

## Proceedings of the NICFD 2016 Seminar

October 19<sup>th</sup> and 20<sup>th</sup>, Villa Monastero, Varenna, Italy

### Preface

This volume contains the papers presented at *NICFD 2016: 1<sup>st</sup> International Seminar on Non-Ideal Compressible-Fluid Dynamics for Propulsion & Power* held on the 19<sup>th</sup> and 20<sup>th</sup> of October, 2016, at Villa Monastero, Varenna, Italy. The conference website is [nicfd2016.polimi.it](http://nicfd2016.polimi.it).

NICFD 2016 promoted the exchange of scientific knowledge and fostered the interaction among researchers and professionals in the field of non-ideal compressible-fluid dynamics, with special emphasis on topics related to propulsion and power applications. The conference themes range from theoretical foundations to advanced numerical and experimental practices and applied technologies. Key themes are: experiments; fundamentals; numerical methods; optimization and UQ; critical and supercritical flows; turbulence and mixing; multi-component fluid flows; applications in ORC power systems; applications in supercritical CO<sub>2</sub> power systems; steam turbines; cryogenic flows; condensing flows in nozzles; cavitating flows; super/trans-critical fluids in space propulsion.

Four keynote lectures reviewed the state-of-the-art and illustrated future studies and applications: *Non-Ideal Compressible Fluid Dynamics: A Challenge for Theory* by Prof. Alfred Kluwick, TU Wien, Austria; *Cavitation Instabilities in Turbopump Inducers* by Prof. Seung Jin Song, Seoul National University, Korea; *Industrial applications of turbomachinery operating on non-ideal fluids* by Dr. Douglas Hofer, GE Global Research, USA; *Wall bounded turbulence in flows with strong property gradients* by Prof. Rene Pecnik, Delft University of Technology, The Netherlands.

The proceedings gather 27 papers reporting on cutting-edge research activities in NICFD for propulsion and power. The review paper by Prof. Alfred Kluwick opens the collection and provides the perspective on past discoveries, the context of present activities and the roadmap of future challenges in this new, exciting scientific field.

We would like to thank all the participants to NICFD 2016 and the members of the Scientific Committee, for providing guidance during the organisation of the conference and for managing the revision of the papers. We thank all reviewers for their invaluable help to attain the high scientific quality of the contributions collected here.

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Varenna, October 2016

Prof. Alberto Guardone, Politecnico di Milano, Chairman  
Prof. Piero Colonna, Delft University of Technology, Co-chair  
Dr. Andrew Wheeler, Cambridge University, Co-chair  
Giorgia Cammi, Politecnico di Milano, Program Manager  
Davide Vimercati, Politecnico di Milano, Submission Manager



## Invited keynote lectures

### *Non-Ideal Compressible Fluid Dynamics: A Challenge for Theory*

by Prof. Alfred Kluwick, Wien Technical University, Austria

Abstract: The possibility that rarefaction as well as compression shocks may form in single phase vapours was envisaged first by H. A. Bethe (1942), *The theory of shock waves for an arbitrary equation of state*, Technical Report No. 545, Office of Scientific Research and Development. However, calculations based on the Van der Waals equation of state indicated that the former type of shock is possible only if the ratio of specific heat at constant volume  $c_v$  to universal gas constant  $R$  is larger than about 17.5 which he considered too large to be satisfied by real fluids. This conclusion was contested by P. A. Thompson, (1971) *A Fundamental Derivative in Gas Dynamics*, Physics of Fluids 14 pp. 1843–1849, who showed that the type of shock capable of forming in arbitrary fluids is determined by the sign of the thermodynamic quantity  $\Gamma = v^3/(2a^2)(\partial^2 P/\partial v^2)_s$ , which he referred to as the fundamental derivative of gasdynamics. Here  $v$ ,  $p$ ,  $s$  and  $a$  denote specific volume, pressure, entropy and the speed of sound. Thompson and co-workers also showed that the required condition for the existence of rarefaction shocks, that  $\Gamma$  takes on negative values, is indeed satisfied for several fluorocarbon vapours. This finding spawned a burst of theoretical studies elaborating on the unusual and often counterintuitive behaviour of flows with rarefaction shocks present. This produced results not only of a theoretical nature but results also suggesting the practical importance of Non-Ideal Compressible Fluid Dynamics (NICFD) in general. The present talk addresses some of the challenges encountered in connection with the theoretical treatment of the associated flow behaviour. Weakly nonlinear acoustic waves of small but finite amplitude serve as a starting point. Here mixed rather than strictly positive nonlinearity generates a wealth of phenomena not possible in perfect gases. Examples of steady flows where these nonclassical effects play a decisive role (and which may be useful also for future experimental work) are quasi 1D nozzle flows and transonic 2D flows past corners. The investigation of dissipative effects reveals completely different mechanisms for the regularisation of shock discontinuities in unconfined and confined flows. As a final example of nonclassical phenomena in NICFD the problem of laminar boundary layers with constant pressure gradient will be considered. In contrast to the classical Howarth problem solutions do not necessarily terminate in the form of a Goldstein singularity but may be continued beyond the point of zero wall shear. The local flow behaviour then is governed by an equation of Fisher type which describes the transition from strictly steady to unsteady periodic flow exhibiting early signs of the onset of turbulence.

### *Cavitation Instabilities in Turbopump Inducers*

by Prof. Seung Jin Song, Seoul National University, Korea

Abstract: Turbopumps deliver liquid fuel and oxidizer into the main combustion chamber in liquid rocket engines and are usually composed of radial pumps driven by axial turbines. Turbopumps operate under extreme environments characterized by high speeds, high pressures, cryogenic temperatures, and steep temperature gradients. Therefore, turbopumps are the critical devices which determine the success of liquid rocket systems. To prevent cavitation in the pumps, turbopumps deploy inducers, and, yet, the inducers themselves undergo cavitation. This cavitation can have thermodynamic, hydrodynamic, and even rotordynamic consequences. This talk will present such issues which arise in turbopump development efforts.

*Industrial applications of turbomachinery operating on non-ideal fluids*  
by Dr. Douglas Hofer, General Electric Global Research, USA

Abstract: Many industrial turbomachinery applications involve fluids that are not amenable to ideal gas assumptions. The classical application is steam turbines where both pressures above  $\sim 20$  bar and condensing liquid in the low pressure turbine leads to significant departures from the ideal gas relationships. In aviation engines and industrial gas turbines the high temperatures result in dissociation effects that render the ideal gas assumptions invalid. The processing of hydrocarbons frequently involves the intersection of non-ideal fluids and turbomachinery with applications ranging from gas compression to multiphase pumping. The emergence of closed loop power cycles using supercritical CO<sub>2</sub> as a working fluid brings another set of challenges for the industry to understand including operation of turbomachinery very near the critical point and potential for liquid and solid condensation. This talk will touch on each of these areas and provide an overview of industrial practice and open questions where further research is needed.

*Wall bounded turbulence in flows with strong property gradients*  
by Prof. Rene Pecnik, Technical University of Delft, The Netherlands

Abstract: Turbulent fluid flows with large gradients of thermo-physical properties can occur in a wide range of engineering applications, such as in flows with strong heat transfer at the wall, high-speed flows and in application with dense gases. The mean velocity, near-wall turbulent structures and mixing of scalar fields are greatly affected by near wall gradients in fluid properties. In order to study these effects, we will use direct numerical simulations with different constitutive relations for density and viscosity as a function of temperature, to mimic a wide range of fluid behaviours and to develop a generalised framework for studying scaling laws and turbulence modulations in variable property flows. The first part of the presentation will be on mean velocity scaling. Based on observations we will discuss a velocity scaling that is solely based on the semi-local Reynolds number. This scaling is able to collapse velocity profiles irrespective of near-wall density and viscosity gradients. In the second part, we will outline how near-wall density and viscosity gradients alter the Reynolds stress generation mechanism and inter-component energy transfer among turbulent stresses. In the last part of the presentation we will discuss how these effects alter heat transfer in turbulent pipe flows with fluids close to the vapour liquid critical point. In addition to that, we will also refer to recent advances in turbulence research for dense gases made by other researchers.

### **Scientific Committee of NICFD 2016**

Prof. Paola Cinnella, Arts et Métiers ParisTech ENSAM, France

Dr. Pietro Congedo, INRIA Bordeaux, France

Dr. Douglas Hofer, GE Global Research, USA

Dr. Christos Markides, Imperial College London, United Kingdom

Dr. Rene Pecnik, TU Delft, The Netherlands

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Dr. Andrea Spinelli, Politecnico di Milano, Italy

Dr. Emile Touber, Imperial College London, United Kingdom

Dr. Teemu Turunen-Saaresti, Lappeenranta University of Technology, Finland

Prof. Rosaria Vetrano, Von Karman Institute, Belgium

### **Review Statements**

Each paper accepted for publication underwent two rounds of review by two anonymous reviewers. The review process of each paper was managed by two members of the Scientific Committee. The first round of reviews took place before the conference. During the conference, each delegate had access to a web portal to input her/his review for each presented paper, in either an anonymous or named way. The second round of reviews took place after the conference and considered the opinion of the two anonymous reviewers as well as the delegates'. Final acceptance was decided by the two managing members of the Scientific Committee together with the Conference Chairman.