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A Coupled PIV/PTV Technique for the Dispersed Oil-Water Two-Phase Flows Within a Centrifugal Pump Impeller

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Abstract **-** The current work presents a framework for the simultaneous characterization of different phases in a dispersed oil-water two-phase flow. The framework is based on the coupling of the PIV and PTV techniques in raw PIV acquisition images. The PIV technique computes the water velocity fields, while the PTV technique calculates the oil drop velocities. Thus, the proposed technique allows the simultaneous measurement of the water phase and dispersed oil drop velocity from the same image. In order to present the advantages of the coupled PIV/PTV technique, the flow within a centrifugal pump impeller is completely analyzed by computing the oil and water phase-ensembled velocities.

***Keywords*:** centrifugal pumps; PTV; PIV; two-phase flows; oil drops

1. Introduction

Centrifugal pumps are widely used as an artificial lift method in oil production. In general, those pumps are designed to operate in single-phase conditions and with low viscosity fluids. However, in some industrial applications, such as petroleum production, the equipment may face unfavorable conditions such as the presence of heavier and/or lighter phases and high viscous fluids. When that is the case, the pump performance decays [1, 2], resulting in operational instabilities that may lead to equipment failure.

In order to better understand the pump performance losses, researchers have conducted over the last years several experimental studies to comprehend how those undesirable conditions affect the flow pattern within the pump. In two-phase flows, high-speed camera images are used to visualize the flow patterns inside the pump [1, 3], or can be used to track the motion of dispersed drops [4, 5, 6]. Alternatively, in single-phase flows, the Particle Image Velocimetry (PIV) technique can be used to characterize the continuous phases, returning the velocity field within the pump geometry [7, 8, 9]. A detailed review of the relevant flow visualization studies on centrifugal pumps can be found in [10].

The objective of the current work is to introduce a framework for the simultaneous characterization of different phases in a dispersed oil-water two-phase flow. For this purpose, this paper presents an experimental study on the dispersed oil-water flow inside the stage of a transparent pump, where oil drops are injected into the impeller channels of the centrifugal pump. The framework is based on the coupling of the PIV and Particle Tracking Velocimetry (PTV) technique, with the latter tracking the motion of oil dispersed drops.

2. Experimental Setup

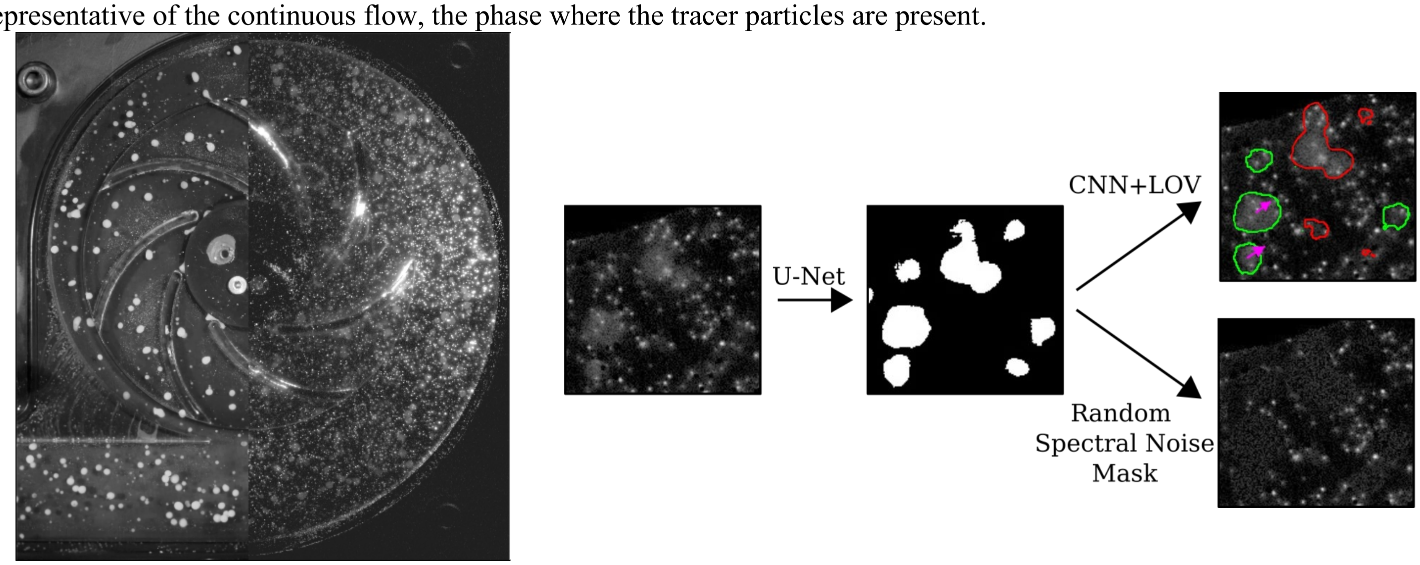
The experimental setup consists of water and oil flow lines, a booster pump, and instruments to measure flow rate, pressure, and temperature. For the flow rate measurement, two Coriolis flowmeters are installed, Emerson's MicroMotion F200 and MicroMotion D6, for the water and oil flow lines, respectively. The test section is a transparent centrifugal pump that was especially developed to enable flow visualization in the impeller and volute. The Time-Resolved PIV (TR-PIV) system is a DualPower 30-1000 model from Dantec Dynamics.

In two-phase flow PIV applications, the interfaces scatter light at a higher intensity than the tracer particles, resulting in images with "bright spots" close to the interfaces [11]. These reflections disturb the PIV cross-correlation results and can even damage the camera CMOS sensor [12]. In order to minimize this effect and also reflections originating from the acrylic impeller blades, fluorescent particles (average diameter of 50 μm) of PMMA doped with Rhodamine were used as tracers.

In the present work, a single experimental condition is studied, where the pump impeller speed is set to N=600 rpm, the water flow rate Q_{water}= 1.80 m^3/h, while the mineral oil drops (viscosity of μ_{oil} = 20.0 cP) were injected at a flow rate of Q_{oil}= 21.25 ml/s. During the design and manufacturing of the pump prototype, care was taken to ensure that the oil phase was injected uniformly in each pump impeller channel. As an example, Fig. 1a) shows a combined illustration of a high-speed camera (left portion) and a PIV (right portion) image acquisitions. In the high-speed camera image, taken during a flow visualization experiment, the mineral oil was dyed in white to increase the image contrast. According to Fig. 1a), the designed prototype can produce uniform oil dispersed oil-water two-phase flow in all the pump's impeller channels.

3. Image processing - Coupled PIV/PTV technique

As detailed in the literature, the application of the PIV technique is not straightforward in two-phase flows [11]. The right half image of Fig. 1a) shows an example a PIV image taken when oil drops are present in the flow. As observed, even though no seeding particles are present and no dye is added to the mineral oil, the oil drops remain visible in the images. Therefore, the oil drops must be removed (or masked out) from the PIV images. Otherwise, the oil drop inter-frame displacement will be during the PIV cross-correlation step, resulting in "spurious" velocity vectors [11], which are not representative of the continuous flow, the phase where the tracer particles are present.



a) b)

Fig 1: a) Left: High-speed camera image of the experimental apparatus and the produced dispersed oil-water two-phase flow. Right: Raw image acquired during a PIV acquisition; b) Image processing steps of the coupled PIV/PTV technique described here.

For this purpose, a dynamic masking method is employed to mask out the oil drops from the PIV image. The masking is based on the development and training of a U-Net convolutional neural network [13]. The U-Net generates a binary mask that can then be used to remove the oil drops from the image. The same strategy was used in [14] to remove the gas bubbles in the PIV raw images. The spectral random masking from [15] is used to mask out the oil drops.

For the PTV technique, the same U-Net mask is used to retrieve the instantaneous drop positions in the PIV images. By coupling an additional CNN (Convolutional Neural Network) model, overlapped drop contours are identified and removed from the image. After the oil drops are identified, the instantaneous displacement is computed throuhg the Labelled Object Velocimetry (LOV) technique [16]. This approach is carefully detailed in [6].

Figure 1b) exemplifies the image processing steps to mask out the oil drops from the PIV image and to calculate the PTV oil drop velocity vectors, showing the different steps in a selected region of the pump impeller. In Fig. 1b) the red colored lines represent contours that the CNN model did not classify as valid oil drops, while the green ones represent the opposite. The pink arrows indicate the instantaneous oil drop velocity vectors. When the LOV correlation is low, the velocity vectors are discarded, which is the case in two of the presented contours.

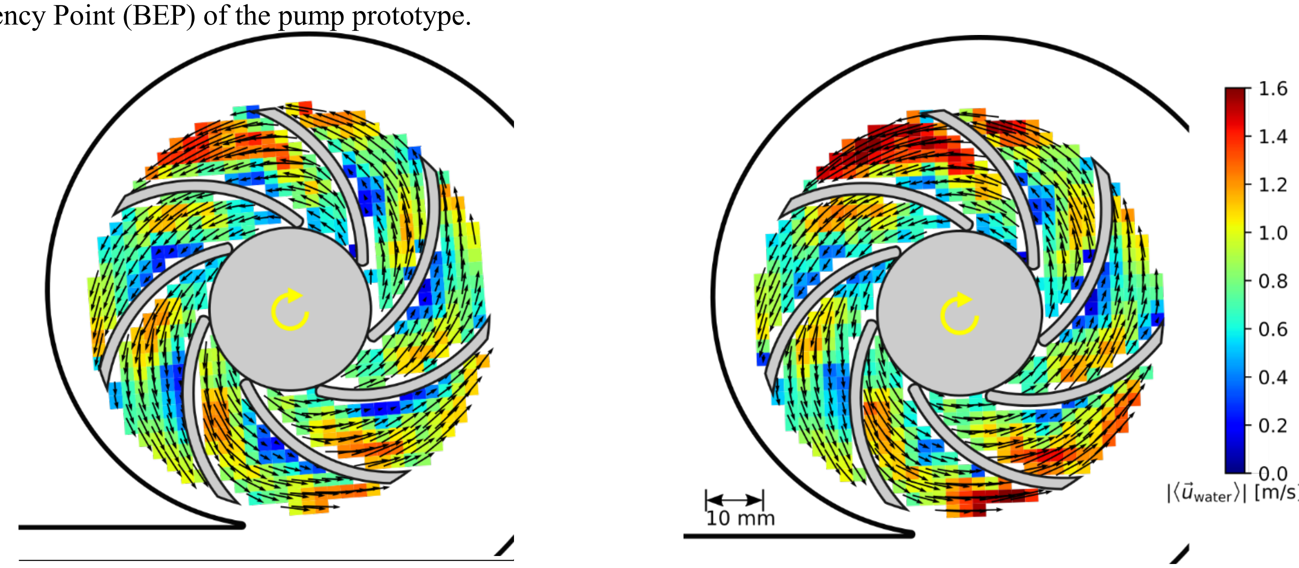
4. Results

The results shown in this section were acquired during a TR-PIV experiment with an acquisition frequency (temporal resolution) of f_{TR-PIV} = 700Hz. In this experiment, a total of 2500 PIV frames were recorded, resulting an acquisition period of t=3.571s were recorded. The velocity vectors were estimated using the OpenPIV package [17] with an interrogation window set to 64 pixels, with a 32-pixel overlap. The images were acquired in a double-frame configuration, with a temporal spacing of ΔT_{PIV}=600 μs between each frame. This value limited the maximum displacement of the tracer particles to 8 pixels between two consecutive frames, following the guidelines discussed in [12].

For the present study, only the fields of the centrifugal pump impeller are studied in the present work. Following [9], before computing the PIV velocity fields, an image rotation step is added to the original PIV images to remove the solid body motion of the impeller blades. In addition, only the phase-averaged results are shown in the present work. From the pre-defined f_{TR-PIV} value and the impeller angular speed N, the impeller completes a full rotation every 70 frames. The impeller has a total of seven channels, and thus due to the geometry periodicity, a channel is at the same position every 10 frames. Since a rotary encoder is mounted on the pump shaft and synchronized with the PIV system, it was possible to average the flow field at a pre-defined rotational angle. Following this description, A total of 250 images were used to compute the phase-ensembled PIV and PTV velocity fields.

The results of the phase-ensemble averaged velocity field in the pump impeller are shown in Fig. 2, where the impeller is at a rotational angle for θ_{blades} = 0.0º degrees, defined as the angular position where the blade tip is aligned with the volute tongue.

For better visualization of the flow structure, the velocity fields in Fig. 2 are shown in a non-inertial reference frame, which rotates with the impeller blades. Figure 2a) shows the results without employing the dynamic masking procedure, while Fig. 2b) shows the phase- averaged velocity fields after applying the dynamic masking. According to the results, when not removing the oil drops during the PIV correlation, the difference in the velocity values can reach up to 40 % close to the impeller outlet and impeller pressure blades. In general, the non-processed lower magnitude velocity fields. As the oil drops are “dragged” by the flow, moving slower than the continuous phase, the spurious contribution of the drops results in lower velocity values in each interrogation window. Regarding the flow pattern within the centrifugal pump impeller, the velocity vectors follow smoothly the impeller blades. This result is expected, since the experimental condition lies on the Best Efficiency Point (BEP) of the pump prototype.

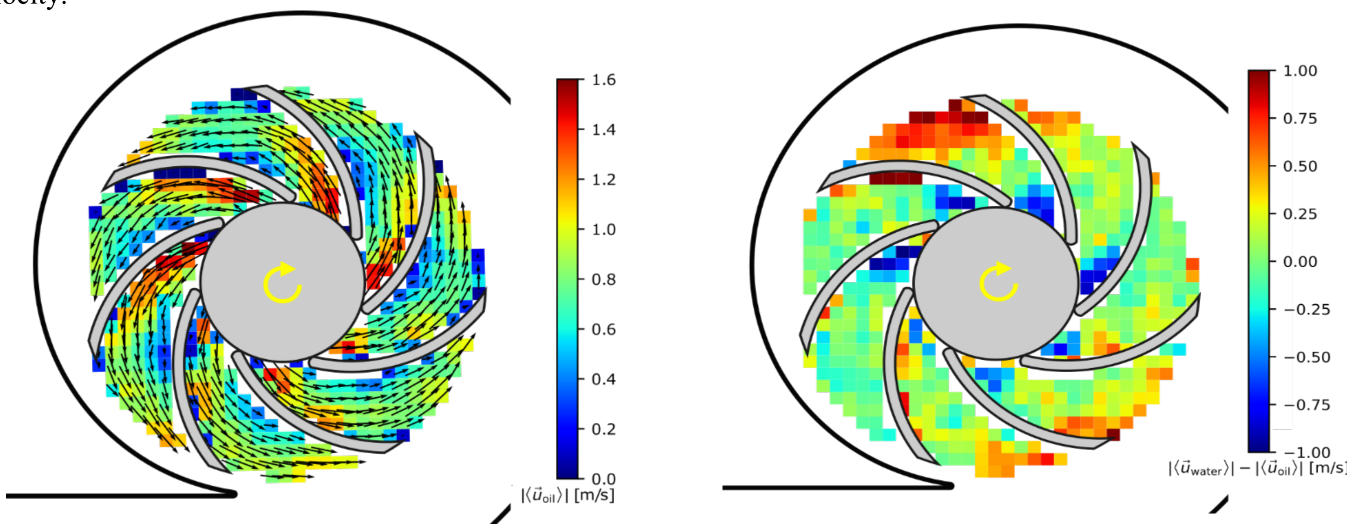


a) without applying a dynamic mask b) applying the dynamic mask

Fig 2: PIV phase-ensemble averaged velocity field. The yellow arrow indicates the counter clockwise motion of the pump impeller blades.

The phase-averaged PTV velocity field of the oil drops is shown in Fig. 3a), while Fig. 3b) presents the slip velocity between the two phases. It is important to state that during the PIV calculations, the period between two frames was, as previously stated, set to ΔT_{PIV}=600 μs. However, for the PTV calculations, the TR-PIV temporal resolution ΔT_{PTV} = 1428.67 μs ($\Delta T_{PTV} = 1/f_{TR-PIV}$ = 1/700Hz) was used. This approach allows for flexibility when defining the interframe temporal resolution.

By comparing the velocity fields of Fig. 2 with Fig. 3, generally, the oil drops travel along the impeller channels slower than the continuous phase. However, the opposite is observed close to the impeller channel inlet regions of the centrifugal pump impeller. This effect can be attributed to the oil drops' injection mechanism, which injects oil drops with a high velocity.



a) b)

Fig 3: Results from the coupled PIV/PTV detailed in this work: a) PTV phase-ensembled average velocity fields of the oil drops and b) Velocity difference (slip) between the water continuous phase and oil drops within the pump impeller channels.

4. Conclusions

The current work presents a coupled PIV/PTV framework for the simultaneous characterization of different phases in a dispersed oil-water two-phase flow. By using the coupled framework, it is possible to simultaneously compute the continuous and dispersed phase velocities from the same image. In addition, to track the motion of the dispersed phase, the framework presented in the current work also generates a dynamic mask to remove the secondary phase from the raw PIV images.

In order to present the advantages of the coupled PIV/PTV technique, the dispersed oil-water two-phase flow within a centrifugal pump impeller is studied. First, it shows the difference in the phase-averaged water velocities with and without using a dynamic mask to remove the oil drops. The results show that the difference in the velocity values can reach up to 40 % in certain locations of the pump impeller channels, exemplifying the importance of using an image processing method to remove the oil drops from the raw PIV images. Lastly, the phase-averaged velocity fields of the oil drops are presented. The results show that the oil drops move slower than the continuous phase on the majority of the impeller channels, except close to the oil injection ports.

These results may help better understand the oil drop dynamics within centrifugal pump impellers, particularly the verification of drag/lift/virtual mass closure models, typically used in Computational Fluid Dynamics (CFD) applications.

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