PIV Measurements in a Transparent Plate Heat Exchanger

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Abstract: *Optical techniques are widely adopted in the fluid dynamic investigations for non-confined flow as well as confined one. Apparently only the limitation in the realization of a transparent wall constitutes an obstacle at the adoption of measurements techniques based on optical effect. In particular the so-called Particle Image Velocimetry (PIV) needs large transparent planar windows due to the intrinsic capability of extract velocity information over a whole plane. In an elevated number of applications, the adoption of large (transparent) surfaces is strongly unwanted due to the unacceptably modification of the boundary conditions. An example of this application is constituted by the plate heat exchanger (PHE). In fact, the well-known geometry will be strongly modified adopting instead of two metallic corrugated adjacent plate, a metallic corrugated plate and a transparent planar one. But in order to perform PIV measurements it is necessaries to extract images not deformed by corrugate transparent surface. In order to eliminate this inconvenient a refractive index matching (RIM) technique as been adopted. In practice the RIM technique attempts to match the refractive index of the working fluid to that of the transparent boundary so that, although the physical flow is present and realistic in geometry, they became optically invisible for the laser beam and optical information scattered by the flow. For the present paper a transparent (acrylic) plate has been realized with the same morphological configuration of the original metal plate adopted for realize the PHE under investigation. The refracted index of the acrylic transparent plate is n=1.49. This value is matched by means of a mixture of oil of Turpentine (n=1,468) with 1,2,3,4-tetrahydronaphthalene (Tetraline n=1,546) in the proportion of about 70 % of Turpentine and 30 % of Tetraline). The investigation has been performed by means of a Particle Image Velocimetry (PIV). In particular the planar flow field developed at the entrance section of the investigated PHE at about 0.8 mm over the corrugated plate, has been measured at three different Reynold number. The measured velocities are reported in a grid with size of 32*32 pixels with an overlap of 50 % (Nyquist criteria) that means in a square grid with size of 2.5 * 2.5 mm.*

Key Words Particle Image Velocimetry, Refractive Index Matching, Heat Exchanger.

1.INTRODUCTION

Plate Heat Exchanger (PHE) are commonly used in a wide range of applications that include installations as heaters, coolers, chillers, condensers and evaporators for a wide range of liquids. In many applications, they are replacing the more commonly used shell and tube heat exchangers. Therefore, they are common in the dairy, beverage, general food processing, and pharmaceuticals industries, where this feature and the thermal control required for sterilization/pasteurization make them ideal. They are used in the synthetic rubber industry, paper mills, petrochemical plants and a variety of other process industry for water-water duties. An example of their varied exploitation is given in the motivation of the present work: the optimization of the heat exchanger needed to port automotive diesel engines (overall output less than 100 kW) to marine installations.

The high turbulence due to the plate corrugations must be assessed for it is the primary reducing factor of fouling. A quantitative analysis of flow patterns, through the local velocity distribution, is additionally needed when the design is to be optimized, i.e. to increase the efficiency and/or reduce the overall surface.

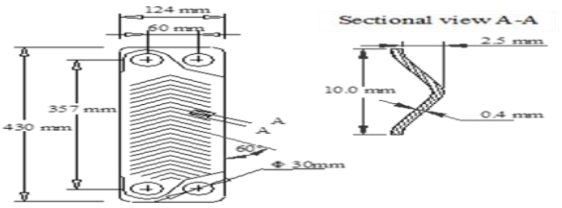
In bibliography a large number of papers are found reporting both numerical and experimental studies concerning the heat exchange technology. These papers are basically divided in two categories. The first category reports study of corrugated plate in which the local and global heat transfer and pressure drop performances are reported in terms of flow field (Reynolds number) and geometric parameters (dimension, inclinations, etc., of the corrugations) usually the measurements were performed in the well-developed flow region. In particular it will be necessary to indicate the work of Gaiser and Kottke [1], in which the authors investigated compact heat exchanger formed by corrugated (undulated) channels exposed with different inclination respect the main flow. Stasiek [2][3] introduced the LCT technique in the experimental determination of the local heat transfer in corrugated surfaces. Rush et al. [4] investigated the local heat transfer for laminar and transitional flows in sinusoidal wavy passages. Cowell et al.

[5] described the operating mechanism of multilouvered fins heat transfer surfaces. Ros et al. [6] by means of a transient-state technique was able to experimentally determine the global heat transfer coefficient between liquid (water) and corrugated surfaces. Sarraf et al. [7] and Freund et al. [8] investigated local heat transfer coefficients in plate heat exchangers with infrared measurements.

In the second category the results obtained directly on a complete PHE, in which the performances of these devices are expressed in terms of averaged heat transfer coefficient (averaged Nusselt) pressure drop, velocity distribution and fouling phenomena for different fluids, are reported, most of them used in the chemical and food industry. In particular the fouling effect in PHE was well investigated by Delplace et al. [9] who investigated the fooling in a six-channels per pass PHE. Bansal et al. [10] investigated the effect of calcium sulphate fouling. Kim et al. [11] investigate the heat transfer in PHE during the pasteurization of orange juice. More recently Berce et al. [12] investigated the fooling due to crystallization of salt into cold and low velocity zone of a PHE. Andika et al. [13] studied the performance of a PHE under velocity variations.

All these experimental investigations showed a few data about the internal flow field generated and its influences on the local heat transfer coefficient and/or on the fouling effect. Both the phenomena, perhaps, are strongly influenced, in a real PHE, by the local inlet flow field, due to the inlet local corrugation, usually adopted for a uniform distribution of the inlet flow. The purpose of this paper is to develop a transparent couple of plate of a PHE in order to investigate the internal flow field specially under different flow rate.

In the present work an acrylic (transparent), figure 1, plate heat exchanger has been experimentally investigated in order to determinate the inside flow field at different mass flow rate. The investigations were performed by mean of the well know Particle Image Velocimetry (PIV) techniques. The working fluid was a mix of Turpentine and Tetraline able to match the refraction index of the acrylic material used for the solid walls of the investigated PHE, in this way a Refractive Index Matching (RIM) has been realized. The investigate mass flow rate was about 0.23, 0.45 and 0.68 kg/s which correspond at a Reynolds number, calculated using the average cross section [2], of about 8000, 16000 and 24000.



Corrugation type	Chevron
Inclination angle	60°
Total plate length	0.4300 m
Total plate width	0.1240 m
Effective plate length	0.3960 m
Effective plate width	0.1000 m
Plate thickness	0.0004 m

Fig. -1: Geometrical characteristics of the tested heat exchanger plate

2. EXPERIMENTAL PROCEDURE

2.1 Particle Image Velocimetry technique (PIV)

Using the PHE showed in Figure 1 several measurements have been performed in order to determine the flow field due to different mass flow rates. All of the measurements have been brought forth by using a Particle Image Velocimetry (PIV) (Figure 2) technique based on two pulsed Nd:YAG laser firing on the second harmonic (green 532 nm). The two obtained beams, properly separate in time, are recombined on the same optical path by means of a polarized dichroic filter. After the recombination the beams are expanded in one direction, by a combination of spherical (negative) and cylindrical lens, in order to obtain a laser sheet of about 100 mm wide and 0.3 mm thick in the measuring region. Then the laser sheet is used to illuminate the liquid flow inside the test PHE realized by means of an acrylic transparent (at 532 nm) plate, faced to an acrylic plate, with some corrugations, realized also in the same material, with a chevron angle of 60°. The transparent plate is kept at 2.0 mm from the corrugated one by means of a transparent (acrylic) frame (5 mm thick) reproducing the gasket contour. The laser sheet is introduced into the heat exchanger through the frame and the images can be collected at 90° through the plate. The obtained images have been collected by of a double frame 1K*1K pixels CCD camera synchronized with the two laser beams and with the frame grabber by means of a dedicated electronic synchronizer device. The collected images are formed by two different layers, each of them containing information about the seeding positions obtained firing one of the two lasers. In this way it is possible to spot the initial seeding positions (first laser beam, image on the first layer) and the final one (second laser beam, image on the second layer). This allowed to the elimination of the polarity ambiguity present in the standard PIV technique [14, 15]. The images were post-processed by means of a dedicated software in order to extract sub-images formed by 64*64 pixels from each layer, and to perform a cross-correlation between the two corresponding sub-images. An interrogation algorithm extracts the correlation peak position from the cross-correlation domain with a sub-pixel precision and, perform the calculation of the two velocity components for those sub-images, by mean of a pixel-to-mm conversion factor. A recursive algorithm repeats the interrogations for the entire set of double frames images

The measured velocity is reported in a grid with size of 32*32 pixels with an overlap of 50 % (Nyquist criteria) that means in a square grid with size of 2.5 * 2.5 mm. For each condition we collected 50 single images. The two laser beams were fired with about 100 mJ per pulse (second harmonic) and a separation time Δt of 40 µs. The overall estimated error [15, 16] was about 4% on the velocity magnitude. These conditions were kept the same for all the tested mass flow rate.

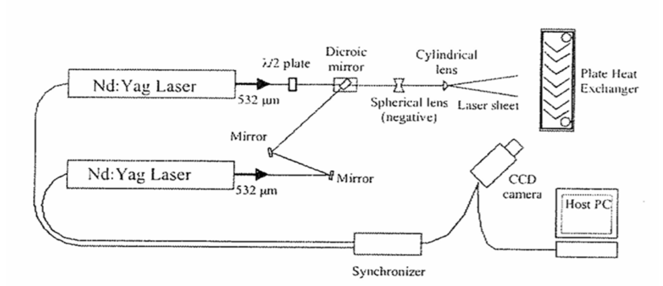


Fig. -2: PIV optical setup

2.2 Refractive Index Matching technique (RIM)

The non-intrusive nature of the optical techniques (PIV) combined with their insensitivity to fluid properties and flow conditions, renders their use suitable for the study of complex flow configurations, provided that adequate optical access can be ensured. The use of optical flats (windows) or transparent models may well provide the necessary optical access in many flow configurations but, in some cases, the presence of multiple or irregular flow boundaries may pose additional limitations. These difficulties arise from differences in the refractive indices of the working fluids and the transparent flow boundaries along the path of the laser beams which form the measurement.

It is on these observations that the principle of the refractive index matching technique (RIM) is based; it attempts to match the refractive index of the working fluid to that of the transparent boundary so that, although the physical flow boundaries are present and realistic in geometry, they become optically invisible for the laser beams of the velocimeter. This enables laser-sheet flow measurement (PIV) to be performed with no distortion of the observation plane and no distortion (i.e. intensity modulation and light spreading outside the optical path) of the laser sheet.

A comprehensive study of the abilities of the RIM techniques is reported in [17, 18, 19]. The fluid often selected to match the refractive index of the cast acrylic models is a mixture of oil of Turpentine with 1,2,3,4-tetrahydronaphthalene (Tetraline). This mixture is chosen for its low toxicity and flammability, combined with its relatively low cost. One particular advantage of this liquid is the low viscosity as compared to many mineral oils which are suitable for refractive index matching. Its main disadvantage is the effect of Tetraline on acrylic material, the surface of which softens and crazes after six months in contact with it and dissolves after one year.

Despite the inert nature of the mixture there are some precautions to be taken with respect to fire hazard and ventilation of the working area. The fumes of the mixture are irritating and prolonged exposure may cause injury to the kidneys and lungs.

The refractive index of the cast acrylic (nd=1.49) lies between the refractive indices of the oil of turpentine (nd=1.468) and Tetraline (nd=1.546). It is therefore feasible to obtain a mixture of the two fluids which, at a given temperature, will match that of the acrylic. The effect of mixture concentration (Cm) in Tetraline on the refractive index as a function of temperature is shown in fig.3, which clearly indicates its sensitivity to both parameters. Fig.4 shows the variation of mixture refractive index with temperature, as a function of Tetraline concentration and light wavelength. This graph also shows the effect of temperature on the refractive index of two common qualities of clear acrylic (Perspex and Diacon). It can be concluded that many combinations of temperature and concentration will achieve refractive index matching of the two media. Fig.3 also demonstrates that the matching temperature may increase sharply by a small increase in Tetralina content (7 C for 1.7% increase in Tetralina content). Since high temperatures will shorten the useful life of the transparent models, the best practice is to set the temperature slightly above ambient (e.g. 25 C) and adjust the content of Tetraline to match the refractive index of the acrylic.

Typical characteristics of a mixture of oil of turpentine (70% volume) and Tetraline (30% volume) are given in Table 1 below, while the effect of temperature on the cinematic viscosity of the mixture is shown in Fig. 5. In Fig. 6 a schematic representation of the RIM set-up is also reported.

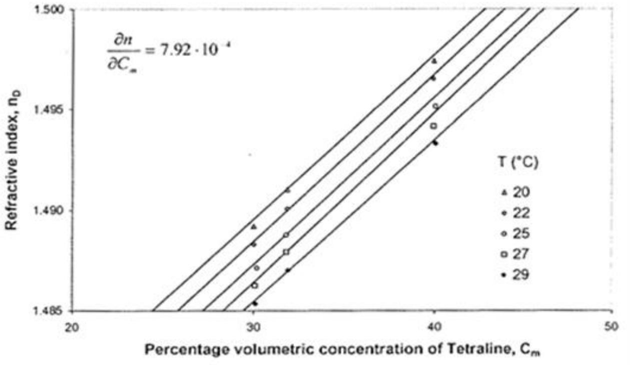


Fig. -3: Variation of mixture refractive index as a function of mixture temperature

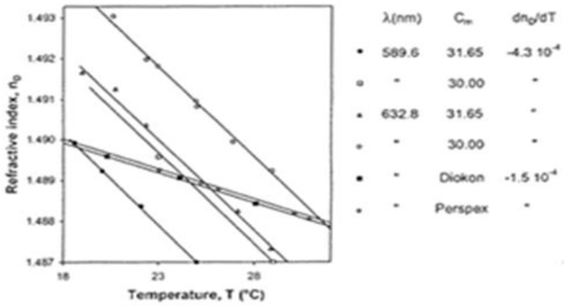


Fig. -4: Variation of mixture refractive index with temperature, as a function of Tetraline concentration and light wavelength

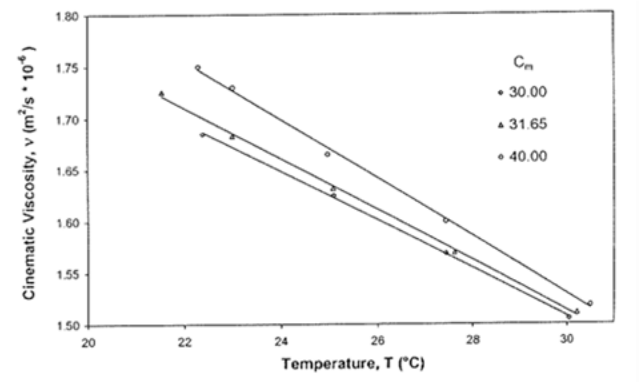


Fig. -5: Variation of mixture cinematic viscosity as a function of temperature

Table 1: Properties of mixture Cm = 30 at 20 °C

Density	$\rho = 893$	kg/m^3
Cinematic viscosity	$\nu = 1.740 * 10^{-6}$	m^2/s
Refractive index	$n_D = 1.4897$ at	$\lambda = 632.8$ nm

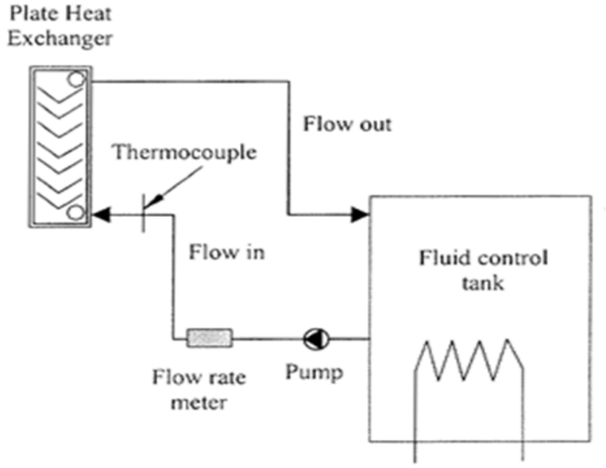


Fig. -6: RIM set-up

3. RESULT AND DISCUSSION

After the PHE section was made of acrylic material, the composition of the working fluid (a mixture of Turpentine and Tetraline) was fine-tuned and the temperature was set to minimize the refractive index between the liquid and the walls. A measurement campaign was carried out to test the technique and verify its measurement capability on the transparent plate heat exchanger model. The first, preliminary measurements were carried out on the inlet section of the exchanger plate, keeping the PHE in the same position and changing the flow rate of the fluid flow in the PHE. In particular the measurements have concerned three Reynolds number respectively Re = 9000, Re = 16000 and Re = 24000. The corresponding results, as velocity vectors distribution, are reported respectively in fig 7, 8 and 9. These images, as mentioned before, are obtained averaging fifty single PIV results for each Re investigated. As it is possible see in all the investigated cases it is possible to observe that the internal flow is not uniform ad is substantially divided in three main flows, probably generated by the local metallic profile engraved in the investigated plate as visible in fig. 10 in which a photography of the investigated plate is reported.

This not uniform velocity distribution at the inlet section of the heat exchanger certainly strongly influenced the overall performances of the PHE in terms of overall heat exchanged and in terms of fouling distribution in the PHE.

The two components velocity distribution reported in Figures 7 to 9 demonstrate the ability to reconstruct the entire flow field under investigation (at least in the illuminated region) of the adopted technique also in a corrugate environment, near the walls without particular deformation of the laser shit and PIV images recorded orthogonally the illumination plane. The adoption of a RIM technique is necessary for achieve these performances.

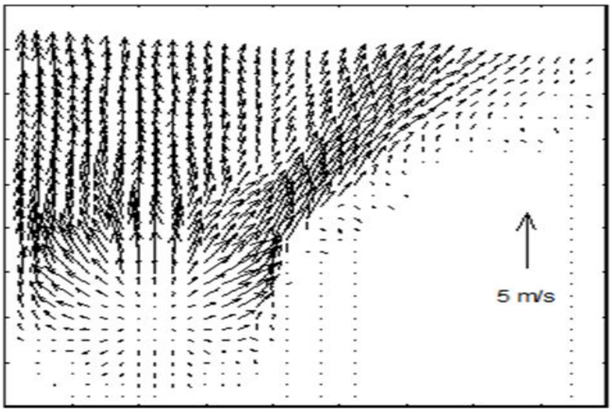


Fig. -7: Inlet local velocity flow field with Re = 8000

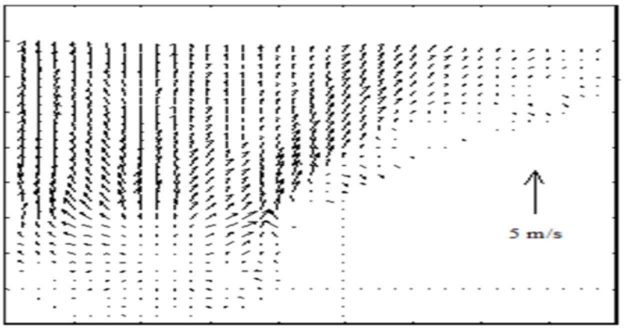


Fig. -8: Inlet local velocity flow field with Re = 16000

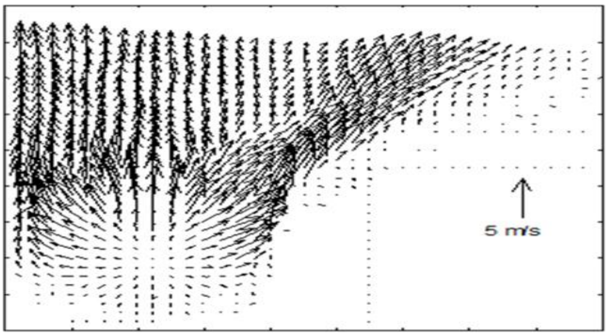


Fig. -9: Inlet local velocity flow field with Re

Fig. -10: The photograph of a plate of the PHE under investigation. Note the inlet section A, the gasket B, the inlet flow distribution corrugations C and the chevron corrugation D

4. CONCLUSION

A transparent model of a commercially available plate heat exchanger (PHE) plate was studied by measuring the internal flow field. The experimental techniques employed were Particle Image Velocimetry (PIV) combined with Refractive Index Matching (RIM). RIM was used to avoid optical deformations due to the corrugations typically found in a plate heat exchanger (PHE). Measurements, performed preliminarily at the inlet section of the PHE, accurately reconstructed the initially non-uniform flow field. Future work will focus on reconstructing the entire internal flow field and, possibly, modifying the corrugations positioned around the inlet section to optimize the performance of the PHE. The PIV measurements can used, also, for calculate the turbulence and vorticity distribution in order to correlate the heat transfer coefficient and fooling effect along the heat exchanger plate.

REFERENCES

[1]. Gaiser G., Kottke V. “Flow Phenomena and Local Heat and Mass Transfer in Corrugated Passages”. Chemical Engineering Technology. 12 400-405, 1989.

[2]. Stasiek J.A. “Experimental studies of Heat Transfer and Fluid Flow across Corrugated-Undulated Heat Excanger Surfaces” International Journal of Heat and Mass Transfer. Vol. 41, No. 6-7, pp. 899-914, 1998.

[3]. Stasiek J.A., Collins M.W., Ciofalo M. Chew P.E. “Investigation of Flow and Heat Transfer in Corrugated Passages-I. Experimental Results” International Journal of Heat and Mass Transfer. Vol. 39, No. 1, pp. 149-164, 1996.

[4]. Rush T.A., Newell T.A., Jacobi A.M. “An Experimental Study of Flow and heat Transfer in Sinusoidal Wavy Passages” International Journal of Heat and Mass Transfer. 42 1541-1553, 1999.

[5]. Cowell T.A., Heikal M.R., Achaichia A. “Flow and Heat Transfer in Compact Louvered Fin Surfaces” Experimental Thermal and Fluid Science. 10 192-199, 1995.

[6]. Ros S., Jallut C., Grillot J.M., Amblard M. “A Transient-State Technique for the Heat Transfer Coefficient Measurement in a Corrugated Plate Heat Exchanger Channel based on Frequency Response and Residence Time Distribution” International Journal of Heat and Mass Transfer. n.7 pp. 1317-1325, 1995.

[7]. Sarraf K, Launay S, El Achkar G, Tadrist L (2015) Local vs global heat transfer and flow analysis of hydrocarbon complete condensation in plate heat exchanger based on infrared thermography. Int J Heat Mass Transf 90:878–893 (str).

[8]. Freund S, Kabelac S (2010) Investigation of local heat transfer coefficients in plate heat exchangers with temperature oscillation IR thermography and CFD. Int J Heat Mass Transf 53:3764–3781 (str).

[9]. Deplane F., Leutiet J.C., Levieux D. A reaction Engineering Approach to the Analysis of Fouling by Whey Protein of a Six-Channels-per-Pass Plate Heat Exchanger”. Journal of Food Engineering. 34 91-108, 1997.

[10]. Bansal B., Müller-Steinhagen H., Chen X.D. “Performance of Plate Heat Exchanger During Calcium Sulphate Fouling – Investigation with in-line Filter”. Chemical Engineering and Processing. 39 507-519, 2000.

[11]. Kim H.B., Tadini C.C., Singh R.K. “Heat Transfer in a Plate Exchanger During Pasteurization of Orange Juice”. Journal of Food Engineering. 42 79-84, 1999.

[12]. Berce J., Matevž Zupančič M., Može M., Golobič I. “Local temperature distribution of a plate heat exchanger undergoing crystallization fouling”. Heat and Mass Transfer (2025) 61:68.

[13]. Andika Syahputra, Asnawi, Ahmad Nayan, Alchalil, Nurul Islami “Evaluation of Fluid Flow Velocity Variations on The Plate Heat Exchanger Performance” TRANSMISI Volume 19 Nomor 1 2023.

[14]. Stucky M.J., Nino E., Gajdeczko B.F., Felton P.G. "Two-Color Particle Image Velocimetry Technique for an Internal Combustion Engine". Experimental Thermal and Fluid Science Journal, 8(4):305-314 1994.

[15]. Raffel M., Willert C., Kompenhans J. “Particle Image Velocimetry” Springer 1998.
[16]. Fouras, A., Lo Jacono, D. & Hourigan, K. Target-free Stereo PIV: a novel technique with inherent error estimation and improved accuracy. Exp Fluids 44, 317–329 (2008). https://doi.org/10.1007/s00348-007-0404-1.
[17]. Budwig, R. Refractive index matching methods for liquid flow investigations. Experiments in Fluids 17, 350–355 (1994). https://doi.org/10.1007/BF01874416.
[18]. Jeffery F., Zhi Yuan W. “Refractive Index Matching: A General Method for Enhancing the Optical Clarity of a Hydrogel Matrix” Chemistry of Materials Vol 14/Issue 11 2002.
[19]. Rivera Y., Bascou D., Blanco D., Álvarez-Piñeiro L., Berna C., Muñoz-Cobo J. L., Escrivá A. “Comparison of Refractive Index Matching Techniques and PLIF40 Measurements in Annular Flow”. Sensors (Basel). 2024 Apr 5;24(7):2317. doi: 10.3390/s24072317.