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Programme, 5th Workshop of ICR

MAICH CONFERENCE CENTRE, CHANIA, CRETE

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Day 1: 27th June 2017

08:15 – 08:45: Coffee and Welcome

Session 1: Experiments

08:50 – 09:00 **Prof Manolis Gavaises** (City, University of London, UK)
Welcome & opening address

09:00 – 09:40 **Prof Joseph Katz** (John's Hopkins University, USA)
Cavitation breakdown in pumps – Prevailing theories and reality

09:40 – 10:20 **Assoc. Prof. Matevz Dular** (University of Ljubljana, SI)
Cavitation and cavitation erosion in cryogenic fluids

10:20 – 11:00 **Dr Karathanassis & Prof Manolis Gavaises** (City, University of London, UK)
X-ray measurements of cavitating vortices in orifices

11:00 – 11:30: Coffee/tea break

Session 2: Numerical Simulations

11:30 – 12:10 **Prof Marc Fivel** (SIMaP, Grenoble INP Materials Science, FR)
Modelling cavitation erosion of metals

12:10 – 12:50 **Dr Koukouvinis & Prof Manolis Gavaises** (City, University of London, UK)
Overview of cavitation models and thermodynamic closure models

12:50 – 14:30: Lunch Break

Session 3: Poster Session

14:30 – 17:00 **15 presentations, 10 min each from the CaFE, HAOS and IPPAD EU-funded projects**

17:00 – 18:00 **Walking in posters**

19:00 – 20:00 **Drinks reception**
20:00 – 24:00 **Gala dinner**

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Day 2: 28st June 2017

Session 4: Ultrasound / bubble dynamics

09:00 – 09:40 **Prof Shuhong Liu** (Tsinghua University, CHN)
Motion of a free-settling spherical particle driven by a growing laser-induced bubble

09:40 – 10:20: **Dr Ian Rivens & Prof Gail Ter Haar** (Institute of Cancer Research, UK)
Cavitation detection for ultrasound imaging guided therapy ultrasound

10:20 – 11:00: **Dr Robert Mettin** (Goettingen, DE)
Direct observation of sonoluminescing bubble dynamics in multi-bubble field

11:00 – 11:30: Coffee/tea break

Session 5: Industrial Applications I

11:30 – 12:10 **Dr Lyle Pickett** (Sandia National Laboratories, USA)
Linking internal nozzle cavitation to variance in Diesel combustion

12:10 – 12:50 **Dr Robert McDavid** (Caterpillar, USA)
Modeling fuel injector cavitation impacts on combustion in large Diesel engines

12:50 – 14:00: Lunch Break

Session 6: Industrial Applications II

14:00 – 14:40 **Dr Russel Lockett** (City, University of London, UK)
Cavitation effects on fuels

14:40 – 15:20 **Dr Christiano Bombardieri** (DLR, DE)
Cavitation and multi-phase phenomena in liquid rocket engine systems

15:20 – 16.00: **Dr Andrew King** (Rolls Royce Controls, UK) **& Dr Mark Brend** (Loughborough University, UK)
Cavitation in fuel pumps

16:00 – 16:30: Coffee/tea Break

16:30 – 17:00: Discussion & Closing remarks

Day 1:

Cavitation breakdown in pumps – Prevailing theories and reality

Prof Joseph Katz (John's Hopkins University, USA)

Abstract

The flow mechanisms causing cavitation breakdown in axial turbomachines has been a long-standing puzzle. Prior conceptual models have attributed this phenomenon to e.g. choking, blockage, complete coverage of the suction side of the blade with vapor, and formation of perpendicular cavitating vortices (PCVs) along the tip region of the blade. The latter postulate has originated in our laboratory. However, recent experimental studies have demonstrated that using circumferential grooves to manipulate the tip leakage flow and suppress the PCVs does not alleviate the rapid performance deterioration in performance during breakdown. Furthermore, the continuous liquid flow along the pressure side (PS) of the blade indicates that breakdown does not involve flow choking. It also occurs when the trailing edge region on the suction side (SS) of the blade is still wetted. However, consistent with prior observations, the rapid reduction in pump performance begins when a slight decrease in pressure extends the attached/sheet cavitation on the blade SS into the blade overlap region. At this phase, the area covered by cavitation initially fluctuates, and then expands rapidly in the axial and radial directions to cover substantial fraction of the blade. These phenomena have led us to postulate that partial blockage to the liquid through-flow occurring when the cavitation reaches the overlap region accelerates the flow along the pressure side, reducing the pressure there, and consequently, the blade loading. Recent stereo-PIV measurements in the non-cavitating fractions of the passage have indeed confirmed that when the mean pressure is decreased below the breakdown threshold, the liquid velocity increases and the pressure decreases significantly along the blade PS. These trends support the postulate that the decrease in performance and the rapid expansion of the cavitation is initiated by cavitation-induced blockage.

Cavitation and cavitation erosion in cryogenic fluids

Dr Matevz Dular (University of Ljubljana, SI)

Abstract

Optimal operation of turbopumps is crucial for all liquid fuel rocket engines. To reduce weight, these pumps often operate at critical conditions, where dynamic instability and cavitation are unavoidable. Many studies were already performed to investigate these phenomena, yet, due to the complexity of the measurements, most avoid experiments in cryogenic fluids. Hence no data on thermodynamic effects of cavitation or on the specifics of cavitation erosion in cryogenic fluids exist, what threatens further progression of technology. In the talk I will show experiments in cryogenic fluids where cavitation is initiated acoustically – by ultrasound. We characterized the development, the dynamics and the physics of cavitation and erosion on an ultrasonic horn, which was operated at elevated pressures in liquid nitrogen.

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X-ray measurements of cavitating vortices in orifices

Dr Karathanassis & Prof Manolis Gavaises (City, University of London, UK)

Abstract

Temporally-resolved, x-ray, phase-contrast visualization of the cavitating flow within an enlarged injector replica has been conducted at the ANL Advanced Photon Source. The flow was captured through side-view, x-ray radiographies at 67890 frames per second with an exposure time of 347ns. Post processing of the radiographies obtained for the examined flow conditions and needle lift demonstrated that cavitation primarily emerges in the form of vortical structures of fluctuating and irregular shape with their interphase exhibiting high morphological variance. The spatial resolution of the x-ray technique employed, enabled the capturing of fine features that cannot be resolved using optical imaging techniques, e.g. shadowgraphy or Schlieren. Besides, the temporally-resolved nature of the measurements allowed the characterization of the string dynamical behaviour, as well as the magnitude of the underlying secondary flow motion, while it was made possible to obtain local velocity measurements in the string region for cases of both low and high cavitation extent.

Modelling cavitation erosion of metals

Prof Marc Fivel (SIMaP, Grenoble INP Materials Science, FR)

Abstract

Cavitation erosion tests have been performed on three metallic samples, in a dedicated cavitation tunnel available at LEGI, Grenoble. The eroded surface is observed after a few hours of erosion, during the incubation time.A large number of isolated pits are evidenced and measured in term of their diameter and depth.

An inverse finite element method is then conducted in order to determine the loading conditions that should be imposed in the modeling in order to get the exact same pit profiles. This gives an estimate of the flow aggressiveness in the cavitation tunnel.

The inverse method relies on an accurate description of the tested materials. We show that indentation tests complemented by Split Hopkinsin Pressure Bar test give a good estimate of the elasto-visco-plastic behavior of the three tested materials.

Finally, a damage criterion is introduced in model which gives first estimates of mass loss curves.

As a perspective to this work, improvements are proposed in order to account for the fluid/structure interactions either by coupling the FEM code to a fluid solver or by using Smoothed Particles Hydrodynamics simulations where both the solid and the fluid parts are managed by the same code.

Simulation of cavitating vortices – comparison with X-ray measurements

Dr Koukouvinis & Prof Manolis Gavaises (City, University of London, UK)

Abstract

Cavitating vortices are prevalent in many real-life applications, including fuel injection systems. In this work the flow inside an enlarged injector orifice is analyzed; the injector features the main components of a fuel injection system, such as a regulating (hemispherical) needle and a sac volume. Numerical investigations involve a barotropic cavitation model in conjunction with LES turbulence modelling. Analysis of the flow shows a pair of highly unsteady vortical structures emerging from the tip of the hemispherical needle and extending inside the orifice. Due to the intense vorticity, these vortical structures may periodically cavitate, forming a pair of two cavitating tubes inside the orifice. Simulations complement the experimental investigations, due to the inherent limitation of the latter providing only a side view of the flow.

Day 2:

Motion of a free-settling spherical particle driven by a growing laser-induced bubble

Prof Shuhong Liu (Tsinghua University, CHN)

Abstract

We document experimentally four different interactions of a laser-induced bubble and a free-settling particle, with different combinations of the geometric and physical parameters of the system. Our analytical model shows that four factors, i.e. the particle radius, the maximum bubble radius, the initial separation distance between the particle and bubble centers, the fluid viscosity, and the particle and fluid densities, influence the bubble-particle dynamics. Furthermore, the model accurately predicts the maximum particle velocity and the limiting condition when the particle starts to “bounce off” the bubble. In particular, we also investigate the high-speed ejection of the particle, and the supercavity forming behind the particle, in cases when initially the particle is in very close proximity to the bubble center. These observations offer new insight into the causal mechanism for the enhanced cavitation erosion in silt-laden water.

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Cavitation detection for ultrasound imaging guided therapy ultrasound

Dr Ian Rivens & Prof Gail Ter Haar (Institute of Cancer Research, UK)

Abstract

Therapy ultrasound can be delivered using a variety of regimes with different intent,ranging from high intensity for thermal ablation and high pressure for histotripsy (liquefaction), to lower pressure transient tissue permeabilisation which can be achieved by activating microbubbles. The coupling of these modes of therapy with ultrasound imaging guidance for hyperecho detection during exposure can make acoustic cavitation detection challenging. Techniques for achieving detection in vivo will be presented.

Direct observation of sonoluminescing bubble dynamics in multi-bubble field

Dr Robert Mettin (Goettingen, DE)

Abstract

Sonoluminescence (SL) is an intriguing phenomenon where light emission occurs due to the strong compression of gas in a collapsing bubble. When driven in an ultrasonic field, the extreme energy focusing by the bubble can reach 12 orders of magnitude, and indications for a plasma core in SL bubbles have been found. Although investigated now for decades, still open questions concern the exact oscillation dynamics and the collapse geometries of light emitting and/or chemically active bubbles, crucial factors for energy focusing and liquid/gas distribution in the bubble's "hot spot". Individual bubbles have been well studied under isolated conditions (e.g. in single bubble traps and single-bubble sonoluminescence, SBSL), but the typical environment of SL and applications of cavitation is an ultrasonically driven bubble cloud – the emissions are then termed multi-bubble sonoluminescence (MBSL).
While the analogy of the phenomena in a multi-bubble cloud as compared to single bubble experiments is still under debate, surprisingly up to now (and to the best of our knowledge), never any light emitting bubble has been clearly and doubtlessly identified within the multi-bubble environment, nor its respective oscillation dynamics. Here we demonstrate for the first time by high-speed imaging the simultaneous recording of emitted light flashes and the underlying bubble dynamics in multi-bubble fields, with up to 0.5 million frames per second. Among other findings, we observe frequent jetting dynamics of SL bubbles, which is different to standard single bubble experiments. Recorded transient bubble dynamics could be fitted numerically to obtain estimates of collapse peak temperatures (in one case 38000 K). We expect that our imaging technique will generally pave the way to more realistic pictures of collapsing bubbles in ensembles and to MBSL activity mappings on individual bubble level. This will help to better define the potential and the limits of this type of energy focusing in applications – beyond chemistry as well for surface treatment or in medical science.

Linking internal nozzle cavitation to variance in Diesel combustion

Dr Lyle Pickett (Sandia National Laboratories, USA)

Abstract

This presentation will provide an overview of detailed measurements and CFD predictions of internal nozzle flow, spray development, vaporization, ignition, lift-off stabilization, and soot formation for different types of diesel nozzles. The research includes effects of cavitation as well as differences between single, axial-hole nozzles to more realistic multiple, side-hole nozzles, all of which are targets of the Engine Combustion Network international working group. The cavitating Spray C nozzle produces a large spreading angle in the near-field, while the non-cavitating Spray D spreading angle increases gradually as it develops. The increasing spreading angle in the far field creates a virtual origin, or mixing offset, several millimeters downstream. Remarkably, this mixing offset appeared to globally influence the liquid penetration and lift-off stabilization location over a wide range of operating conditions. The multi-hole Spray B produces a spray spreading angle that varies in time, creating transients in liquid penetration that shorten or lengthen in response. The lift-off length of Spray B increases as the jet narrows, in an opposite trend compared to Spray A where the lift-off length decreases slightly with time. An overall theme is that cavitating flow significantly alters spray mixing processes, which in turn, affects combustion.

Modeling fuel injector cavitation impacts on combustion in large Diesel engines

Dr Robert McDavid (Caterpillar, USA)

Abstract

When developing heavy duty diesel engines for higher power density, careful consideration of the combustion system design is necessary as it is the key driver of engine performance and durability. As power density and engine size increases, fuel mass flow rates, injector hole sizes and thermal loads all increase significantly. While avoiding in-nozzle cavitation while achieving the higher fuel delivery to meet rated power targets is in itself very challenging, it is compounded by the need to meet mandated emissions levels. Both from a physical and computational perspective, achieving these competing targets becomes more difficult when combined with the geometric scale of diesel engines rated above 2MW. With a focus on fuel injection systems, this talk outlines the overall approach, tests and simulations employed in the design and development of large, heavy duty diesel engine combustion systems, while highlighting gaps in current simulation technology.

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Cavitation effects on fuels

Dr Russel Lockett (City, University of London, UK)

Abstract

Modern high-pressure diesel fuel injection equipment (FIE) meter the diesel fuel supply to the injectors and engine from one or more of the high-pressure pump, the pressure accumulator (common rail), and the injectors. The fuel metering process requires the separated fuel to be returned back to the fuel tank via control valves. The relaxation flow of the high-pressure metered fuel across the metering valves is likely to produce cavitation. There is a concern in the fuel industry and in the FIE manufacturers that metered fuel may be compositionally degraded by cavitation.

This paper reports the results of two experiments conducted at City, University of London, on (1) cavitation inception in model return valves, and (2) alteration of the composition of diesel fuel as a result of cavitation.

Experiment (1) involves the manufacture of optically accessible acrylic model pressure control valves characteristic of those found in diesel injectors. The models have been subjected to varying upstream to downstream fuel pressures in order to characterise the conditions required for cavitation inception.

Experiment (2) has been conducted in two parts, identified by 2A and 2B. In experiment 2A, 11 commercial diesel samples have been subjected to cavitation flow tests in a purpose-built high-pressure recirculating flow rig operating at 550 bar upstream pressure. The diesel samples have been subjected to in-situ optical extinction measurements at 405 nm. The composition of these diesels has been examined before and after the cavitation tests using two-column gas chromatography. A decrease in the volume fraction of mono-aromatics and di-aromatics has been observed, together with a corresponding increase in particle count.

In Experiment 2B, unadditized middle distillate diesel has been subjected to cavitation flow tests in a purpose-built high-pressure recirculating flow rig operated at 1,650 bar upstream pressure. The diesel samples have been subjected to in-situ optical extinction measurements at 405 nm. The composition of these diesels has been examined before and after the cavitation tests using uv-vis absorption spectrophotometry, and two-column gas chromatography. The uv-visible absorption spectra reveal a monotonic destruction of mono- and di-aromatics in the diesel sample, while the two-column gas chromatography reveals a decrease in the volume fraction of mono-aromatics comprising the diesel.

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Cavitation and multi-phase phenomena in liquid rocket engine systems

Dr Christiano Bombardieri (DLR, DE)

Abstract

During the start-up of a Liquid Rocket Engine (LRE) several multi-phase phenomena can take place in the propellant feedline. Among them, vaporous and gaseous cavitation occurring after a fast transient are of particular importance, as they affect the pressure evolution of the fluid. In satellites, the priming of an evacuated feedline involves flash evaporation, and the same happens in the combustion chamber when the propellants are injected in supercritical conditions while the spacecraft is exposed to the vacuum of space.

In launcher systems a common propellant combination is liquid oxygen and liquid hydrogen. Since these cryogenic fluids are usually near their saturation properties, they are prone to cavitation. Sheet cavitation is likely to happen at the pump impeller and inducer, which typically run at rotation speeds of the tenth of thousands of rpms.

Cavitation in fuel pumps

Dr Andrew King (Rolls Royce Controls, UK)
Dr Mark Brend (Loughborough University, UK)

Abstract

The main engine fuel pump on a gas turbine engine receives fuel from the airframe feed system and increases the pressure sufficiently for delivery to the downstream control devices. A twin pinion gear pump commonly forms the main stage of such a device and the rapid fluctuation of pressures and velocities around the meshing teeth requires good porting design in order to avoid cavitation erosion and achieve high flow efficiency. Reliable analytical tools are an important part of the design process and Rolls-Royce has invested in the development of advanced tools and techniques over many years. An important element of this is flow visualisation and a new study has recently been conducted that captures key aspects of flow behaviour in this demanding environment.