent with experimental results, while the peak temperature differs by about 600 K, especially when the oxygen concentration is low. It is shown by Aminian et al [8] that the prediction of minor species is sensitive to temperature fluctuation in RANS. These results suggest that the applicability of conventional modeling approaches should be validated either by using advanced laser diagnostics or DNS. In this study, DNS of MILD combustion with EGR has been carried out. Partially premixed mixture fields are carefully constructed to achieve appropriate EGR and MILD combustion conditions.

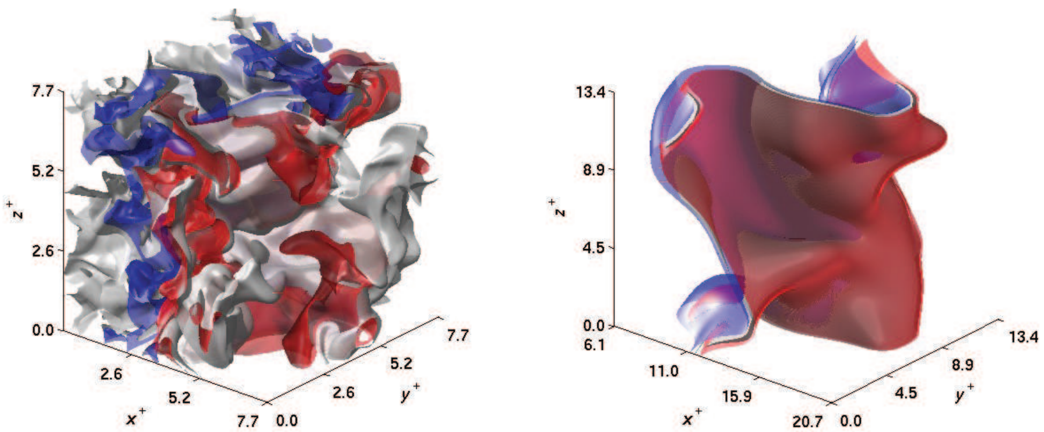

Figure 1: DNS results of MILD (left) and conventional (right) combustion. Iso-surface are the progress variable, c=0.4 (blue), c=0.7 (red) and 1.3 of the normalised reaction rate (white).

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High Temperature Condensation Particle Counter

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Condensation Particle Counters (CPCs) are commonly used to measure the number concentration of airborne nanoparticles in various applications. A typical CPC consists of three major stages. They are: a saturation stage where an aerosol sample is saturated with vapour of a fluid e.g. butanol; a supersaturation stage where the nanoparticles grow to optically detectable sizes by condensation of the vapour on particle surfaces; and an optical particle counter (OPC). The working temperature of a typical CPC is around ambient or slightly higher.

This work is connected with the development of a CPC that operates at such a high temperature that volatile material is not measured, due to it being evaporated or prevented from condensing. The obvious application is measurement from internal combustion engines, where the European legislated particle number method (PMP) requires a complex system for the removal of volatile material, prior to measurement by a conventional CPC.

The study involves theoretical modelling, design, construction and testing of a high temperature CPC. Di-Ethyl-Hexyl-Sebacat (DEHS) has initially been chosen as the working fluid because it is non-toxic, is a liquid at room temperature and has a high boiling point. The supersaturated region in the condenser where particles are grown, is modelled by numerically solving the heat and mass transfer equations based on the finite difference method. The model was found to be in good agreement with an alternative model due to Stolzenburg and McMurry (1991). The simulations suggest that the high-temperature CPC will be able to grow and detect fine particles. The saturator and condenser would be held at approximately 210˚C and 190˚C respectively.

Experimental Study

A step decrease in particle concentration was introduced at the aerosol inlet. Particle pulses in the optical signal were counted over periods of 20 ms. The particle number vs. time is shown in Figure 1.

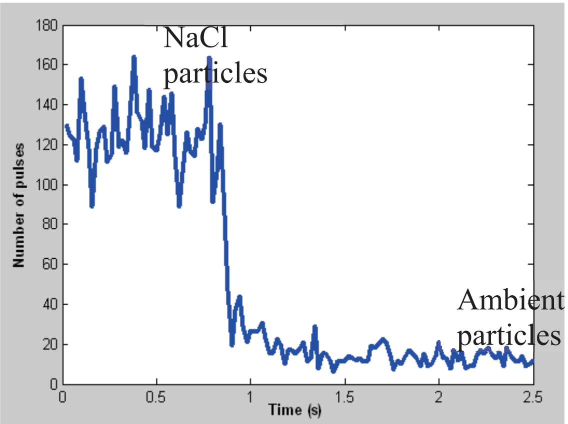

Figure 1. Testing of the high-temperature CPC
Particle counts vs. time

The high-temperature CPC has been shown to successfully grow and detect NaCl particles and ambient particles.

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Uncertainties in Aircraft Engine Soot Emissions

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Abstract:
Aircraft gas turbine engines emit particles with a geometric mean particle diameter less than 100 nm consisting of non-volatile and volatile particles (*1*). The non-volatile component is primarily black carbon soot (BC). Current regulation is concerned with the visibility of aircraft exhaust, quantified via the engine smoke number (SN) and each engine type is measured before entering service (*2*, *3*).

Impact assessment of BC on climate and air quality requires mass based emissions estimates. As a result, a method called the First Order Approximation v3.0 (FOA3) is currently endorsed by the US Federal Aviation Administration and the International Civil Aviation Organization to estimate mass emissions of BC (*4*). This method relies on an empirical relationship between BC mass concentration in an exhaust sample and resultant SN. This method, relying on SN, shows a factor of ten or more discrepancy with recently published measurement data for 40% of cases compared.

Flexibility within the SN measurement standard procedure is potentially a significant contributing factor and results from a recent experimental study to examine the influence of changing parameters including incident flow velocity (a function of filter diameter), within the prescribed ranges. These results are important to quantify the error associated with current estimation methods used in airport emissions inventories and motivate the development of alternative methods independent of SN.

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Developing a Dimensionless Evaluation Framework for Oil Extraction by In Situ Combustion

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Abstract:
New in situ combustion (ISC) method variants hold much promise in the way of ultimate oil recovery as well as recovery rates. We investigate the interactions of thermal and reaction waves for ISC recovery of heavy oils, a hugely abundant natural resource.

Using an in house code, we simulate ISC. A set of dimensionless screening parameters is developed in order to investigate important phenomena i.e. ignition delay time, flame thickness and propagation, ultimate recovery and recovery efficiency.

Defining a heavy oil Damkohler number (Da_O) allows us to discern three performance regions of ignition delay: thermal diffusion limited, chemistry limited, oxygen supply limited. There exists also a coke Damkohler number (Da_C) threshold for the combustion wave to propagate or else extinguish. The ISC process efficiency and recovery rate are observed to be functions of the Da_C number.

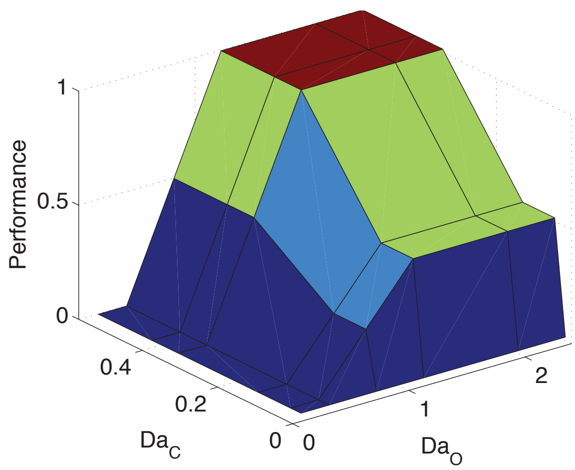

Figure 1: ***Context free performance of the ISC method plotted vs.*** Da_O ***and*** Da_C***, which were found to be the dominant governing dimensionless parameters.***

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Turbomachinery group abstracts

Unsteady interaction between annulus and turbine rim seal flows

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Abstract:
In high-pressure gas turbines relatively cold air is purged through the hub gap between stator and rotor in order to ensure the mechanical integrity of the blade root and the rotor disc. Although rim sealing mass flow rates are comparatively small, their effect on the rotor hub endwall flows and therefore on the performance of the turbine can be significant.

In this paper, results from numerical flow simulations are validated against test data from a scaled turbine configuration. The numerical model is then used to study the interaction between the annulus and rim purge flows in detail. Stage parameters are used to evaluate turbine performance. It is found, that the rim seal flow field is strongly influenced by the sealing mass flow rate, the sealing tangential velocity and the circumferentially non-uniform pressure field of the rotor blades. At typical sealing flow conditions, the flow interaction at the rim seal interface is found to be inherently unsteady, with periodical vortex shedding into the rotor passage. Finally, experimental evidence for the unsteady rim seal flow interaction is presented.

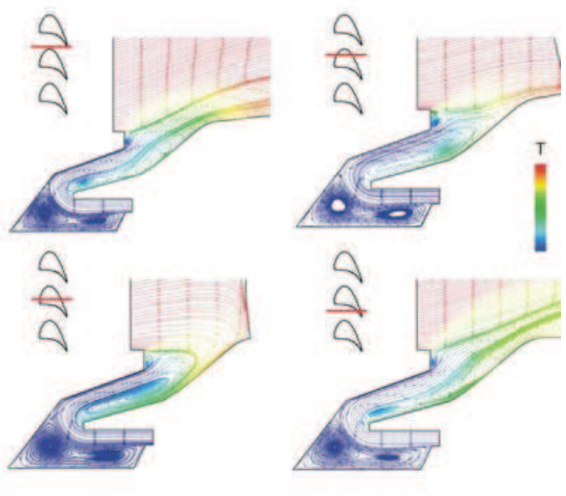

Figure 1: ***Circumferential variation of rim seal flow field, illustrated with streamline-projections coloured by local temperature***

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DNS of surface roughness effects on wall turbulence at low Reynolds number

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Abstract:
Direct numerical simulations of fully developed incompressible turbulent channel flow over smooth, wavy and highly irregular rough walls were performed to reveal the surface roughness effects at low Reynolds number. The unsteady incompressible Navier-Stokes equations were directly solved by the method of artificial compressibility utilizing the parallel structured high-order finite difference CFD solver — BOFFS [1, 2]. Time-averaged statistical quantities of the smooth and wavy wall cases compare favorably with previous DNS and experimental datum [3, 4, 5]. Mean streamwise velocity profile of the highly irregular rough wall case aligns well with the classical Prandtl-Schlichting sand-grain theory, and the variations of the turbulent fluctutions and the Reynolds shear stress show the same trends as the measurements at higher Reynolds number [6]. The distinctly different characters of the near-wall coherent structures over the three surfaces studied suggest the substantial influence of surface roughness to the wall-bounded turbulence, especially in the bursting process of turbulence production [7, 8, 9], even though the basic elements of the coherent motions are similar.

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Large Eddy Simulations in Turbines

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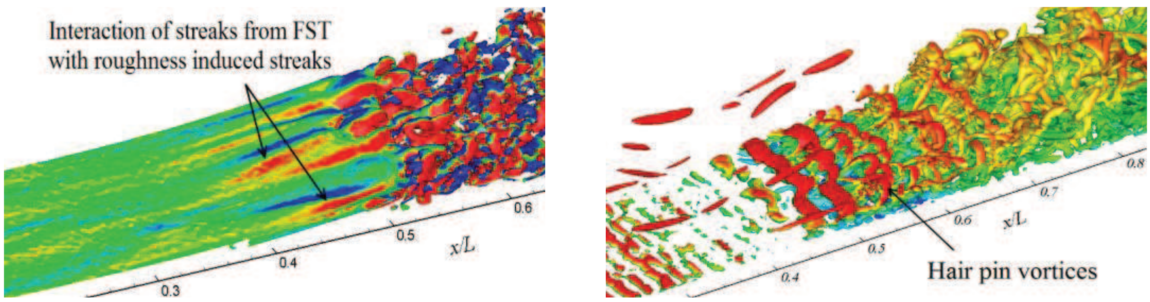
Abstract:
The Low Pressure Turbines (LPTs) of modern aero engines employ "high-lift" blade designs. They typically feature a laminar separation bubble on the suction surface due to high loading. The size of the separation bubble is governed by the state of the separated shear layer (SSL) which is highly sensitive to the inherent unsteady environment (which includes background free-stream turbulence (FST), unsteady wakes shed by the upstream rotor blades, roughness on the blade surface, etc.) [1].

The objective of the current study is to numerically investigate the individual and coupled effects of incoming free-stream turbulence (FST) and surface roughness on the separation of a boundary layer over a flat plate, with an imposed pressure distribution representative of low pressure turbine (LPT) loading. The formation of streamwise streaks in the presence of FST and roughness and their role in promoting earlier transition are captured. The potential '*roughness benefit*' [2] obtained in the case of highly loaded turbine blades in terms of its significant reduction of profile loss is also shown. A brief note on the ongoing simulations with incoming wakes and the effective inflow conditions in turbomachinery flows will be discussed.



(a) (b)

Figure 1: (a) Iso-surfaces of z-vorticity (z =-100) contoured with y-vorticity over the separated shear layer and (b) the corresponding Q surfaces (Q =50) contoured with streamwise velocity

References:

[1] Coull J. D. and Hodson H. P., (2011), Unsteady boundary-layer transition in low-pressure turbines. *J. Fluid Mech.*, vol. 681, pp. 370-410.
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Hybrid RANS-NLES for Jet Turbulence and Noise for Realistic Configurations

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Abstract:
Noise is one of the most challenging issues being faced by people living near airports. Industries have been focussing on alleviating engine noise which has second lagrest contribution from jet noise after fan noise. We here, are focussing on practical LES rather than rigorous LES[1] for Jet noise. Robust industrial solvers which are independent of grid resolution are required for this purpose . The validation study of one such industrial solver with hybrid RANS-NLES technique[2] is done for a round jet configuration to establish a set procedure to deal with the complex geometry configurations. The noise post-processing is done using Ffowcs Williams Hawkings(FWH) formulation for jet nosie. The noise preditions for round jet have succesfully agreed with noise data published in past. The real gometry jets that are under study are the real jet exhaust nozzle, the exhaust nozzle with eccentricty, nozzle with

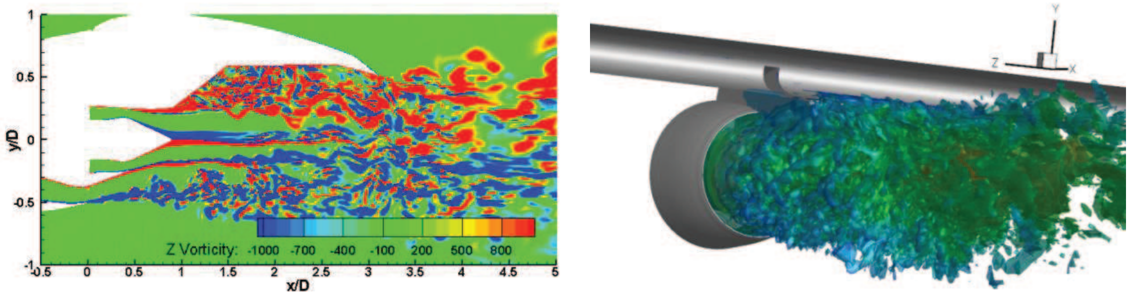

Figure 1: ***2D vorticity contours(Left) and 3D vorticity isosufaces for jet nozzle with pylon, wing and flap(Right)***

pylon and wing with flap. The jet inlet conditions are also realistic with hot inner core and cold fan air. The noise predition for realistic geometries will give an idea about noise magnitude and directivity in lower hemisphere(towards the ground) during flight take-off . Figure. 1 shows 2D contours and 3D isosurfaces of vorticity for the most realistic jet exhaust configuration.

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[2] Eastwood, S. & Tucker, P. (2011). Hybrid LES-RANS of complex geometry jets. *International Journal of Aeroacoustics*, 10, 661-686.

Clocking In Multi-Stage Axial Turbines

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Abstract:

The overall fuel consumption of high-bypass aero engines strongly depends on the efficiency of the Low Pressure (LP) turbine. Current designs already have efficiencies in the range of 92% - 94%, but significant effort is devoted to achieve further improvements. The "clocking" of multi-stage machines is a potentially attractive method of improving efficiency, whereby the relative circumferential position of stationary or rotating components in adjacent stages is altered. When the number of rotating or stationary components in a stage are the same as that of the next stage the wakes and wake segments from one stage can be in phase with the alignment of the next stage. By clocking the adjacent stage, the phasing of wakes and wake segments onto the downstream aerofoils will be altered, either onto the leading edges or into the mid-passages, with potential improvements of the aerodynamic efficiency.

The aim of this project is to assess the clocking effect within multi-stage axial turbines, applying both numerical and experimental techniques, however only the experimental data will be discussed in this presentation. The experimental testing is completed on the Low Speed Research Turbine (LSRT), known as the Peregrine rig, located at the Whittle Laboratory. This presentation includes the experimental results for a two-stage High Pressure (HP) turbine with four stator clocking positions and outlines the planned experimental work the two-and-a-half-stage LP turbine.

The clocking effect has been investigated experimentally and the efficiency variation between the maximum and the minimum efficiency clocking positions is measured to be 0.37%. For an intermediate efficiency clocking position it is seen that the wake segments from the upstream stator impinge in the mid-passage region near the downstream stator suction surface. Further investigation of a two-stage LP turbine with upstream rotating bars to simulate upstream rotor wakes is planned to investigate the effects of real geometry features, such as stator and rotor shrouds, knife-edge seals and cavities.

Notes

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