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Simultaneous Measurements of Temperature and Velocity by Optical Methods in mixing jets

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Abstract

The CEA performs thermal-hydraulics studies on nuclear reactors cooled by sodium to develop the 4th generation sector. There are thermal-hydraulics issues of the upper plenum which can't be studied from past reactors' feedback and numerical simulations. So, there is a need to validate the numerical approaches in order to qualify the codes. Since sodium and water have similar properties in terms of viscosity and density, measurements can be performed on a water model. In this purpose, the water model MICAS mock-up was constructed. To study the thermal-hydraulics issues, the challenge is to implement non-intrusive optical techniques to simultaneously measure temperature and velocity fields.

Temperature is measured by Laser Induced Fluorescence (LIF) and velocity by Particle Image Velocimetry (PIV). In LIF, a fluorescent dye is dissolved in a fluid and then illuminated by Laser. It absorbs a portion of the excitation energy and spontaneously re-emits a portion of the absorbed energy as fluorescence. This fluorescence emission is temperature dependent. In PIV, the fluid is seeded with tracer particles then illuminated by laser so that particles are visible. The motion of the seeding particles is used to calculate speed and direction of the flow being studied. An experiment representative of the mixing flows in the MICAS mock up is constructed. It is made up of two jets. The first jet is hot and the second cold. The interaction between the two jets at different temperatures and configurations is studied regarding the main dimensionless values such as Reynolds, Richardson and Froude numbers. The challenge exists in the application of LIF and PIV simultaneously on this rig. For this reason, the characterization system requires two perpendicular transparent faces. The setup consists of a tank having transparent walls for optical access which allows the implementation of LIF and PIV simultaneously.

1 Introduction

There is no doubt that energy has been driving and will drive the technological progress of the human civilization. It has been projected that the energy demand will almost double by the year 2040 (based on 2010 energy usage), which must be met by utilizing the energy sources other than the fossil fuels such as coal and oil. Thus many countries realized the importance of clean nuclear energy due to its sustainability and usage in power generation with less contribution to greenhouse gas emissions when compared to fossil fuel power generation.

Sodium cooled fast reactors have been developed in France for nearly 50 years. After Rapsodie, Phenix, Superphenix and the European Fast Reactor project, the new target for 2020 is ASTRID: Advanced Sodium Technological Reactor for Industrial Demonstration. It is a 4th generation reactor cooled by sodium [1]. Figure 1 is a sketch of the actual design of ASTRID. Sodium flows from the external vessel to the upper plenum through the core where it is heated. Around 90% of the sodium ejected from the core is deviated by the Upper Core Structure (UCS) to the upper plenum. The other part flows across the UCS, then to the upper plenum. The hot sodium (550°C) of the upper plenum enters inside the Intermediate Heat Exchangers (IHX) to heat a secondary sodium circuit. This latter is connected to a steam generator. This scheme avoids the primary sodium to be in contact with water in case of leakage. The outlet of the IHX is connected to the external vessel where the sodium is pumped and sent back to the core.

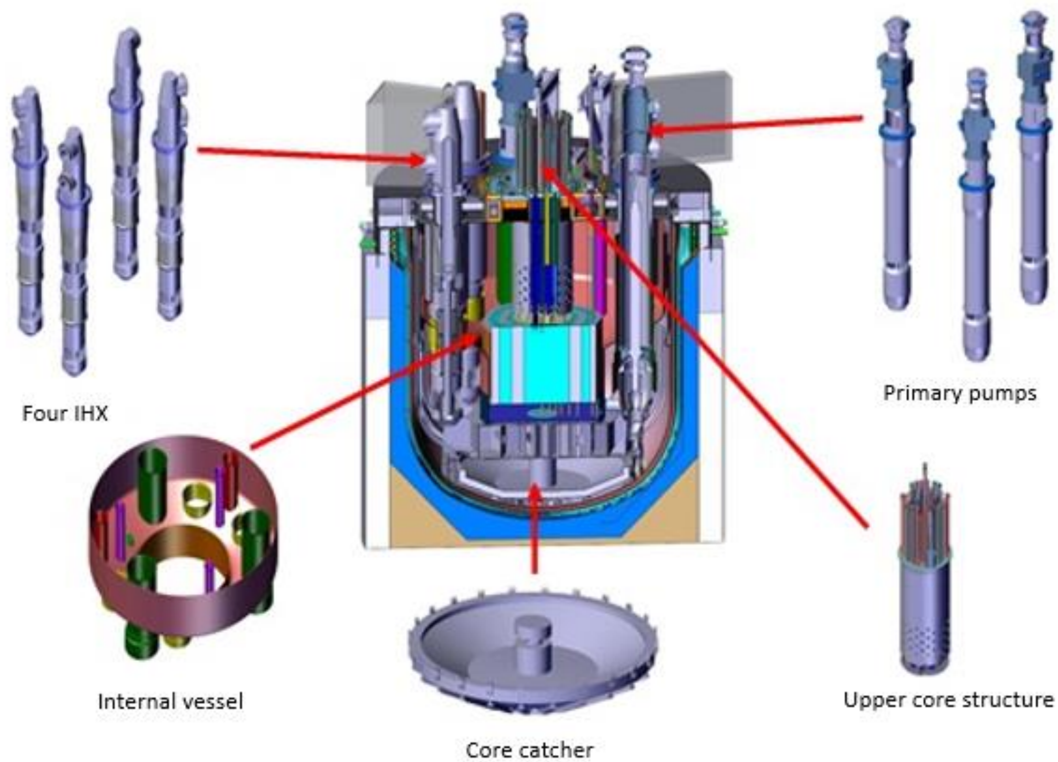

Figure 1: A cut view of ASTRID primary circuit

Sodium experiments are very complicated to perform since sodium is opaque and reacts violently with water, thus it was more useful to perform measurements on a water model. A dimensional analysis between sodium and water was done to perform a similitude between ASTRID and the model. X* was defined by the ratio $X_{mock\text{-}up}/X_{ASTRID}$.

Richardson number was used to study the thermal flow aspects, thus all the parameters characterizing the flow can be calculated by setting $Ri^*=1$.

From what preceded, a water model MICAS mockup of ASTRID was designed. It is made up of PMMA (Poly methyl methacrylate) for optical measurements, about 2.5 m diameter and 1.7 m height and a scale of around 1/6.

Figure 2 shows a cross view and a top view of the model. The core is supplied by two different water temperatures: a hot one in the central zone and a cold one in the outer areas. This mock up is built to study several issues such as thermal behavior between the hot and the cold jets. Those will be investigated using optical measurements since they are non-intrusive.

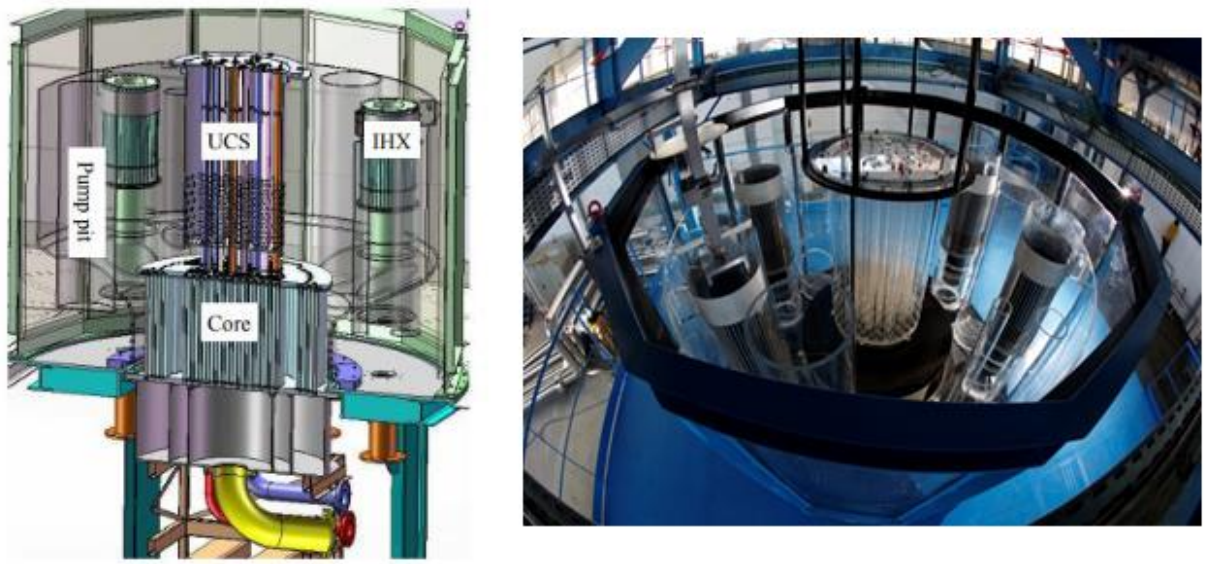

Figure 2: Left: Cross view of MICAS mock up; Right: Top view.

Laser Induced Fluorescence LIF and Particle Image Velocimetry PIV are used to measure temperature and velocity respectively.

2 Laser Induced Fluorescence LIF

Laser Induced Fluorescence (LIF) is a quantitative, non-intrusive technique for liquid flows commonly used to excite a fluorescent species within the flow. The tracer is an organic fluorescent dye such as Fluorescein or Rhodamine. It absorbs a portion of the excitation energy and spontaneously re-emits a portion of the absorbed energy as fluorescence. The fluorescence is measured optically and used to infer the local concentration of the dye. The fluorescence intensity F at a specified point is modelled by equation 1.

$$F = I_0 (1 - e^{-\varphi \varepsilon b C}) \quad (1)$$

$$F = I_0 \, \varphi \varepsilon \mathrm{b} C \quad (2)$$

where I_0 is the incident light flux, φ is the quantum efficiency, ε is an absorption coefficient, b is the thickness of the laser sheet and C is the concentration of the dye solution. Thus, a linear equation is obtained when the product $\varphi \varepsilon b C$ is small as seen in equation 2.

A dye is a necessary component of LIF. The suitability of a dye is based on an absorption spectrum that is compatible with the laser excitation wavelength. The fluorescent tracer must be water-soluble with high quantum efficiency so that signal strength is maximized.

One color LIF technique is the method in which one single fluorescent dye and one spectral band of detection are used. In general, the linearity of the fluorescence signal with respect to the incident laser energy and dye concentration is reported. Such experiments were the first to be conducted in the temperature measurement field.

In the two color two dye LIF techniques, the temperature is determined from the ratio of the signal of two dyes, which have highly different temperature sensitivities. That is one of the dyes should be sensitive to temperature and the other should not or only very weakly. This technique eliminates the laser light intensity dependence.

This is a general introduction about LIF. The next paragraph is dedicated to the calibration experiments done using several fluorescent dyes.

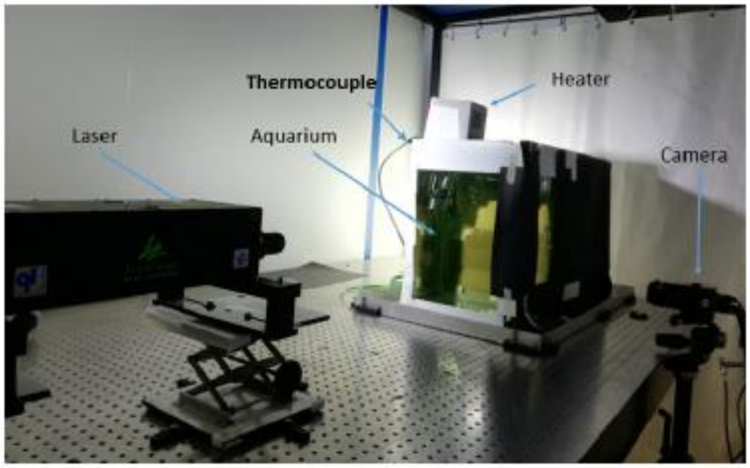

Figure 3: Calibration facility

List of components in the setup:

- 532 nm Nd-YAG Quantel EverGreen laser.
- PowerView 4MP-HS camera, 12 bit of resolution 2048 by 2048 pixels.
- A JULABO GmbH heating thermostat.
- Thermocouples type K.

The filter used is a notch filter. It allows a transmission band pass between 400 to 517 nm and 548 to 710 nm.

Classical Fluorescein, FL27, Rh6G, RhWT and De -copperized Cholorphyll Sodium Salt are the dyes chosen to be studied in our approach.

The concentration of these dyes ranged between 10^{-8} M to 10^{-5} M. We also tried to change the position of the camera by approaching it towards the aquarium. Several experiments were done and we realized that the sensitivity coefficient is constant whereas the initial fluorescence response changes at each condition. However the sensitivity coefficient was always positive in both cases. The fluorescence response of Fluoresceins increases with the increase in temperature. This is due to the increase in the absorption cross section at 532nm. For Classical Fluorescein, we found low response at 10^{-8} M whereas at10^{-5} M, the coefficient is 3.38%/^{0}C. However the response was unstable, this is due to the composition of Classical fluorescein which is pH dependent. In our experiments we can't add chemical solutions that can stabilize the pH since our experiments later are applied on a complex geometry. Concerning FL27, the solution was prepared with a concentration of 10^{-7} M. The coefficient sensitivity is 3.02%/^{0}C and the increase in response is constant. This makes FL27 a better candidate as a temperature dependent dye in our experiments
Figure 4 shows the fluorescence response of dyes as function of the variation of temperature.

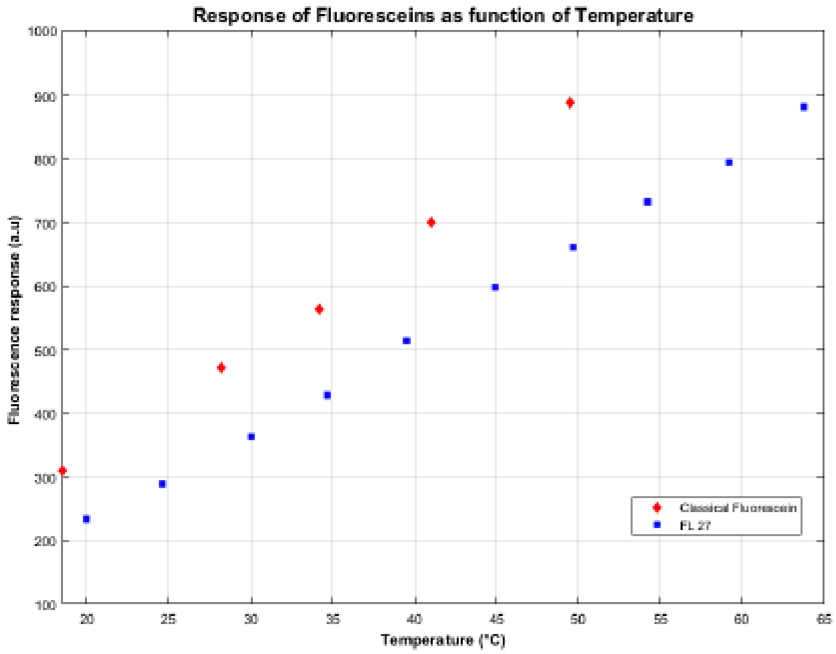

Figure 4: Response of Classical Fluorescein and FL27

The other dyes are known to be temperature independent. In our approach, we tested their response to choose the most stable one. A temperature independent dye serves as a reference dye in the two color two dye LIF method. It corrects for laser power fluctuations and dye absorption.

The graphs below show the response of these dyes as function of temperature variation.

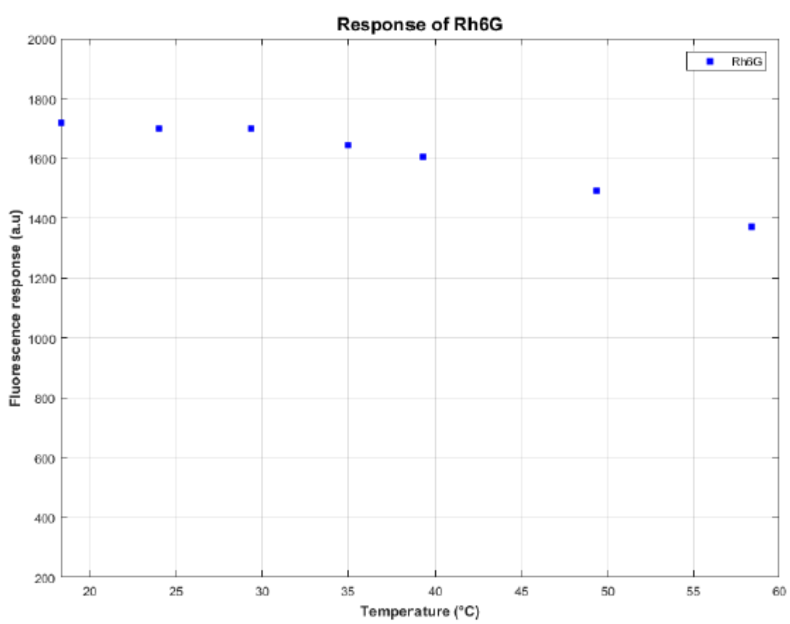

Figure 5: Response of Rh6G as function of temperature

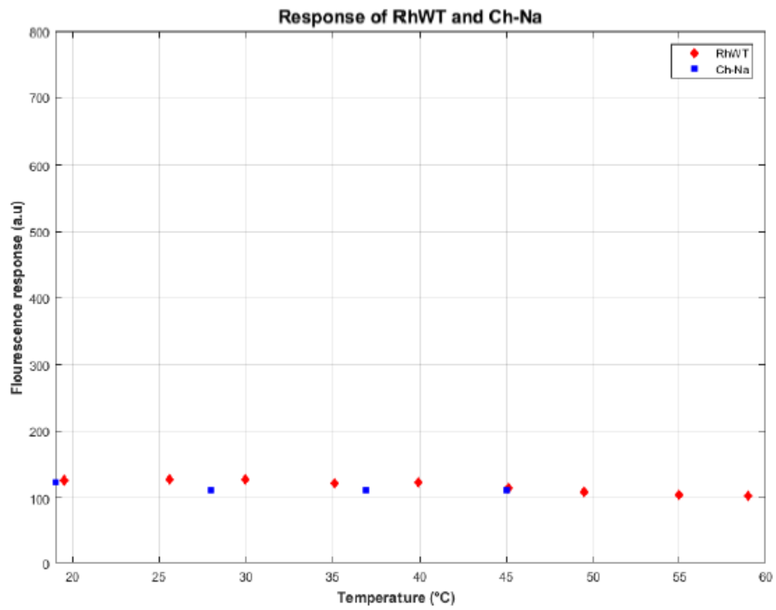

Figure 6: Response of RhWT and Ch-Na

The concentration used for Rh6G is 10^{-5} M. The level of fluorescence was high which is normal since the concentration used is high too. The coefficient sensitivity is 0.56%/^{0}C. We can say that Rh6G is a temperature independent dye but the response is not stable during the variation of temperature. We realize a decrease in this response after 40°C. However concerning RhWT, the coefficient sensitivity is 0.50%/^{0} C at concentration of 10^{-6} M. The response is approximately stable during the variation of temperature even at high values. Regarding Ch-Na, it shows no variation in fluorescence response as a function of temperature. However the value of response is very low even at high concentration. We increased the concentration until 10^{-5} M in which the color of the solution became dark green. The coefficient sensitivity then was 0.36%/^{0} C. In conclusion, RhWT seems to be the best candidate among the others due to many reasons. Its fluorescence stability is better than that of the others, its sensitivity coefficient is lower than that of Rh6G. Although its sensitivity coefficient is higher than that of Ch-Na but from another aspect, a small concentration is needed for RhWT when compared to Ch-Na.

After studying the response of the fluorescent dyes we had, FL27 and RhWT show to be the best couple of dyes to be used for this technique.

3 Particle Image Velocimetry PIV

PIV is a non-intrusive velocity measurement technique. It provides instantaneous velocity information in fluids. The principle of PIV is simple. First, the flow is seeded with tracer particles. The light sheet which is a laser illuminates these particles at least twice within a short time interval. Then the camera takes images of the target area. It captures each light pulse in separate frame images. The displacement of the particles between the light pulses is used to determine the velocity vectors.

4 Two jet flow experimental facility

This part shows the experimental facility that was constructed for the purpose of studying the interaction between two parallel jets using PIV and LIF techniques.

These measurements aim to study the complex mixing flows present in the MICAS mock up. The configuration of the facility was designed to study different parameters that affect the mixing flows between a cold and a hot jet.

The parameters are those in general that affect the dynamics of the flow of fluid such as the flow rate, the temperature in the test section, the temperature in each jet and the distance separating them. The facility consists of a hydraulic loop called OLYMPE and a test section called TABOULE (Two-jet flow Analysis By Optical methods Using LasEr). Figure 7 shows the experimental facility.

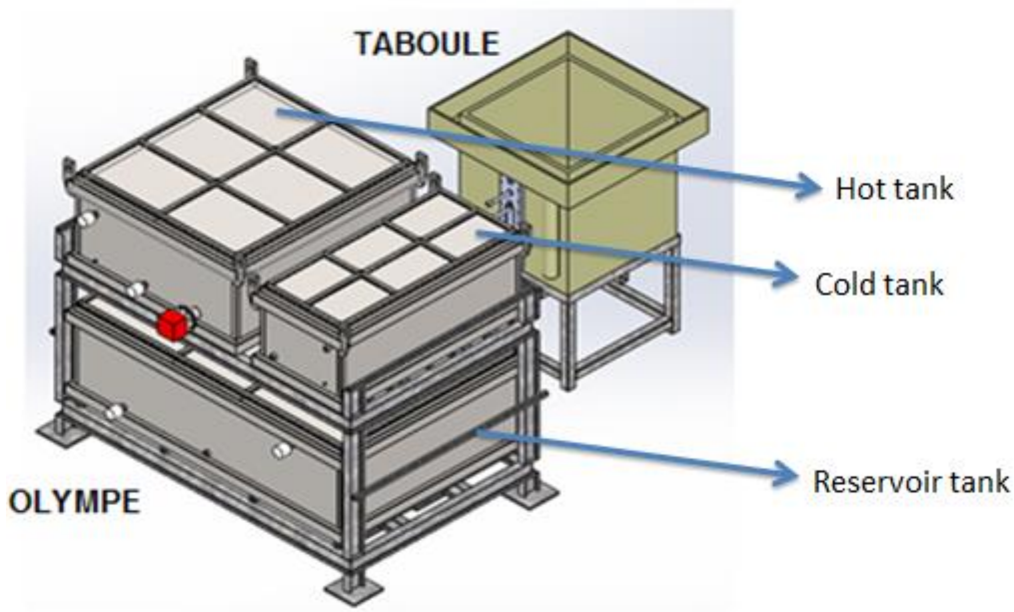

Figure 7: The two jet flow experimental facility

TABOULE is a test section of volume $1m^3$ made up of plexi-glass PMMA. It consists of two transparent parallel jets of outer diameter 25mm and inner diameter 20 mm.

The two jets are constructed on a plate that allows us to vary the distance between them starting from 5 cm till 20 cm. Since de-mineralized water is used, then there is a risk of corrosion in the tanks. That's why the hydraulic loop is made up of stainless steel to prevent such a process.

The first tank has a volume of $1m^3$. It serves as a source of water at ambient temperature for the first jet in TABOULE.

The second tank has a volume of $2m^3$ and is occupied by an immersed heater thus it serves as a source of water at high temperature (50 to 60 °C). Both tanks are equipped with temperature sensors that allow us to know when to inject the solution in the test section.

The third tank however is of volume $3m^3$ and is used either to fill up the other tanks or to empty them. All the tanks are equipped with drain plugs and with low and high level sensors.

Two thermocouples are located on the cold and hot circuits very near to the parallel jets outlets.

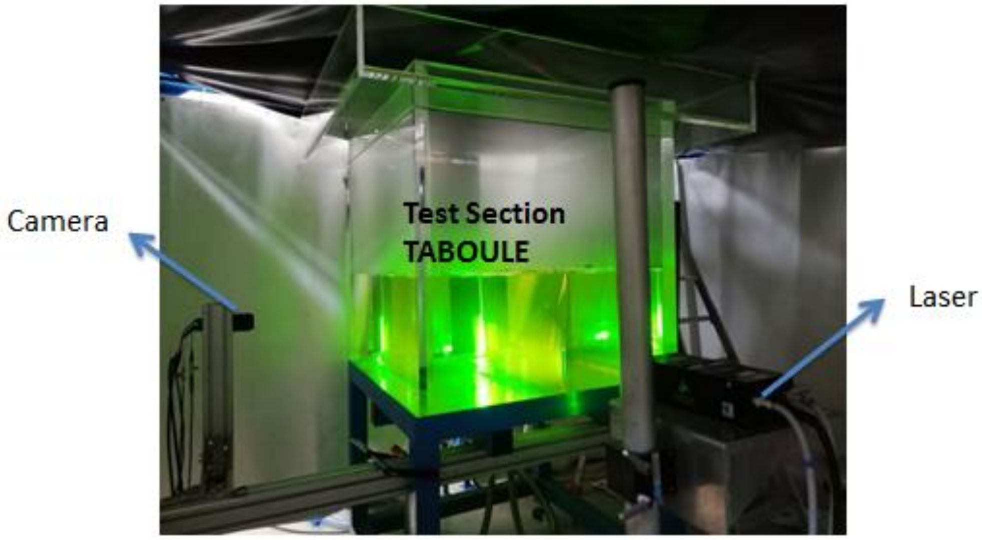

Figure 8: Test section of TABOULE

The geometry of the two jets exhibits interesting features. Experiments are going on to analyze the flow dynamics of a single jet and the interaction between two jets. Then, simultaneous application of PIV and two color two dye LIF techniques are being applied to analyze all the results.

References

David Guenadou, I. Tkatschenko, P.Aubert (2015) Plateau Facility in Support to Astrid and the SFR Program: An Overview of the First Mock-Up of the Astrid Upper Plenum *Proceeding of Nureth 16, Chicago*.

Sutton J, Fisher and J Fleming (2008) A laser induced fluorescence measurement for aqueous fluid flows with improved temperature sensitivity, *Experiments in Fluids* [45]:[869-881].

Crimaldi P (2008) Planar laser induced fluorescence in aqueous flows, *Experiments in Fluids* [44]:[851-863].

Copetta J and C Rogers (1998) Dual emission laser induced fluorescence for direct planar scalar behavior measurements, *Experiments in Fluids* [25]:[1,15].

Lemoine, F Guillard and M Bruchhausen (2005) Instantaneous measurement of two-dimensional temperature distributions by means of two-color planar laser induced fluorescence (PLIF), *Experiments in Fluids* [38]:[45-55].

Deprédurand V, Miron P, Labergue A, Wolff M, Castanet G., et al. (2008) A temperature-sensitive tracer suitable for two-colour laser-induced fluorescence thermometry applied to evaporating fuel droplets, *Measurement Science and Technology*, [19]: [105-403].