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The Cambridge workshop on turbomachinery for heat recovery and low-carbon power

The Whittle Laboratory
University of Cambridge
19th May 2015

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The purpose of this workshop

This 1-day workshop aims to bring together academics, research students and people working in industry, involved in turbomachinery and thermofluid dynamics of real-gas flows. The workshop aims to discuss the technological and research challenges for modern and future low-carbon technologies, such as low-carbon power generation, advanced cycles and heat recovery systems. The topics for discussion will include:

- Organic Rankine Cycles
- Supercritical CO2
- Non-equilibrium flows
- Thermodynamic Cycle analysis
- Real-gas/Dense-gas flows

This workshop is funded by the EPSRC through the EPSRC Fellowship scheme (EP/L027437/1). This project is entitled 'Transforming heat-recovery system performance by exploiting multi component turbine flows'. Further information about this project can be found at http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/L027437/1

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1. Programme

09:00 Arrival

09:30 Introduction. *Andy Wheeler (Whittle Lab, CUED)*

09:45 Industrial Applications of Turbines Operating on Multi-Component Fluids. *Doug Hofer (GE Global Research)*

10:15 Twin-screw positive displacement expanders for ORC applications. *Matthew Read (City University London)*

10:45 Predicting radial turbine off-design performance within organic Rankine cycles (ORC) when operating conditions and working fluids change. *M White and A I Sayma (City University London)*

11:15 Break

11:45 Non ideal compressible fluid dynamics (NICFD) - an overview on science and applications. *Piero Colonna (Delft* University of Technology*) and Alberto Guardone (Politecnico di Milano)*

12:15 Shock-refraction properties in dense vapours. *Emile Touber (Imperial College)*

12:45 ORC: It's All About Cost. *Clive Whitbourn (DRD)*

13:15 Lunch

14:15 Real gas flow in turbomachinery. Derek James Taylor (ALSTOM)

14:45 Recent work to validate an in-house wet steam CFD solver. *J. Starzmann and F. R. Hughes (Hopkinson Laboratory, CUED)*

15:15 Fluid curtains for enhancing seal performance in applications from ORC expanders to large steam turbines. *Simon Hogg (Durham University)*

15:45 Break

16:00 A study of trailing-edge losses in Organic Rankine Cycle Turbines. Francisco Dura Galiana *(Southampton University)*

16:30 Analysis of a thermo-fluidic feed pump for ORC applications. *Edward Richardson (Southampton University)*

17:00 Close. For those attending dinner at Downing College: *pre-dinner drinks from 7pm at the West Lodge, followed by dinner at 7.30pm in the Maitland Room*

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2. Abstracts

Industrial Applications of Turbines Operating on Multi-Component Fluids

Doug Hofer, GE Global Research

Turbines operating on multi-phase and multi-component working fluids are increasingly being employed in a range of industrial applications. This talk will provide an overview of some important applications of turbines operating on multi-component fluids and the challenges faced by designers of these machines.

Twin-screw positive displacement expanders for ORC applications

M.G. Read, Centre for Positive Displacement Compressor Technology
City University London

Maximising net power output from an ORC system is a compromise between increasing the mean temperature of heat addition, and increasing the amount of heat extracted from the source fluid. By the use of a twin-screw expander, instead of the more conventional turbine, it is possible to admit the working fluid to the expander as wet vapour and thereby eliminate both the need to desuperheat the vapour after expansion and, simultaneously to raise the evaporation temperature, thus improving the cycle efficiency while also maximising heat recovery; this has significant implications for the potential cost and performance of ORC systems. A multi-variable optimization program has therefore been developed to investigate the performance of Wet Organic Rankine Cycles (WORC) for generating power from low temperature heat sources. The cycle model contains a detailed thermodynamic model of a twin-screw expander, and allows the characterisation of system components at specified design conditions. Results will be presented showing optimised WORC performance at both design and off-design conditions for a range of applications and the potential advantages of these systems will be discussed.

Predicting radial turbine off-design performance within organic Rankine cycles (ORC) when operating conditions and working fluids change

M White and A I Sayma, City University of London

Small-scale ORC technology has yet to reach commercial maturity, mainly due to the lack of suitable expanders such as radial turbines. For these systems, due to the economy of scale, it is reasonable to assume that the same turbine must be able to operate efficiently within a range of different ORC applications. Within such applications, it is not suitable to assume that expander performance remains constant and therefore models to predict off-design performance are necessary. This presentation summarises work investigating the applicability of similitude theory to ORC turbines, where predictions made using similitude theory are compared to CFD results. Initial cycle analysis results coupling ORC thermodynamic analysis with similitude theory also

show how one turbine design may be successfully implemented within a range of different ORC applications.

Non ideal compressible fluid dynamics (NICFD) - an overview on science and applications

Piero Colonna, Delft University of Technology
Alberto Guardone, Politecnico di Milano

Compressible flows of fluids whose thermodynamic properties do not obey the ideal gas law are interesting from a scientific and practical point of view. Examples of these flows are those occurring in the dense vapor thermodynamic region, close to saturation, in the supercritical thermodynamic region, and also vapor-liquid flows at high reduced temperature/pressure. The fluid can be pure, or a mixture. Research on this topic increased substantially starting from the early 2000 and the trend continues, driven by scientific curiosity due to the predicted unconventional features of the flow fields, and by innovative applications in the power and propulsion sector, especially related to renewable energy systems.

The basics of the theory of NICFD are treated starting from the definition of the fundamental derivative of gas dynamics. A short of overview of the current research is provided, together with highlights on the most recent topics that open new venues to investigation, especially nonclassical gas dynamic phenomena in vapor-liquid flows close to the critical point, and in dense vapor mixtures. The overview is concluded with the illustration of some applications in turbomachinery related to practical problem currently studied by the Propulsion and Power group of the Delft University of Technology.

Shock-refraction properties in dense vapours

Emile Touber, Imperial College

Shocks are known to act as effective acoustic and turbulence amplifiers. However, such interactions have exclusively been considered in the context of an ideal gas. Can dense-gas inter-molecular forces significantly alter the nature of such interactions? In this presentation, we explore dense-vapour effects on the refraction properties of a normal shock. In particular, we show that the amplification factors of entropic and acoustic perturbations can either be significantly increased or damped when compared to an ideal gas. Such changes can occur over a very narrow range of upstream Mach numbers. Whilst a specific concern to ORC turbines, these salient dense-gas effects may also be exploited.

ORC: It's All About Cost

Clive Whitbourn, DRD Power Ltd

In a nutshell we will be saying that nobody will buy an ORC system unless it gives good value for money compared to other sources of electricity. All costs need to be considered: capital cost, installation cost, maintenance costs, and the costs of refrigerant and lubricant. Ideally, we don't

want a lubricant. Safety and the environment have an impact on cost, so liquids that are toxic or flammable should be avoided, and what you don't have can't leak.

Real gas flow in turbomachinery.

Derek James Taylor, ALSTOM

Accurate modelling of real gas flows in turbomachinery, and other components within a power generation cycle, is becoming increasingly important. Firstly, correct prediction of losses is vital in ensuring that tender and contract guarantees can be met. Secondly, real gas modelling allows for additional scope to component, e.g. condensers, optimisation that could not be considered when using perfect gas modelling. This talk presents an overview of the current practices within ALSTOM as well as looking at the areas considered to be of high importance for the future.

Recent work to validate an in-house wet steam CFD solver

J. Starzmann and F. R. Hughes, Hopkinson Laboratory, Cambridge University

In modern steam power plants condensation occurs in the last stages of the low pressure turbine as well as in the high pressure turbine. The droplets that are formed can cause erosion damage and are responsible for additional power losses. Over the past decades a great deal of experience in modelling phase change in such rapidly expanding steam flows has been accumulated in Cambridge. However, a new wet steam solver has recently been developed and this has renewed the question about the ability of available wet steam models to accurately predict droplet formation and droplet growth under non-equilibrium steam conditions. The present contribution summarises the recent work on different Laval nozzle test cases and includes a comparison of different equations of state.

Fluid curtains for enhancing seal performance in applications from ORC expanders to large steam turbines.

Simon Hogg, Durham University

This presentation gives an overview of recent work at Durham University on using fluid curtains and jets to create blockage and enhance the performance of aerodynamic seals in turbomachinery applications. The technology has the potential to improve the performance of all scales of turbomachinery from ORC expanders with power outputs in the kW range up to large steam and gas turbine plant with outputs of order 100 MW. The results from idealised generic proof of concept laboratory experiments are described together with some early results from a first application in an ORC expander and some proposals for how the new technology could be applied to larger turbomachines.

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A study of trailing-edge losses in Organic Rankine Cycle Turbines

Francisco Dura Galiana, Aerodynamics & Flight Mechanics Group, Southampton University

In this study vane trailing-edge losses which occur in Organic Rankine Cycle (ORC) turbines are investigated. Experiments are performed to study the influence of dense gas effects on trailing-edge loss in supersonic flows using a novel Ludwieg tube facility for the study of dense-gas flows. The data is also used to validate a CFD flow solver. The computational simulations are then used to determine the contributions to loss from shocks and viscous effects which occur at the vane trailing-edge. The results show that dense gas effects play a vital role in the structure of the trailing-edge flow, and control the extent of shock and viscous losses.

Analysis of a thermo-fluidic feed pump for ORC applications

Edward Richardson, Aerodynamics & Flight Mechanics Group, Southampton University

The feed pump in a low-temperature Organic Rankine Cycle (ORC) can consume more than 10% of the expander power output. Feed pump technology therefore has a great impact on both thermal efficiency and return on investment in ORC power plant. The objective of this study is to evaluate and improve the thermodynamic performance of a recently proposed thermo-fluidic ORC feed pump. In contrast to traditional mechanical feed pumps, the thermo-fluidic pump is powered directly by heat, and it relies on thermal expansion in the evaporator to compress the fluid. A thermodynamic model for the thermo-fluidic pump is derived and used to evaluate performance metrics that characterise pump operation and its impact on the overall efficiency. The analysis indicates that the thermo-fluidic pump can give a thermal efficiency superior to an ideal mechanical feed pump in a low-temperature ORC.

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3. Delegates

Alison	Auld	Durham University
James	Betts	Weir/Allen Steam turbines
Piero	Colonna	DELFT
John	Denton	Emeritus Professor, Cambridge University
Martin	Dietrich	BOC
Francisco	Dura Galiana	Southampton University
Alberto	Guardone	Politecnico di Milano
Cesare	Hall	Whittle Lab, Cambridge University
Doug	Hofer	GE Global Research
Simon	Hogg	Durham University
Fiona	Hughes	Hopkinson Lab, Cambridge University
Roger	Mallinson	DRD Power Limited
Jonathon	Ong	GE Global Research
Rene	Pecnik	DELFT
Matthew	Read	City University
Edward	Richardson	Southampton University
Abdulnaser	Sayma	City University
Christoph	Schreiber	Whittle Lab, Cambridge University
Carl	Sequeira	Whittle Lab, Cambridge University
Gursharanjit	Singh	ALSTOM
Joerg	Starzmann	Hopkinson Lab, Cambridge University
Derek-James	Taylor	ALSTOM
Emile	Touber	Imperial College, London
Andrew	Wheeler	Whittle Lab, Cambridge University
Clive	Whitbourn	DRD Power Limited
Martin	White	City University
Alex	White	Hopkinson Lab, Cambridge University
Liping	Xu	Whittle Lab, Cambridge University
John	Young	Hopkinson Lab, Cambridge University
Luying	Zhang	ALSTOM