# CRYOGENICS ACTIVITIES @VKI - CAPABILITIES

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## ENVIRONMENTAL AND APPLIED FLUID DYNAMICS DEPARTMENT

The activities of the EA department cover a wide range of domains in response to the demands of the industry. Multiphase flows, aeroacoustics, wind engineering and cryogenic flows are some of the disciplines covered by this multidisciplinary department.
Since 2010, the EA department has created a cryogenic laboratory to answer to the large demand coming from the industrial partners in the framework of cryogenic propellant management and hydraulic elements characterization in cryogenic conditions. An experimental and a numerical team compose the cryogenic laboratory.

## CRYOGENIC LABORATORY

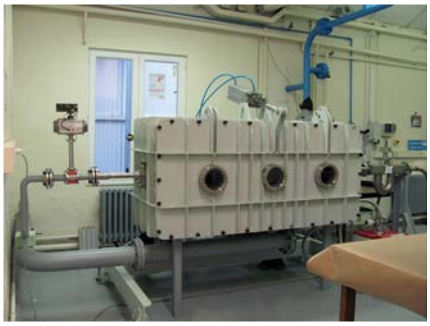
The laboratory is composed by two main facilities:
• The Cryogenic Line facility ***"CryoLine"***
• The Cryogenic Microgravity Experiments facility ***"CryME"***
• The Cryogenic Chill-Down Experiments Facility ***"CHIEF"***

***"CryoLine"*** is a large multipurpose facility, which allows the characterization of cryogenic valves and the study of cryogenic water hammer. The CryoLine facility can be placed horizontally, vertically and at intermediate angles to study the effect of gravity direction on cryogenic two-phase flows. Characterization of Cryogenic two-phase flow is performed using non-intrusive measurement technique, such as high speed and high-resolution visualization.
The facility is equipped with a reservoir of about 600 liters to store Liquid Nitrogen at an adjustable pressure from 1 to 20 bars allowing a maximum flow rate of 1.2 l/s. An on/off control valve allows to prime or to stop the flow of LN2 from the reservoir to the rest of the facility. The whole installation is certified.

The measurements section is composed by:
• A stainless steel pipeline, housing the selected element, and flush mounted measurement sensors (temperature and pressure sensors)
• Vacuum chamber (1.7mm x 0.7m x 0.7 m), surrounding the line offering a thermal insulation of all its elements.

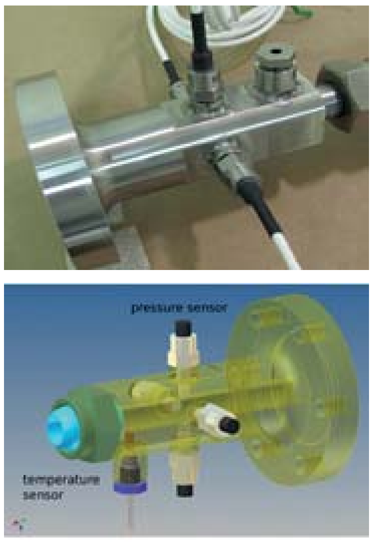
The chamber is provided of optical access (quartz windows).
The facility allows measurement of temperature, pressure, flow rate and visualization of the flow (single phase or two-phase ) during transient and at steady state.
The flow rate is measured by means of a Coriolis flowmeter, while the temperature and pressure sensors are placed in a VKI customized plugin module. The pressure transducers are screwed on the module in four points around the circumference of the inner pipe. The temperature sensor housing requires, instead, a cap that flush-mounts the sensor on the line.

The pressure transducers are Cryogenic Miniature ruggedized CTL-190 M series (Kulite France). The sensible tip has a four arm Wheatstone bridge as measuring principle, vacuum referred.
The temperature transducers are Resistant Temperature Detector (RTD) Cernox CX-1050-AA-HT-1.4L (Lake Shore Cryotronics, Inc).

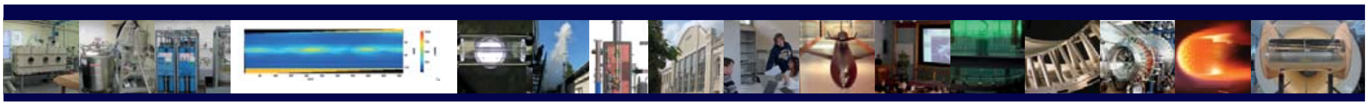


**CryoLine Facility, horizontal position**

**CryoLine Facility, vertical position**




**Temperature and pressure VKI plugin module**



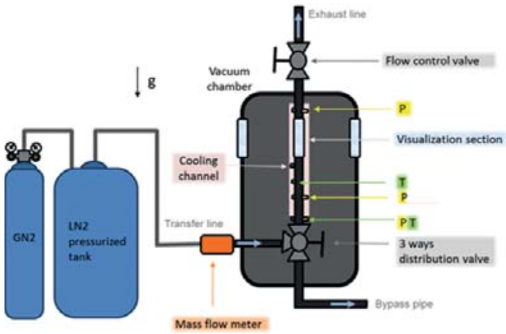
The ***"CryME"*** (Cryogenic Microgravity Experiments) facility is a fully customized cryostat, for the characterization of cryogenic sloshing, boiling and thermal stratification on earth and in microgravity conditions at temperature down to 70 K. The presence of large windows allows the use of non-intrusive optical techniques such as particle image velocimetry or high-speed visualization.

The cryostat is schematically composed by three areas:
• An evacuated space, which provide high thermal insulation of the inner parts;
• An LN2 reservoir, which pressure is properly define to obtain the LN2 temperature between 70 and 77 K;
• The sample area, surrounded by GHe, at temperature selected between 70 and 77 K.

The cryostat has been designed with a large internal sample area providing isothermal condition, with very high temperature uniformity. Different cells can be placed inside the cryostat to perform scientific experiments.

**CryME facility**

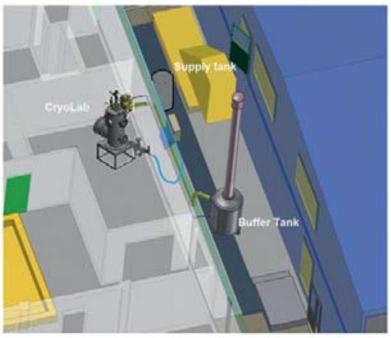
The ***"CHIEF"*** facility is a compact and versatile facility which allows the characterization of cryogenic the chill-down phenomena. The CHIEF facility is vertically oriented, and equipped with a reservoir of about 180 liters to store Liquid Nitrogen at an adjustable pressure from 1 to 6 bars. Different flow rates can be achieved acting on the two flow regulation valves at the end of the test section. A tree ways distribution valve allows to direct the test fluid through the test section or through the by-pass pipe, used to insure full liquid condition at the inlet of the measurement section.




**Schematic of the CHIEF Facility for cryogenic two phase flow characterization**

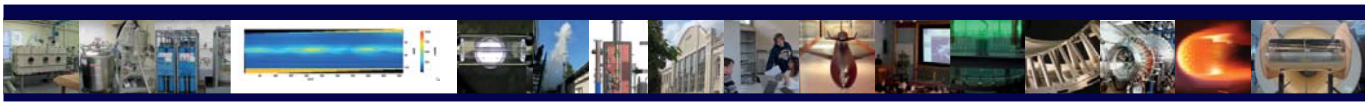
The measurements section is composed by:
• A copper channel, properly instrumented with temperature and pressure sensors in different locations along its length, and provided by transparent modules.
• A vacuum chamber surrounding the line offering thermal insulation of all its elements. The chamber is also provided of optical access.

Characterization of cryogenic two-phase flow is therefore performed by means of measurements of temperature, pressure, flow rate and visualization of the flow (single phase or two-phase ) during transient and steady state conditions. The flow rate is measured by means of a Coriolis flowmeter. The temperature transducers are Resistant Temperature Detector (RTD) Silicon Diodes (Lake Shore Cryotronics, Inc). The pressure transducers are screwed and flush mounted on the channel, the sensible tip has a four arm Wheatstone bridge as measuring principle, vacuum referred (Cryogenic CTL-190 M series Kulite). The flow regimens can be documented using non-intrusive measurement technique, such as high speed and high-resolution visualization.




**Representative view of the CHIEF location inside the Cryogenic Laboratory at VKI with the related LN2 supply and LN2 evacuation installations**

The whole installation is certified in complaint with the safety regulations related to liquid nitrogen installations.



# CRYOGENICS ACTIVITIES @VKI - CAPABILITIES

## COMPUTATIONAL FLUID DYNAMICS & NUMERICAL MODELING

Many space propulsion systems operate by means of cryogenic fluid, and during the design phase it is necessary to have computational tools able to predict accurately the cryogenic system behavior. The von Karman Institute developed a strong expertise in computational fluid dynamics for a wide range of flow regimes, both in the development of physical and numerical model. Current activities foresee the numerical prediction of the behavior of cryogenic liquid in pipes for space applications.

Collaboration with the experimental activity provide a source for updated correlations in order to better simulate heat transfer in cryogenic facilities and similar applications.

Different clusters are available for researchers and students: from a ClusterVision 1792 AMD Opteron cores with 7TB ram high performance cluster recently installed, passing trough an older SGI 512 Intel cores with 1TB ram, ending up with a low performance cluster of around 200 cores used by the students for learning purposes.

Specific numerical models are developed for data processing or for the simulation of physical processes. Engineering equations found through the VKI library, or developed and validated in-house using experimental facilities, are implemented in engineering tools.

## CONSULTING

Short consultation meetings are available to the industry on demand. The expertise of the VKI engineers can help you with a quick solution of your industrial problems.

**$LN_2$ exhausting line**

**$LN_2$ Ranger Station**

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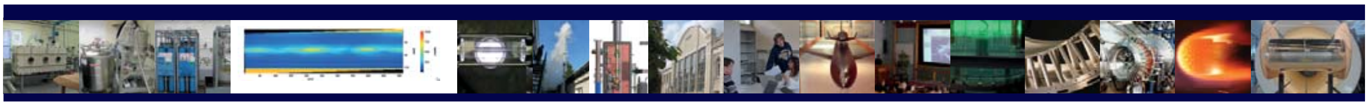
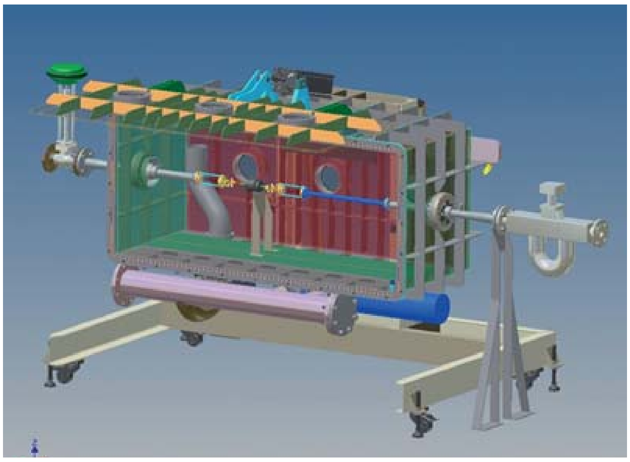
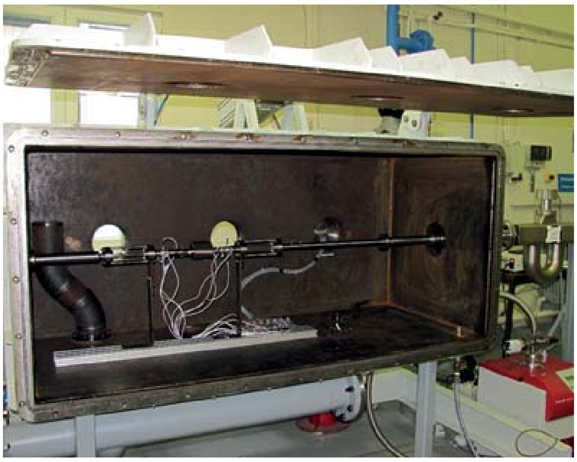


## CRYOGENIC VALVE CHARACTERIZATION

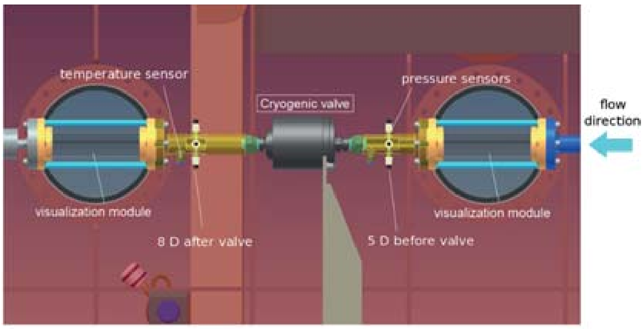
A deep investigation concerning cryogenic valves characteristics and related flow topology is one of the activity carried out thought the "CryoLine" facility. The selected cryogenic valve is hosted inside the vacuum chamber configured in its horizontal position, ensuring a proper thermally insulated environment with multiple optical accesses.

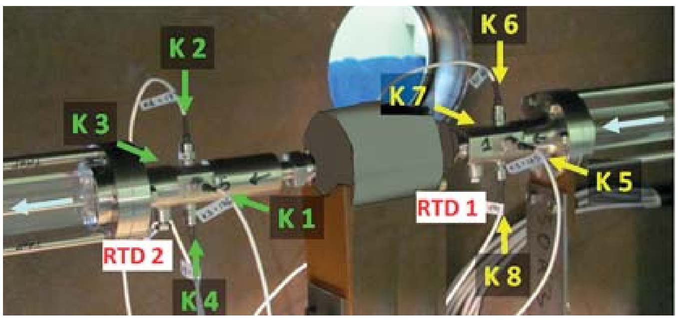




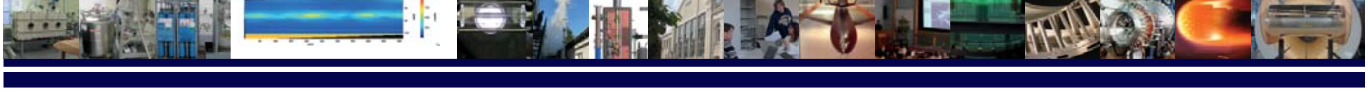
***CryoLine* Facility**
**configured for valve characterization testing**

The setup configuration is carefully designed in compliance with the current guidelines concerning the International Standard testing rules for valve components. Specific modules upstream and downstream the valve are foreseen to correctly plug the pressure transducers (Kulite CTL-190 M series) and the temperature sensors (Lake Shore Cryotronics Cernox CX-1050-AA-HT-1.4L) in a flush-mounted configuration. A Coriolis mass flow meter (Yokogawa RotaMASS RCCS38) is placed upstream the vacuum chamber. All the transducers are specifically chosen and positioned on the pipeline to ensure the best data accuracy and reliability, and the minimum flow disturbances. The cryogenic valve can be therefore extensively studied by means of these dedicated measurements. Flow visualizations thought the quartz transparent modules upstream and downstream the valve allow to collect additional scientific information for a comprehensive description of the valve behaviour: the flow topology trough the valve (single phase or two phase flow) can be documented with high speed visualizations by means of non-intrusive techniques.

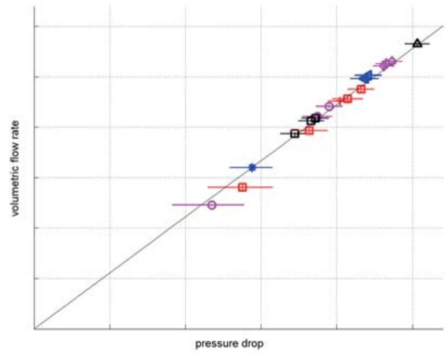


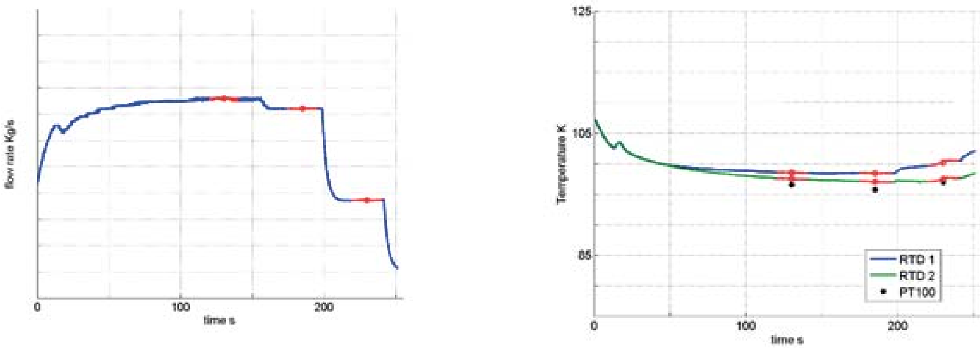

***CryoLine* Facility valve measurements section:**
**pressure and temperature transducers and flow visualization modules**



A measurement campaign is performed following a specific procedure to correctly operate the facility: after a proper cool-down phase to bring the pipeline down to cryogenic temperatures, the required upstream pressure is selected in a 600 l liquid nitrogen reservoir and the fluid is let flowing through the pipeline. Only when the steady state is reached, the data are considered valid for the valve characterization. During one run, it is possible to obtain different points along the valve characteristic curve regulating the LN2 mass flow rate acting on a downstream valve. In case the upstream reservoir pressure is changed between one test to another, it is possible as well to get different points along the curve.



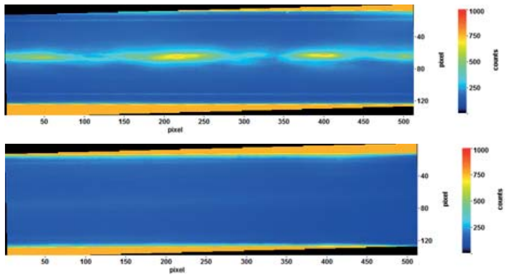

**Cryogenic valve characteristic curve in linear regime**




**Mass flow rate and temperature time evolutions during one test of an experimental campaign**

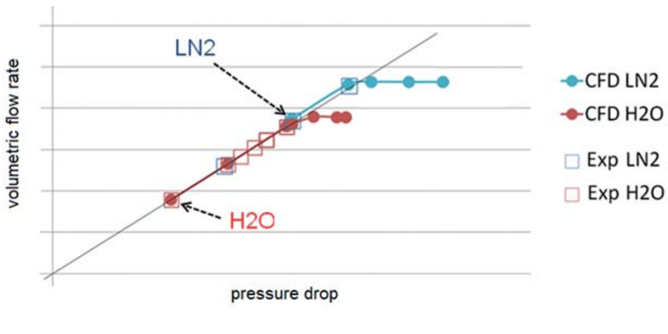
The results obtained by means of the CryoLine facility are unique and provide information that are not currently seen in the literature data for valve components. Following a very attractive prospective of experiments comparison, the cryogenic valve characterization activity can be further extended: the test campaign with liquid nitrogen can be associated to a characterization using water as test fluid, thanks to the “Becassine” facility at VKI.

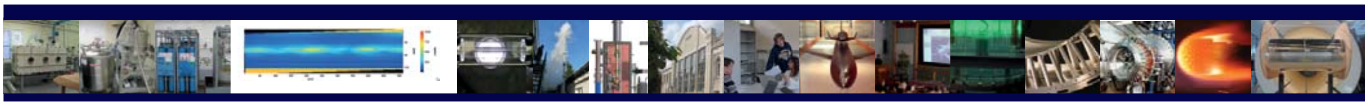
Numerical modelling of the valve physics is also possible as further investigation of the selected valve. Using the commercial code CFD-ACE+, is possible to calculated the mass flow rates in order to have a comparison with experimental data obtained at VKI, using liquid nitrogen (LN2) and water (H2O) as working fluids. Additionally, semi-critical and critical flow conditions, where cavitation is occurring through the valve can be as well investigated.



**Light intensity color map in fully liquid conditions during the steady state (above) and two phase flow during chill down (below)**

**Comparison between numerical results and experimental data**

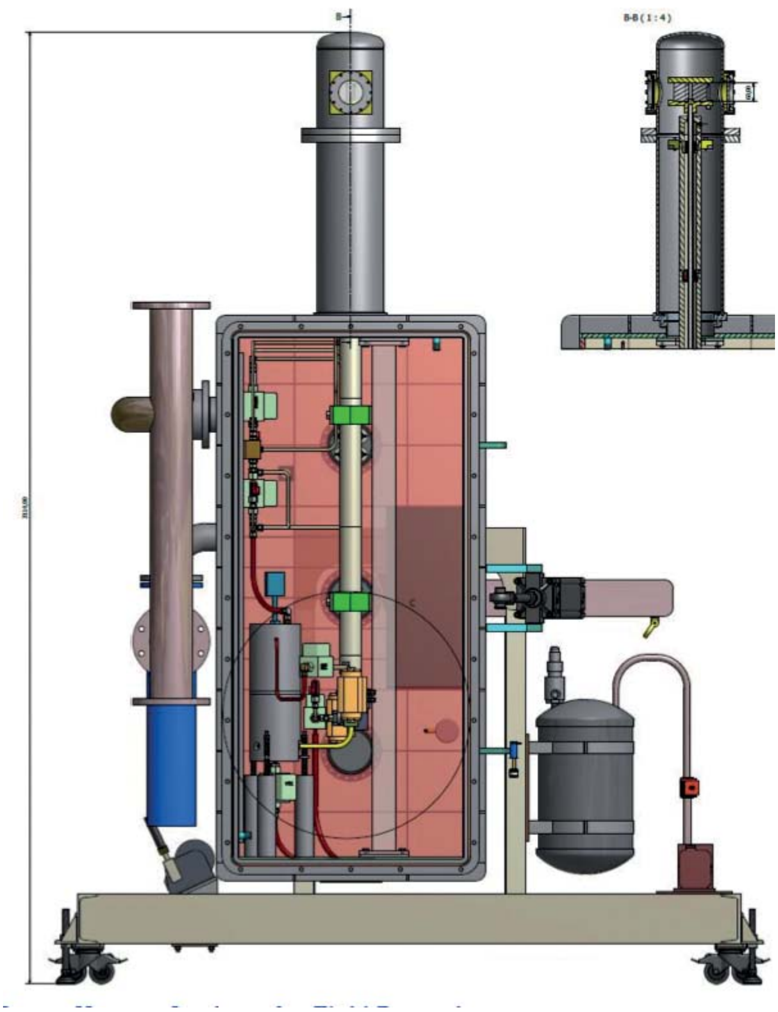


## CRYOGENIC WATER HAMMER

The von Karman Institute is studying since several years the fluid hammer produced when a pressurized liquid is discharged by a fast opening valve into a confined environment kept into high vacuum conditions. The presence of very low pressure or vacuum complicates the fluid hammer due to various multiphase phenomena such as cavitation, absorption and desorption of a pressurizing gas, boiling, etc….
Such configuration is of special interest in the operation of space propulsion systems. A dedicated test facility has been developed in the past to operate liquids at room temperature such as water, ethanol, and acetaldehyde in order to build a reliable database to validate the physical models.

Today, a new facility is currently under construction at the von Karman Institute to extend the experimental database to cryogenic fluids (LN2). This facility is capable to withstand pressure pulses of 150 bars. Helium could be used as non-condensable gas (NCG) for tank pressurization and back-pressure in the line. The test facility operates in the vacuum chamber to ensure a thermal insulation of the different components. The pressure and temperature evolutions are recorded with measurement modules installed at the impact location. A transparent module attached to the end of the line together with high speed imaging techniques will allow characterizing the multiphase behavior of the flow.



**Cryogenic water hammer**

# CRYOGENICS ACTIVITIES @VKI - CAPABILITIES

## CRYO-SLOSHING EXPERIMENTS

"Sloshing means any motion of the free liquid surface inside its container. It is caused by any disturbance to partially filled liquid containers. Depending on the type of disturbance and container shape, the free liquid surface can experience different types of motion. When interacting with its elastic container, or its support structure, the free liquid surface can exhibit fascinating types of motion in the form of energy exchange between interacting modes"[cit. Ibrahim]. The problem of liquid sloshing inside containers is of great interests in many fields. Nowadays one of the most important applications is to aerospace propulsion: the sloshing effects can indeed dramatically influence the trajectory of space vehicle during their flight. For this reason, it is of fundamental importance the understanding and the prediction of this motion. In the laboratories of the von Karman Institute, it is possible to study experimentally the sloshing thanks to two different sloshing tables: the small sloshing table (Fig. 1a) and Shakespeare (acronym of "SHaking Apparatus for Kinetic Experiments of Sloshing Project with EArthquake REproduction) (Fig 1b).

The small sloshing table is able to move with a uniaxial sinusoidal motion with amplitudes in the range [1-10] mm and with frequencies in the range [0.1-6.6] Hz and it can carry till 70 Kg. Shakespeare is able to move in three different axis at the same time. The movement is controlled by hydraulic pistons which can be numerically controlled. It can move with a maximum displacement on each axis of 10cm and with frequencies till 10Hz; it is able to carry till 500Kg of instrumentation. In those facilities, sloshing of liquids can be studied experimentally by means of non intrusive measurement techniques (Fig. 2): visualizations, Particle Image Velocimetry (PIV) and 3D Free Surface Reconstruction (Figs. 3 and 4).

**(a)Small sloshing table** **(b) Shakespeare**

**Figure 1 - Sloshing facilities at VKI**

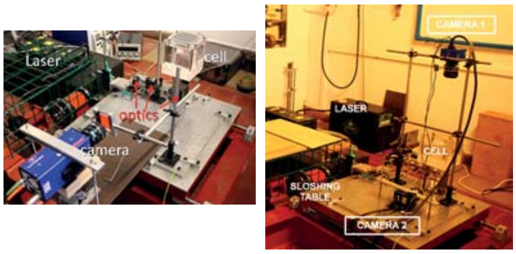



**Figure 2 - Non-intrusive measurement techniques applied to sloshing phenomenon**

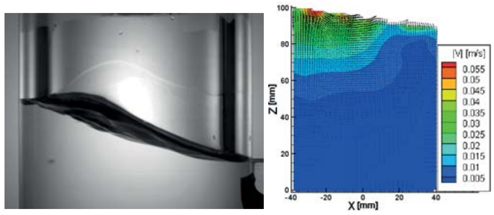



**Figure 3 – Visualization and PIV on sloshing**

Coupling the strong experience of non intrusive measurement techniques of VKI with the activity on cryogenics, it is possible to perform cryosloshing measurement in the facility CryME. A specific cryo cell has been developed, in order to perform liquid nitrogen sloshing in a partially filled quartz cylinder (Fig. 5). This cell is provided by temperature and pressure sensors and it is completely transparent in order to be able to apply imagery techniques for a complete characterization of cryogenic sloshing.

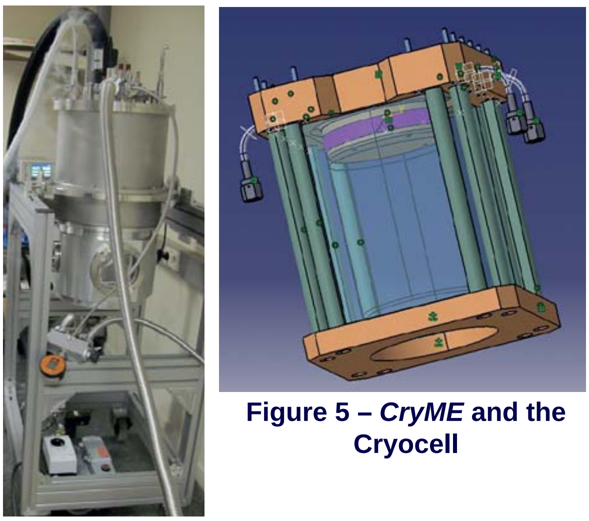


**Figure 5 – *CryME* and the Cryocell**

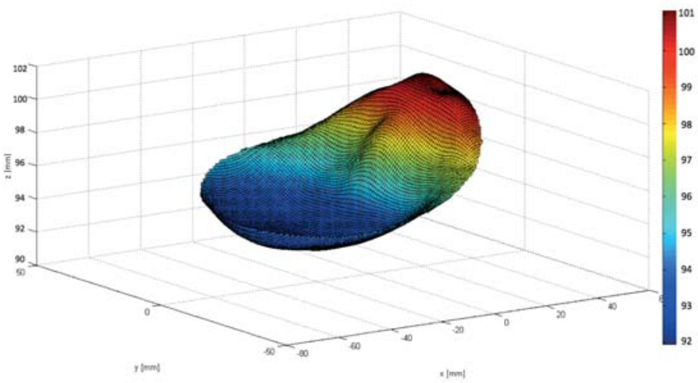
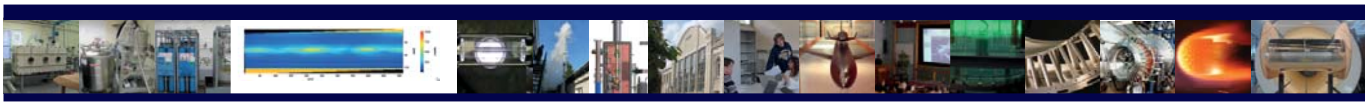


**Figure 4 – 3D free surface reconstruction applied on sloshing**

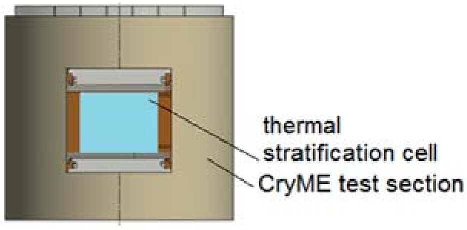


## CRYOGENIC THERMALLY STRATIFIED FLOW

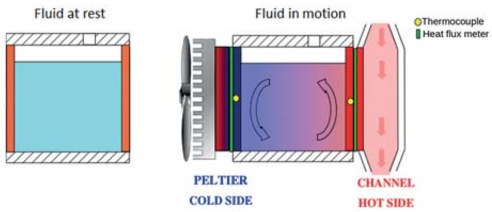
Internal natural convection is an heat transfer mode, resulting from the interaction between a finite-size fluid system and the thermal exchange with the lateral walls confining it. Temperature gradients in the medium are induced by the balance between the gravity field and the buoyancy forces acting on the fluid element.

The problem of liquid natural convection inside closed cavity is of great interests in the field of aerospace propulsion. The thermal effects can dramatically influence the propulsive system performances of space vehicle during their flight. In the laboratories of the von Karman Institute, it is possible to study experimentally this phenomena. By means of the ***"CryME"*** (Cryogenic Microgravity Experiments) facility, a fully customized cryostat, experiments of natural convection in liquid nitrogen are developed, in both normal gravity conditions (at VKI) and micro gravity environments (at the Zarm Drop Tower, Bremen).

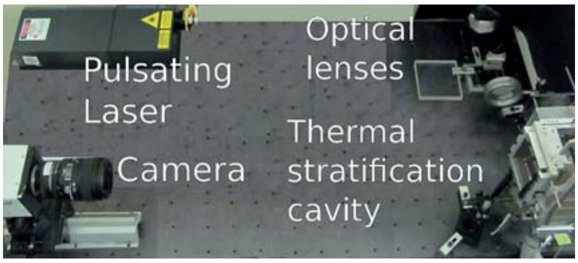
Prior to perform the cryogenic test campaign, water experiments are carried out as preliminary activity, to assess the cell design, define the measurements technique parameters, optimize the experiments procedure in view of the next more challenging study in liquid nitrogen.
The water setup is carefully designed to properly impose the thermal boundary conditions and apply different non-intrusive technique such as Particle Image Velocimetry (PIV) and Laser Induced Fluorescence (LIF). The velocity field and the temperature field can be therefore obtained imposing well define boundary conditions. This findings are fundamental for understanding, modelling and prediction of the phenomena and are a necessary step through the future experiments in cryogenic conditions.



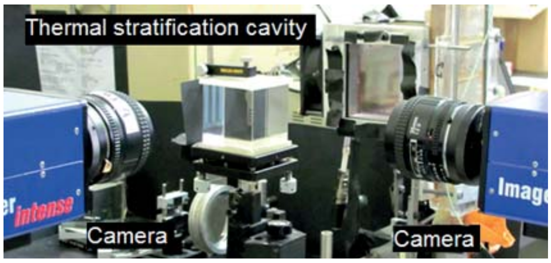

***CryME* facility and thermal stratification cell**



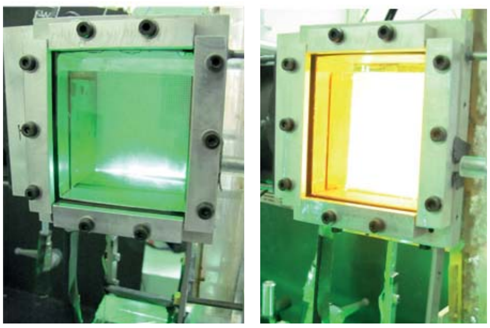

**Water facility working principle**




**Water facility optical setup for PIV experiments**

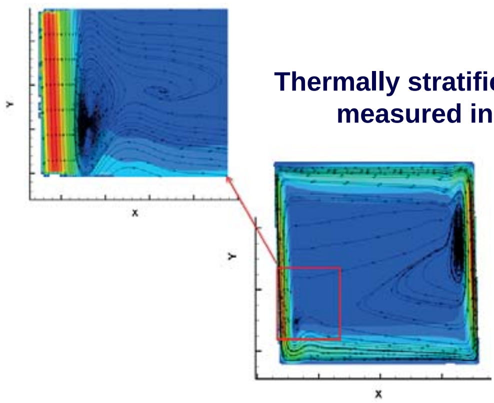


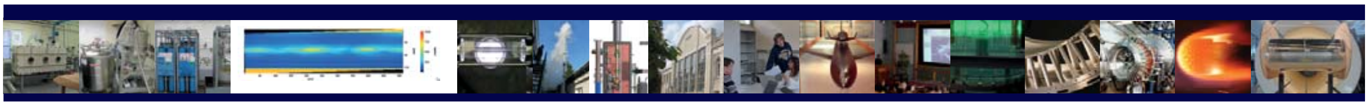

**Water facility optical setup for LIF experiments**



**Water facility test section during PIV and LIF experiments**

**Thermally stratified PIV field measured in water**





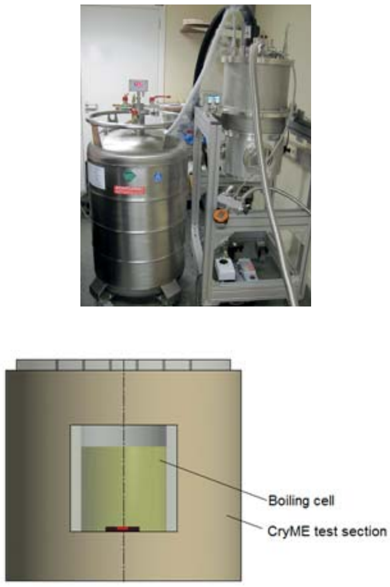
## CRYOGENIC POOL BOILING

Pool boiling is an heat transfer mode, resulting from the interaction between a finite-size fluid system at rest and a solid surface, providing energy. Phase change in the medium is induced, resulting in vapor bubbles growing at the hot surface and then detaching in the fluid, both phenomena are widely influenced by the gravity field and the buoyancy forces acting on the fluid element.

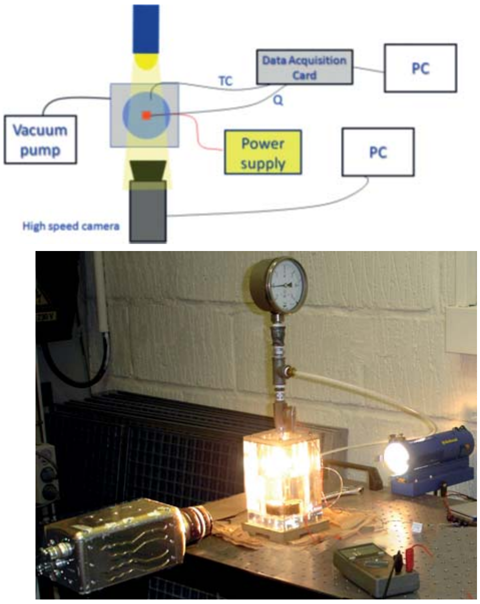
The problem of boiling inside closed cavity is of a great interest in the field of aerospace propulsion. The thermal effects can dramatically influence the propulsive system performances of space vehicle during their flight. In the laboratories of the von Karman Institute, it is possible to study experimentally this phenomena. By means of the “CryME” (Cryogenic Microgravity Experiments) facility, a fully customized cryostat, experiments of pool boiling in liquid nitrogen are developed, in both normal gravity conditions (at VKI) and micro gravity environments (at the Zarm Drop Tower, Bremen).

Prior to perform the cryogenic test campaign, water experiments are carried out as preliminary activity, to assess the cell design, define the measurements technique parameters, optimize the experiments procedure in view of the next more challenging study in liquid nitrogen.

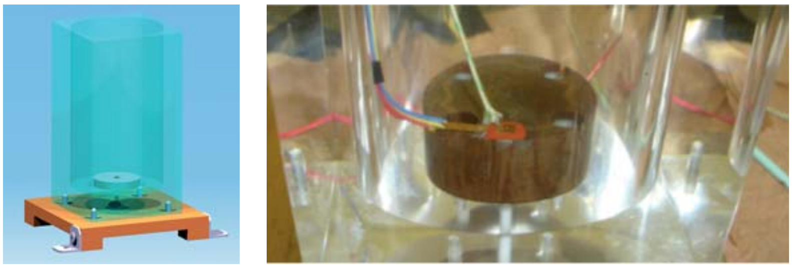
The water setup is carefully designed to properly impose the thermal boundary conditions and apply non-intrusive technique, such as background lighting visualizations. Meaningful quantities like the bubble velocity, shape and detachment frequency can be therefore obtained from the images. This findings are fundamental for understanding, modelling and prediction of the phenomena and are a necessary step through the future experiments in cryogenic conditions.



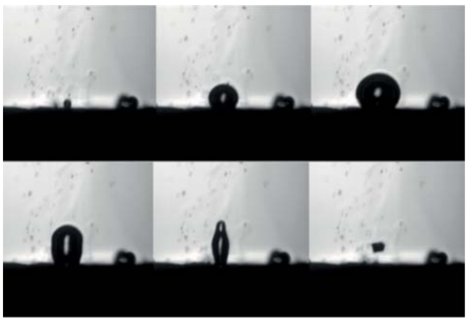

***CryME* facility and boiling cell**



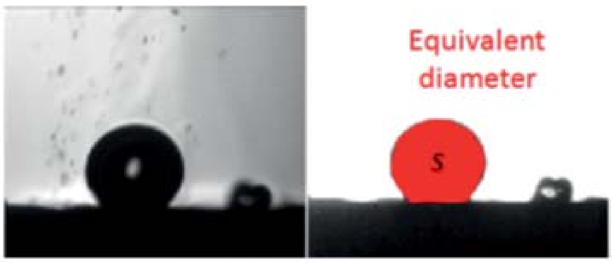

**Water facility optical setup for visualization**



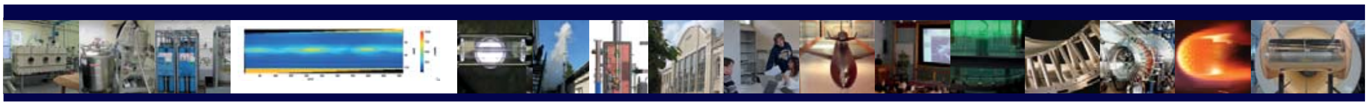
**Water facility test section equipped with heater and thermocouple**



**Sequence of images taken every 1ms showing the growth and dissolution of a vapour bubble**

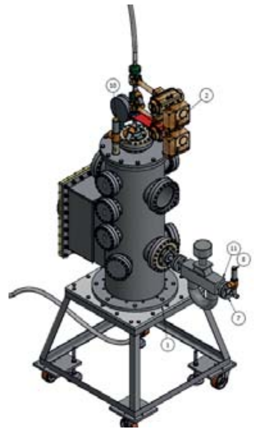



**Example of image post processing to define the vapour bubble equivalent diameter**



# CRYOGENICS ACTIVITIES @VKI - CAPABILITIES

## CRYOGENIC TWO PHASE FLOW CHARACTERIZATION



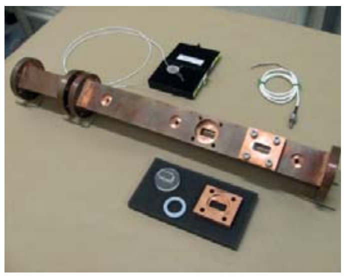
In the framework of space propulsion systems, operating with cryogenic liquid propellants, the chilldown is one of the most relevant phenomena as it impacts the design and performances of launch vehicles. The word "chilldown" defines the highly unsteady heat exchange happening when a cryogenic liquid is introduced into a system at much higher temperature. Heat exchanges between the fluid and the system lead to vaporization and boiling phenomena as well as a cool down of the whole system. The cryogenic liquid flowing inside a pipe with wall at ambient temperature turns instantaneously into vapor at the wall, thus creating an outer ring of vapor. The liquid inner ring slowly warm up evaporating, consequently the vapor becomes superheated. This process cools down the walls allowing the liquid inner ring to reach a new downstream portion of the component eventually filling it completely with liquid.

Even if the chill down is a well-known process, its prediction remains uncertain due to the complexity of the two-phase flow and the boiling heat transfer involved. Moreover the specific physical properties of cryogenic fluids do not allow the use of the empirical and semi-empirical correlations extensively obtained for common fluids.

For these reasons, a deep investigation concerning cryogenic two phase flow characteristics and related flow topology is one of the activity carried out through the "CHIEF" facility. The selected test section is a liquid nitrogen line, in copper, representative of a real rocket engine cooling channel. The pipe is hosted inside the vacuum chamber to ensure a proper thermally insulated environment with multiple optical accesses.

**CHIEF Facility configured for cryogenic two phase flow characterization testing**

The main objective is to provide accurate measurements and high quality optical visualizations of the phenomena, to support the development of the cooldown modeling and validate its prediction. The liquid nitrogen mass flow rate (Yokogawa RotaMass) and related pressure drop (Kulite CTL-190 M series) along the cooling channel section are obtained. Temperature measurements (Lake Shore Silicon Diodes) in both axial and radial direction are performed in order to reconstruct the whole thermal field in the test line during the cooldown. All the transducers are specifically chosen and positioned on the pipeline to ensure the best data accuracy and reliability, and the minimum flow disturbances. The inlet conditions ca be varied in mass flow rate, pressure and temperature to investigate the impact of the different parameters on the phenomena. Some relevant similarity rules are then matched so that the obtained results can be compared with a real rocket engine cooling channel working conditions.



**CHIEF Facility test section representative of a real rocket engine cooling channel**

The optical measurements mostly concern the definition of the flow topology, when possible the velocity of the gas phase, i.e. the velocity of the $N_2$ bubbles. The evolution of the liquid film thickness present at the wall during chilldown can be also evaluated.

All these information would allow the determination of semi-empirical laws for the correct design of $LN_2$ cooling channels.