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PRELIMINARY BCP FLOW FIELD INVESTIGATION BY CFD SIMULATIONS AND PIV IN A TRANSPARENT MODEL OF A SRF ELLIPTICAL LOW BETA CAVITY

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Abstract

Standard vertical Buffered Chemical Polishing (BCP) is one of the main surface treatment for Superconducting Radiofrequency (SRF) cavities. A finite element Computational Fluid Dynamic (CFD) model has been developed. Uncertainties in the solution of fluid simulations are not negligible due to the complex geometry of a SRF cavity; thus without an experimental validation, results from this type of simulations cannot be confidently used to improve the process. To this aim, an experimental study was started to investigate the fluid dynamics of the BCP process by means of Particle Image Velocimetry (PIV) technique. Similitude on Reynolds number and Refractive Index Matching (RIM) technique were also implemented to replace the dangerous BCP mixture with a glycerine-water mixture. The paper describes the preliminary results from simulations and experiment.

INTRODUCTION

Buffered Chemical Polishing (BCP) is crucial for the treatment of SRF resonator with complex geometry. However, even if the overall behaviour has been widely understood, there are still particular features that remains obscure. Strong and unexpected asymmetry in wall temperature profile or removal rates has been recently observed after BCP treatment in ESS-medium beta resonator. Some researchers have demonstrated with experiments how this asymmetries are imputable to the fluid velocity and temperature field [1, 2].

To better understand this behaviour, some researchers have modeled chemical treatment with computational fluid dynamic [2–5]. However, given the dangerousness of the acids used in this process, it is very difficult to create a numerical model to describe their chemical and physical properties. This, together with a complex geometry of a RF cavity, increase the uncertainties in the solution of fluid simulations. Therefore without an experimental validation, results from this type of simulations can only show a general behaviour of the treatment fluid-dynamic.

To this aim, a cooperation started between INFN-LASA and the Laboratory of Combustion and Optical Diagnostics (Politecnico di Milano) to experimentally investigate the fluid dynamics of the BCP process by means of the Particle Image Velocimetry (PIV) and the refractive index matching (RIM) technique. While flow visualizations have been already reported in [3, 4], to the author's knowledge it is the first time that PIV and RIM techniques are applied to study the BCP treatment.

Purpose of this article is describe the methodology and the experimental set up we design to perform our PIV measurement and to report the preliminary results obtained so far.

EXPERIMENTAL SET UP

PIV and RIM

PIV is a non-intrusive laser optical measurement technique that allows to describe the velocity field in a desired region of a fluid field. It is particularly used for research and diagnostics into flow, turbulence, microfluidics, spray atomization, and combustion processes. In our case, this technique allowed us to reproduce the flow field of a BCP treatment inside an elliptical cavity when the following two aspect are satisfied:

- a transparent copy of a cavity is needed in order to allows PIV cameras to see what happens inside it;
- employing a transparent model, however, is not sufficient to guarantee a clear image of the interior of the cavity. In fact the mismatch between the refractive index of the transparent copy and that of the used fluid, generates strong optical distortion preventing the use of PIV techniques. RIM technique proposed by Budwing [6] is a method that consist in employing a fluid that matches the refractive index of the solid transparent object. In this way any optical distortion can be neglected inside our cavity model since solid and fluid can be considered as a single material characterised by a single index of refraction. To further decrease image distortion, we totally submerged our cavity model in a large box containing the matching fluid, as proposed by Cozzi et al. in [7]. Doing so the transparent cavity totally disappears inside the box and for that reason we called it "phantom".

Following this consideration, we design our experimental set up as schematised in Fig. 1: both the external box, that we call "aquarium", and the phantom have an octagonal shapes in order to allow cameras and lasers to impact perpendicularly on their surface minimising any possible refraction

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of light. A laser blade illuminates a meridian section of our cavity model: this section represent the measured region of the fluid field. Two CCD cameras placed 90° from each other and at 45° from the laser plane complete our experimental setup.

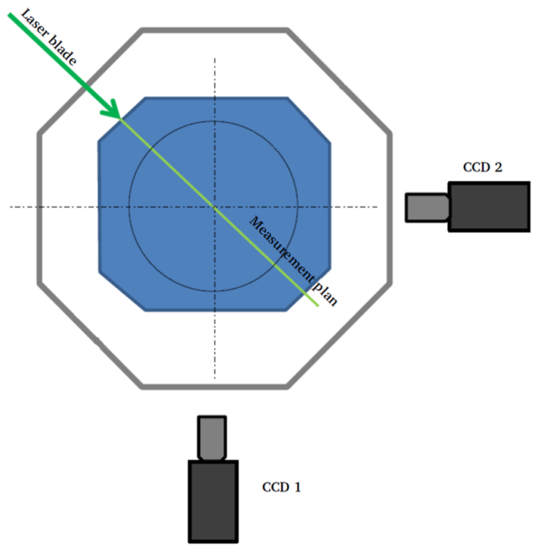

Figure 1: Schematisation of our PIV experimental set up.

Phantom and Matching Fluid

Even if we obtained lots of information about the BCP treatment of ESS medium beta cavity, for the phantom model we decided to reproduce the PIP-II 650 MHz low beta cavity geometry scaled 1:4. This decision was made because ESS series production was almost at the end, while PIP-II is at its first stages. Furthermore the CFD model validation is not strictly linked to a specific cavity geometry, but to the generic geometry of a superconducting elliptical cavity.

The cavity model was made of Sylgard 184, a very stable silicone elastomer characterised by relatively low refractive index (n = 1.4118 @ 589 nm). This feature allowed us to use a cheap, non-corrosive, non-toxic, water/glycerol (W-G) mixtures as a RIM fluid [6-8]. The polynomial fit for W-G mixture proposed by Helmers et al. [8], gave us a first estimation of the mixture mass fraction: about 61% glycerol and 39% water. Furthermore, an Abbe refractometer was used to measure the refractive index of both silicon and mixture samples. Only small systematic difference (less than 0.1%) between our results and the Helmers's fit has been found.

In Fig. 2(A) it is depicted our silicon transparent cavity. From that image we can clearly see that the material is transparent. However due to the different index of refraction between air and silicon, the cavity shape is visible inside the phantom meaning a great distortion of light on that interface. Under that conditions, a PIV acquisition would not give any reliable results. Fig. 2(B), instead, shows the phantom model inside the aquarium that has been completely filled with the W-G mixture. A simple hydraulic system fed the

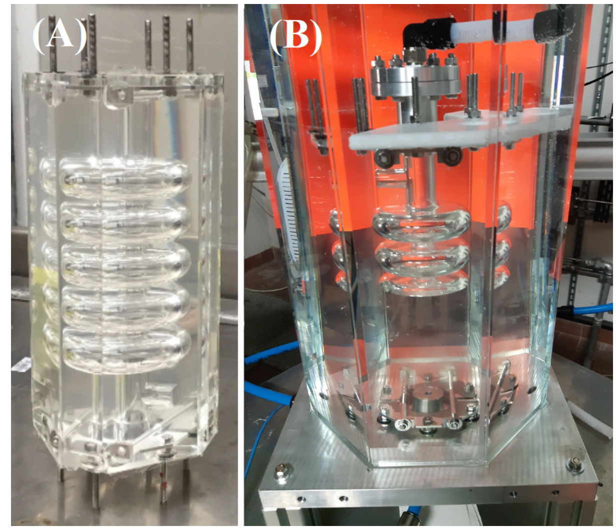

Figure 2: (A) Phantom model. (B) Experimental set up with phantom inside the aquarium filled with W-G mixture.

cavity with a volumetric flow rate Q from below. In this picture it is clear that only the top half part of the cavity model has not been filled with the matching fluid since it is the only visible part inside the acquarium.

Fluid-Dynamic and Geometric Similarity

To ensure the fluid field similarity between our model and the real BCP flow, both the geometric and the fluid dynamic similarity has been imposed. This means that the Reynolds number has to be the same in both cases. Calling A a reference area of a reference section, L a reference length and ν the kinematic viscosity of the fluid, the Reynolds number can be calculated as follow:

$$Re = \frac{QL}{A\nu} \tag{1}$$

Combining Eq. (1) with the geometrical scale factor $M = L_{model}/L_{actual} = (A_{model}/A_{actual})^{1/2}$ we obtain:

$$Q_{model} = Q_{actual} M \frac{\nu_{model}}{\nu_{actual}} \tag{2}$$

In our case $M = 1/4$ thus according to Eq. (2) and to data in Table 1, the W-G flow rate required by the similarity is 2.5 l/min.

CFD SIMULATIONS

For CFD simulations, we considered a slightly simplified cavity geometry. In particular we used as baseline geometry a meridian section of the PIP-II cavity neglecting both pick up and coupler tube. This because, as first attempt, we consider the flow field completely axisymmetric. Mesh was built employing Ansys® ICEM, while simulations has been performed in Ansys® Fluent employing the viscous laminar model.

From simulation results, as depicted in Fig. 3(B) for a single cell, we can highlight the following main flow characteristics:

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Table 1: Fluid characteristics where: D_{inlet} diameter of the injection port, reference diameter for the Reynolds number, ρ density, μ viscosity (for the W-G mixture it is evaluated according to Cheng et al. [9]) and v_{inlet} injection velocity

	Units	BCP	W-G mixture
D_{inlet}	[m]	0.032	0.008
ρ	[kg/m^{3}]	1490	1154
μ	[Pa.s]	0.022 (15 °C)	0.013 (17 °C)
Q	[l/min]	13.5	2.5
v_{inlet}	[m/s]	0.28	0.82
Re		584	584

- from the inlet port, a central fluid jet flows upward without break since this is not a turbulent flow. Due to the entrainment process the jet diameter of the central column grows moving downstream until it reaches the outlet port.
- here the flow field divides into two different direction: part of it flows through the outlet and leaves the cavity, while part of it reverses its direction starting to flow downward. This secondary motion flows with appreciable difference in velocity between irises and equator.

Taking into account this consideration, we can subdivide the flow field in three specific region: the central jet column in which the fluid field has the highest velocity, the back flow recirculation at irises where velocity is almost an order of magnitude less than the central jet column and the back flow recirculation at equator in which velocity is two order of magnitude less than the central column. This result tell us that inside the cavity cells, and in a more accentuated way near the equator, the fluid field is practically stationary.

EXPERIMENTAL RESULTS

In Fig. 3(A) is depicted the results from PIV measurement inside a single cell. Here every single arrow is a PIV measured point that describe the magnitude and direction of fluid in that point. Comparing images from Fig. 3 we can see that the overall behaviour predicted by simulations has been confirmed by experimental results: main jet column and back flow recirculation is clearly recognisable also in the experimental results. However there are two consideration that have to be made:

- in simulations, the maximum velocity reached at the cavity axis seems to be three times higher than experiment. The reason of this difference is a misalignment of the laser blade with respect to the cavity axis. This is a systematic error, acceptable in this preliminary phase, that can be adjusted in future acquisition.
- in the experimental results, the recirculation inside the cell seems to flows towards the equator. This means that in the real case the fluid fields is not perfectly axisymmetric and it has to be an azimuthal component that justify this behaviour. To better describe the real fluid field, a 3D CFD simulation is needed.

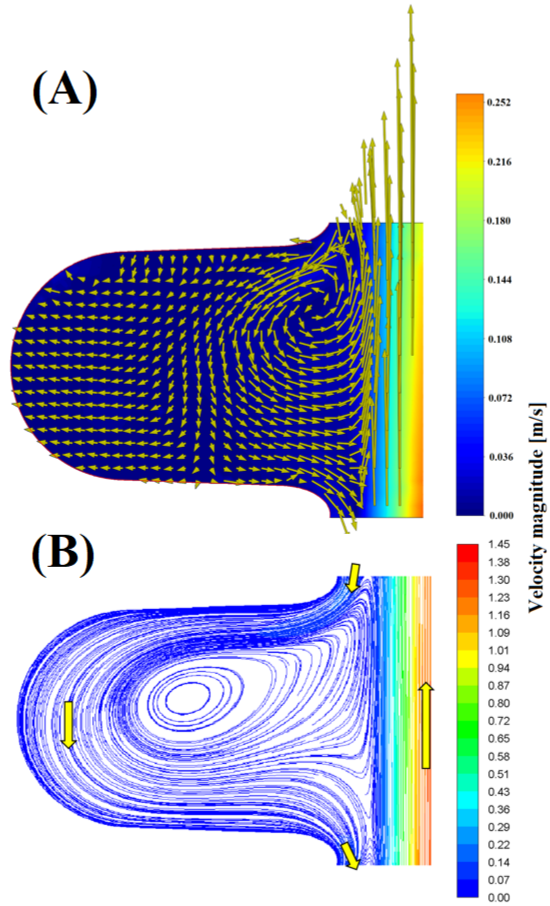

Figure 3: (A) PIV experimental results and (B) CFD simulations results.

CONCLUSION

Our preliminary experimental set up confirmed the possibility to analyse qualitatively and quantitatively the flow field of a BCP process inside an elliptical cavity thanks to a very good RIM matching between phantom and the W-G mixture. As a first approximation, the overall complex behaviour predicted by CFD simulations has been verified with good consistency; in particular experimental results confirmed that inside cells, fluid is almost stationary. Further measurements and 3D CFD simulations are required to fully clarify the flow field structure and fully validate CFD simulations.

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