Study of Thermal Stratification in a Natural Convection Loop by One Color Laser Induced Fluorescence

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Abstract Due to the simplicity and reliability of its working principle, natural convection is often used in nuclear systems for the transport of residual decay heat. In the liquid metal pool concept all the primary system components are located in a large Liquid Metal pool and the secondary fluid is circulating in one or more heat exchangers [1]. The pool type reactor typically consist in an upper and bottom tank communicating through the core, the heat exchangers and the pumps. A perforated skirt is usually interposed between the core and the vessel, in order to increase the velocity of the fluid exiting the core [2]. Differently from the nominal case, in which the forced convection guarantees a high degree of turbulence and mixing, the passive heat removal may be affected by the development of stratification, with a consequent formation of hot stagnation zones that could compromise the mechanical integrity of the components. VKI has designed and constructed a simple two dimensional natural circulation loop for the study of the flow patterns in natural convection inside the Upper Plenum of a liquid pool reactor. The small water model is thereby provided with an upper tank that reproduces the essential geometry of a pool type liquid metal reactor. In order to study the buoyant jets spreading in the upper plenum of the vessel and to qualify the mixing the application of planar laser techniques is proposed. The techniques applied are Laser Induced Fluorescence for temperature mapping and Particle Image Velocimetry for the velocity mapping. LIF and PIV images are gathered at the same moments of repeated experiments, while the thermocouples acquisition covers all the duration of the tests. Since the natural convection is a relatively slow phenomena the acquisition frequency selected is not higher than 40Hz. The illumination was as a consequence provided by scanning a continuous laser beam through the test section with a rotating mirror. A Scientific CMOS camera characterized by high quantum efficiency was synchronized with the rotating mirror in order to achieve an exposure for every scanning. The study was carried out for different configuration of the vessel in order to analyze the influence of the vessel geometry on the temperature distribution. The characteristic Rayleigh number of the experiments is of the order of 10^{10}.

1. Introduction

Natural circulation is extensively applied in energy systems: the simplicity of the principle of working of natural recirculation loops (thermosyphons) make this kind of systems reliable and very attractive. However this kind of heat removal should be assessed when nuclear reactor is concerned. The developing of new generation pool type liquid metal cooled reactors lead to numerous advantages in the nuclear energy technology, such as a higher power density and improved operating safety. The reactor must be designed in order to be able to operate in natural convection decay heat removal conditions. In passive heat removal conditions a liquid metal mass flow rate establishes as a consequence of a balance between frictional pressure losses of the hydraulic loop and Archimede forces driven by the heating power [3],[4]. In these conditions a buoyant jet rises in the upper vessel. Since the high of the vessel is limited by the free level surface a thermal stratification may take place [5]. A too strong stratification of the upper plenum is undesired, since it affects the efficiency of the heat removal [6] and could compromise the integrity of the structure. The object of this analysis is to determine which are the geometrical details of the upper vessel that affect mostly the importance and shape of the temperature profile. For the purpose a simple water
model was designed as described in [7]. The model is a thermostyphon closed loop. As shown in Figure 1 the model is provided with an upper tank in which are indicated the position of the barrel holes and the position of the buffer plate with respect to the free surface level. Number of holes and the position of the buffer plate were changing during the study, originating different flow topologies and temperature profiles.

The measurement techniques selected for the analysis are thermocouples, Particle Image Velocimetry and Laser Induced Fluorescence.

2. Facility and optical set up

Figure 1-a shows a sketch of the water model used to carry out the experiments. The facility is one m high, 0.5 m large and has a depth of 15 cm. The flow circulates in a anticlockwise direction. The main elements of the system are:

1. Core: series of flat electrical resistances (maximum power = 2.5 kW).
2. Skirt: a inter exchangeable perforated plate provided with circular holes.
3. Buffer Plate: a plate with adjustable high to simulate the Heat Exchangers entrance level.
4. Heat Exchanger: a serpentine were water cooled by an external refrigerating system is circulating.

![Figure 2: a) facility; b) Experimental Set Up: the water loop is seeded with a proper concentration of RhB. The mirror is connected to an external synchronizer through which he send a signal to the camera acquisition systems at every scan of the laser](image)

Figure 1-b shows the optical arrangement. An Argon-Ion Laser produces a continuous beam picked at 515 nm. The power of the beam selected for the study is 2.1 W and it is kept constant during the measurements. The Laser beam, reflected by a rotating mirror, scans a section of the vessel, while the Scientific CMOS camera, provided with a high pass filter of 580 nm, detects the fluorescent signal for temperature measurements or detects the light scattered by the particles for PIV measurements when a band pass filter centered on 514 nm is applied. Each acquisition occurs when the disk rotating together with the mirror concludes a revolution: an opening in the disk activate a
sensor that sends a signal to the synchronizer, activating the camera. The frequency of acquisition of this set up as a consequence determined by the speed of rotation of the mirror. The Rhodamine B concentration used for the LIF experiments is 1.6 mg/liter. The PIV tracers seeding the water are hollow glass spheres of the size of 32 μm. The concentration of particle is 0.025 g/liter.

3. Test Matrix

Table 1 list the tests performed and the measurements techniques applied for every case. Nevertheless the experimental scheme doesn't change from test to test (Figure 3), only the results useful to the interpretation and discussion of the LIF measurements are presented in this document.

<table>
<thead>
<tr>
<th>Test</th>
<th>Variable Geometry</th>
<th>Measurement Techniques</th>
<th>Acquisition Frequency</th>
<th>Camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case a</td>
<td>Buffer Plate-high</td>
<td>TCs</td>
<td>50 Hz</td>
<td>PCO Pixel Fly</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LIF</td>
<td>5 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PIV</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Case b</td>
<td>Buffer Plate-high</td>
<td>TCs</td>
<td>50 Hz</td>
<td>PCO Pixel Fly</td>
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<tr>
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<td></td>
<td>LIF</td>
<td>5 Hz</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>PIV</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Case c</td>
<td>Skirt Porosity</td>
<td>TCs</td>
<td>50 Hz</td>
<td>Scientific CMOS</td>
</tr>
<tr>
<td></td>
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<td>Hamamatsu</td>
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<tr>
<td></td>
<td></td>
<td>PIV</td>
<td>19 Hz</td>
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<tr>
<td>Case d</td>
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<td>Scientific CMOS</td>
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<td></td>
<td></td>
<td>LIF</td>
<td>NA</td>
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<tr>
<td></td>
<td></td>
<td>PIV</td>
<td>19 Hz</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: geometrical details changing during the analysis. All the tests were performed for Q= 2W of heating power.

The vessel configuration of each test is displayed in the Figure 4, while the scheme followed for each experiment is described by the table of Figure 3.

Figure 3: Experiments scheme. each test last at least 30 minutes, the Thermocouples acquire temperature continuously, while PIV and LIF images are recorded every 5 minutes.
4. Corrections applied to light intensity.

The main drawback of one color LIF for temperature measurement is the dependency of the fluorescent signal on the input laser light. The light distribution along the test section, and as a consequence the fluorescent signal, for a given temperature and a given concentration is never perfectly uniform. Moreover if we consider one single pixel of the domain the signal change from image to image due to the oscillations of the laser beam power or due to impurities travelling in the flow. Figure 5 shows that a asymptotic value of the standard deviation $\sigma$ of the fluorescent intensity, and as a consequence a significative reduction of the error associated to the measurement [8], is achieved for this particular optical arrangement by averaging a number of 60 images gathered at constant and uniform temperature. However, following the indications of [8] it is possible to reduce furtherly the standard deviation by dividing the images in windows and applying a spatial average. In the present study the window size selected for the spatial average is 8x8 pixel.
The standard deviation $\sigma$ for one pixel is calculated as:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (I_m - I_i)^2}$$

Where $I_m$ is the average value of fluorescent intensity over N elements and $I_i$ is the measured value of fluorescent intensity of each element.

Furthermore, even if the optical configuration described in chapter 2 allows a more uniform distribution of light with respect to the one obtainable with a pulsed Laser, we cannot neglect the absorption of light in crossing the Rhodamine seeded water. The graph of Figure 16 shows that the absorption follows an exponential law independently from the temperature of the fluid. This behavior is due to the well known Beer-Lambert Law.

$$I = I_0 e^{\epsilon cy}$$

Where $\epsilon$ is the molar absorptivity of the fluorescent dye, $c$ is its molar concentration and $y$ is the optical path coordinate. The fluorescent intensity distribution along the laser beam direction $Y$ (expressed in camera pixels) is plotted in Figure 6. The curves follow an exponential trend and the exponential coefficient retrieved is the same for all the temperatures measured [9].

In conclusion, the corrections applied to the LIF images were:
1- normalization of the image based on the removal of the exponential trend
2- averaging of 8x8 pixels
3- median filtering on the final results applied to sub matrices of 4 windows each.

5. Results: One Color LIF for stratification measurements (case a and case b)

The experiments were repeated in the same modality of the test of the analysis explained in Figure 3: the refrigerating system was started 8 minutes after the resistances in order to provide a stratified
plenum as a starting condition.

Figure 7 shows the results of the temperature fields for case a and case b, computed as the average of 300 fluorescent signal mapping gathered at a frequency of 5 Hz at several moments of the experiments. A normalization based on the removal of the exponential trend on the images were applied. It is possible to notice an increase in the temperature during the first 10 minutes, caused by the resistances. Few minutes after the starting of the refrigerating system we assist at the developing of the mixing region with a consequent decrease of temperatures in correspondences of the bottom part of the region of interest.

Figure 7–b shows the results obtained for several moments of the case of barrel plate high of 20 cm. The mixing region reaches a higher position with respect to case a. In this particular experiment LIF shows that the border between stagnation region and mixing region is sharper with respect to the reference case.

Local values of temperature as measured by LIF in correspondence of the thermocouple array position were compared by the values recorded by the same thermocouples for the data corresponding to the 40 min measurements. Figure 8 shows a good agreement between the trend measured by thermocouple and the trend retrieved by LIF. In particular the LIF data were a normalization based on the removal of the exponential root was applied better match the thermocouple temperature values.

![Figure 7 - Normalized planar temperature fields and temperature profiles retrieved at several moment of (a) case a and (b) case b experiment.][10]
The results presented in this chapter refers to a preliminary study of the applicability of one color LIF to cases of stratification. The results refer to the configuration of case a and case b. The measurements were carried out with a low frequency of acquisition, and with low gray level resolution CCD camera. Nevertheless the technique was judged satisfying for the temperature mapping of stratification in a water tank.

6. Results: PIV and One Color LIF for stratification measurements (case c and case d)

The results presented in this chapter refers to the vessel configurations of case c and case d. Figure 9 shows the comparison of normalized profiles of temperature in the vessel for case c and case d at the end of the experiment. The temperature distribution is more homogeneous for case d than for case c. The reason of this can be explained by observing the vectors field obtained by applying PIV technique to case c and case d (Figure 10-a and b). Due to the higher porosity of the perforated skirt an entrainment is produced in the above core region and a certain percentage of mass flow doesn't enter the heat exchangers but circulates back in the vessel, enhancing the mixing in the vessel and allowing a more uniform temperature distribution. The most interesting case to be measured with LIF may as a consequence be the case c, where a sharper temperature step is expected.

Since the PIV images and the LIF images were not gathered simultaneously but acquired during two different tests of the same experiment for case c, it is important to check the repeatability of the tests. Figure 9-b shows a comparison of the normalized profiles of temperature for two different time of the experiment c, at the beginning (4 minutes) and at the end (29 minutes) of the experiment. The profiles indicate quite a similarity in the profiles developed in the two different tests, especially at the beginning of the experiment. As a consequence, the case c LIF results selected for this analysis are the one acquired at the beginning of the experiment.
Figure 9 Normalized temperature profiles acquired in the vessel of the water model for the case c and the case c. a) profiles comparison in between the two case, b) profiles for the same case c but obtained in two different tests, corresponding to the test in which PIV images were recorded and the test during which LIF images were recorded.

Figure 10-c compares the normalized profiles of velocity magnitude of case c and cased d. The greatest difference in the two profiles is due to the entrainment in the lowest hole and a weaker entrainment in the second lowest hole developing in case d, that cause the partial recirculation of mass flow in the vessel.

Figure 10 a) Vector fields measured at the beginning of the experiment "case d", b) Vector fields measured at the beginning of the experiment "case c". The vector fields are the results of an average of 100 images. c) normalized profiles of velocity magnitude for case c and case d extracted at the exit of the perforated skirt.

Figure 11 shows the mapping of the temperature in the vessel measured after 4 minutes from the beginning of the experiment "case c" with one color LIF technique. The mapping was obtained by
averaging 800 images and by applying the corrections illustrated in Chapter 4. The window size selected for case c was 8X8 pixels. Graph a and graph b of Figure 11 show instead the comparison of the temperature profiles obtained with LIF technique with the point value of temperature measured by the thermocouples array in the vessel and by the thermocouples placed in each hole of the perforated skirt. Nevertheless the values of temperature indicated by the thermocouples are included in a quite small range (20.5-23.3 °C) the one color LIF allows to distinguish clearly the two different regions of the vessel (higher and lower temperature) developing in case c. Moreover it became possible to plot the temperature profiles at the exit of the perforated skirt. In the profile plotted in Figure 11 a) peaks of temperature in correspondence of each hole are observable, with the exception of the lowest hole. Figure 11 b shows a good agreement on the trend of the temperature in the region closest to the heat exchangers, with a maximum difference of 0.5 °C between the two measurements.

As a final remark, it should be mentioned that the calibration was performed in two ways:

- The first one, or rather the standard way, consists in gathering images at uniform temperatures for a certain range of value of temperature and retrieving a map of calibration coefficient.

- The second one was applied here and is the one that allowed the most precise comparison with the thermocouples. It consists in selecting two different regions, the closest possible to thermocouples, and to associate the intensity of the fluorescent signal of these two regions to the value measured by the thermocouples corresponding to the selected region. The coefficients for the calibration are then retrieved by interpolating the intensity and temperature selected with this method.
7. Conclusion

The mixing of buoyant hot fluid in the upper vessel of a liquid metal pool type reactor is an important issue in the thermo hydraulic design of a nuclear reactor: too strong gradients of temperatures are undesired since they may affect the integrity of the components. The present study wants to underline the influence of the geometry of the vessel on the flow topology and temperature mapping. In particular case a and case b shows the effect of the presence of a buffer plate in front of the heat exchanger entrance: the consequent stagnation region extends towards the lower part of the vessel as much as the buffer plate is immersed in the water. In case c the buffer plate is placed in the bottom of the vessel, and the hot flows outgoing from the resistance enters directly the heat exchangers, encountering no resistance. Nevertheless it is not correct to speak about a stagnation region in this case, it is still possible to distinguish a region characterized by higher temperature in the top of the vessel.

In the configuration of case d the porosity of the skirt is increased. Part of the flow enters the heat exchangers a of flow remains confined in the vessel, and enters the upper core region from the lowest holes of the perforated skirt. The mixing results improved and the temperatures are more uniform.

Concerning one color LIF, calibration and experiments were performed in the vessel of the small natural convection loop without changing the optical system or fluorescent dye concentration. Planar calibration curve were obtained and applied to the measurements images. However the best results were obtained by correcting the absorption of light in the Water-Rhodamine solution and by retrieving a intensity/temperature correlation on the same measurement image by using the values of temperature measured with the thermocouples. Beside the relative high uncertainty the main drawback of one color LIF for temperature measurement is the dependency of the fluorescent signal on the laser light. Being the laser light not constant in time it is not possible to obtain instantaneous temperature mappings, but only averaged fields. The solution is then to select a frequency of acquisition high enough to achieve quasi instantaneous measurements. In the present case a frequency of acquisition of 41 Hz and the averaging of all the images acquired within one second allows quasi instantaneous measurements.

8. Acknowledgements

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9. References


[8] - Temperature Field Measurements with High Spatial and Temporal Resolution Using Liquid Crystal Thermography and Laser Induced Fluorescence-PhD dissertation-Ralph Nasarek
