MATEC Web of Conferences **367**, 00015 (2022) https://doi.org/10.1051/matecconf/202236700015
Power System Engineering 2022

Investigation of heat treatment process using Particle Image Velocimetry

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Abstract. Martensitic hardening is a technology widely used in mechanical engineering practice to increase the hardness and abrasion resistance of ferrous alloys. To achieve martensitic hardening, the workpiece must be cooled the workpiece very quickly, which can be achieved through using various refrigerants. The quality and the properties of these coolants have a great influence on the success of the process, so their investigation is essential. Throughout the investigation method – according to ISO 9950 standard –various aqueous suspensions used as refrigerants are studied by placing a heated cylindrical specimen in a refrigerated container (which will be described later) and by recording the temperature change over time. The flows generated in the tank during the heat treatment influence the nature of the heat transfer, thus the hardening process itself. The task is to map these flow conditions to give a comprehensive description of the qualification process in question. With the advancement of measurement technologies, there are more and more possibilities to determine the velocity of flowing media, even at several points simultaneously. Using the available PIV (Particle Image Velocity) system, the two-dimensional vector field of the flow can be determined on a complete plane surface. In the present research, the applicability of seeding particles required for the PIV measurement technique is also investigated as part of the mentioned project, establishing further research possibilities. The classification of eight different seeding particles is presented. As a final result, seeding particles suitable in the current arrangement for proper flow display are listed.

1 Introduction

In industrial applications, it is important to know the effects of certain factors that influence heat transfer during the application of a given refrigerant (heat treatment). In case of water-based polymer solutions used as refrigerants, the heat removal characteristics vary within certain limits due to the simultaneous influence of temperature, concentration, and flow rate. Knowing the trend and extent of the change, heat removal can – to a certain extent – be optimized for the given process [1-2]. Their quality and properties can greatly influence the success of the whole process, so their investigation is essential. According to ISO 9950 standard, the use of different aqueous suspensions employed as refrigerants is studied by

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placing a heated cylindrical specimen in a refrigerated container designed for this purpose, then recording the temperature change over time. The flows generated in the tank during the heat treatment influence the nature of the heat transfer, thus the hardening process itself. To study the flow processes, a planar or a spatial measurement can be performed. A conventional PIV measurement is a non-intrusive optical method that can provide an instantaneous flow velocity field in a single plane. Although non-intrusive, the technique requires seeding particles to operate. Particles should be neutrally buoyant, and usually micron sized. The exact size, type and density of particles mixed with the working fluid can vary for every measurement. Seeding particles must meet two important requirements. First, they must follow the flow well. Second, they must reflect the light emitted by the light source (usually a LASER or high-power LED) effectively. Since the recording cameras need a clear view of particles, the medium must also be transparent. If seeding particles can't properly reflect light in the given conditions, then the obtained images are not reliably processable and will provide spurious results. It is possible to increase the intensity of illumination and/or the sensitivity of the camera to improve image quality [3]. For the same flow medium, the flow properties of smaller particles are more favorable, but larger particles reflect light to a greater extent. Considering these two effects, the flow properties, and the properties of the light source, the optimal diameter of seeding particles can be obtained [4].

2 Measurement system

Particle Image Velocity (PIV) is an optical measurement method, with which planar images of the velocity field can be obtained. Seeding particles are fed into the main flow. Using a precisely timed light source, the area of interest is illuminated twice with a short time gap between the two pulses. Seeding particles reflect some of the light, which then can be captured with a recording unit (one or more high-speed cameras, matrix detector). Particle images are recorded simultaneously with the light pulses. The displacement of a given particle can be determined from subsequent images, from which its velocity can be derived. The time gap between two pulses can vary depending on the peak velocity and seeding properties of the measured flow. An appropriate displacement of particles is essential for a good correlation. In the present research, illumination is provided by a double-pulsed laser, and the recording is done by a CCD camera. After processing and post-processing, the results of the completed images, valuable information about the given flow can be obtained [5].

The whole PIV system consists of several subunits. These include lasers and other optical devices for illumination, seeding particles and their feeding apparatus, a camera for capturing images, and post-processing hardware and software. Figure 1 shows the elements of a typical PIV measurement set-up [5].

When dealing with low-velocity liquid flows, it is very important that the settling rate of the particles be as low as possible, thus tracers with a density similar to that of the flow medium should be used. An example is polystyrene seeding particles, which have a density of 1050-1090 [kg/m^3], but their reflectivity is rather poor. Silver-coated polystyrene particles could be used to overcome said disadvantage, but their price is a notable drawback. At relatively low cost, hollow glass spheres can be used with the highest efficiency within the size range of 1-100 μm. With air filling the inside of the glass spheres, their density can be controlled during production. The air / glass transitions also have a high refractive index; hence they provide good visibility. When investigating gaseous flows, some form of water aerosol or oil can be used as a seeding medium. The density of these particles are several times higher than that of the gas, the settling rate can be reduced by setting a small diameter for the particles. Seeding particles are usually of the order of 1 μm are used in this case [3].

In case of liquid flows, a trivial solution is most often present, namely the solid particles can be mixed in the liquid to form a suspension. In case of gaseous media in particular, the challenge is to introduce the seeding particles into the area of investigation in a sufficient quantity and in a sufficiently homogeneous distribution without disturbing the flow itself. Possible solutions to feed the seeding particles into the main flow if the particles are liquid can be atomization or condensation, while if the particles are solid, the atomization of their dispersion can be a solution.

Acquired images are divided into smaller parts, called the interrogation zones. For each interrogation zone, one vector field is calculated. Particles that leave the interrogation zone are lost, reducing the number of particles that contribute to the correlation. Particles inside an interrogation zone must move homogeneously in the same direction, else the statistically calculated vector fields will show spurious results. Usually, there should be about 10-15 particles in each interrogation zone, which may increase at higher flow rates [4].

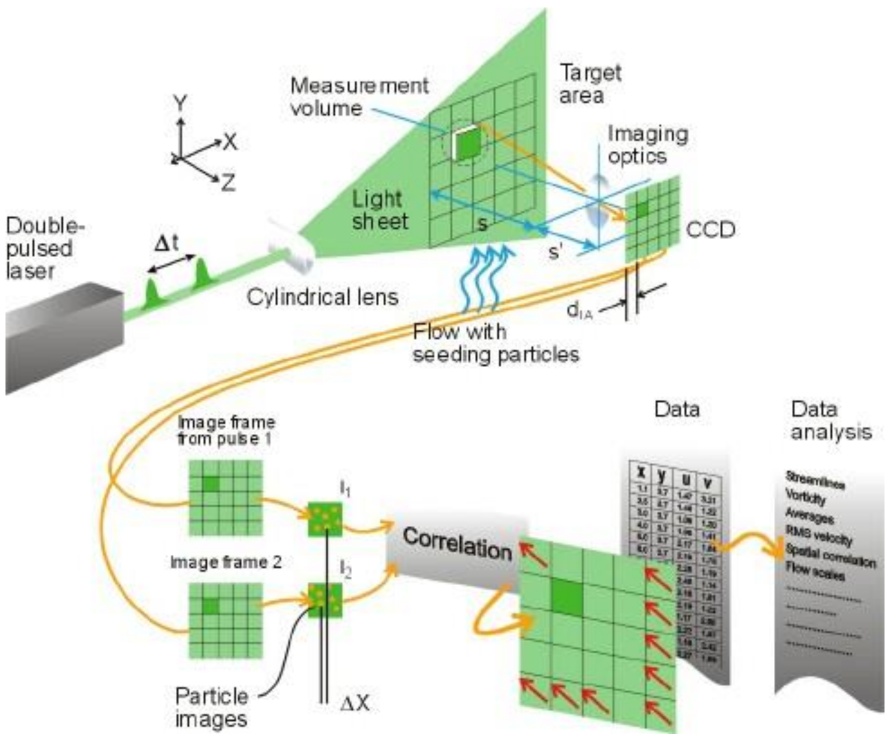

Fig. 1. Principle of PIV measurements [5].

3 Measurement setup

The measurements were performed in a container designed for the qualification of heat treatment media according to the ISO 9950 standard. The wall of the container was made of plexiglass to make it possible to use PIV measurement technique. During the heat treatment process, a steel rod heated to 850 °C was placed in the opening fashioned for this purpose, and the temperature change of the rod over time is recorded. The flow within the container is enhanced by a propeller stirrer with adjustable speed [2]. The container and its associated accessories are shown in Figure 2. The aim of our investigation was to select the optimal seeding particles to use, then use them to examine the nature, velocity, and homogeneity of the flow in relevant volumes.

During our investigation, the specimen, its fixation, and the temperature measurement devices were removed. The flow regime created by the mixer was divided into two regions

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by a plexiglass sheet, as a result of which the flow transpired continuously in the formed channel in a well-defined manner.

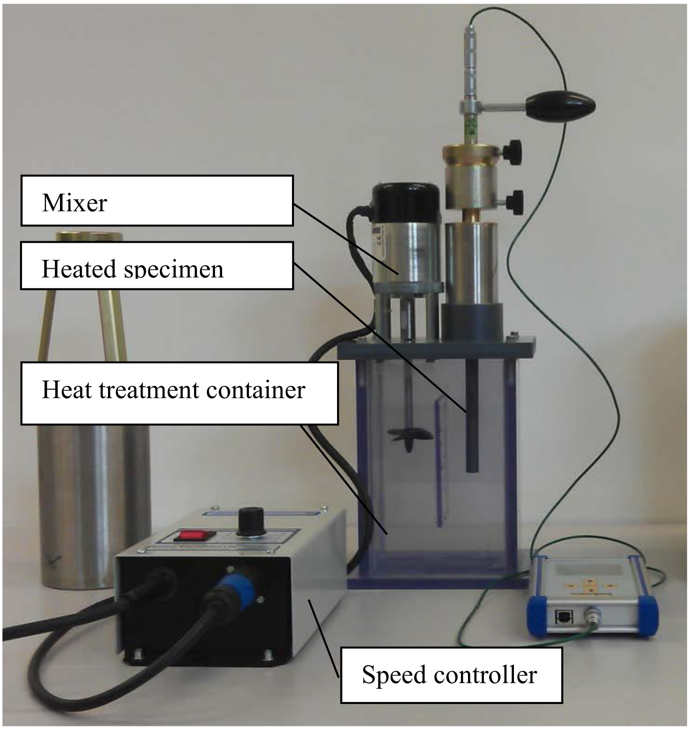

Fig. 2. The container and its associated accessories.

One of the main elements of the PIV measurement technique is the laser light emitted by the high-energy laser, which illuminates the investigated area in a plane section after proper optical imaging. The light of the Nd: YAG double-pulsing laser was refracted twice at angles of 90° on plane mirrors, then by directing it through the light sheet optics the necessary 2D planar light sheet was generated. The test area was located on the symmetry plane "x" of the container, and its size covered the entire cross-section of the flow. Figure 3 shows a schematic of the applied measurement arrangement with the laser, light paths, heat treatment container, and the camera.

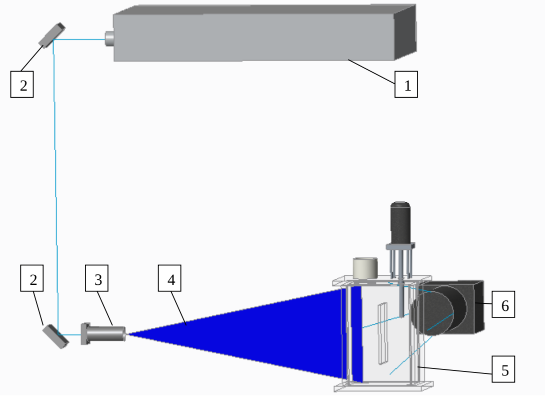

Fig. 3. Schematic of the applied measurement arrangement: 1: double-pulse laser; 2: plane mirrors; 3: light sheet optics; 4: 2D planar light sheet; 5: heat treatment container; 6: camera.

Three operating parameters of the laser were controlled. These were: Δt time difference, laser frequency and intensity. The value of Δt shows the time elapsed between two laser pulses. Based on preliminary measurements, Δt was chosen as 50 ms. Evaluation accuracy is increased during post-processing by changing the size of the computational area. The recording frequency of the camera was 7.5 Hz. Hereinafter, five subsequent image-pairs form a measurement series. The strengths of the two laser pulses can be controlled independent of one another within the range of 0V-10V. These parameters were optimized during experiments pro re nata.

The requirements for the facilitated camera are: they must be able to take images at a sufficiently high resolution and with a sufficiently short shutter speed. The TSI Power View 630059 CCD camera we use perfectly meets these requirements; it captures images at 4 MP resolution with shutter speeds of up to 200 ns [7]. Figure 4 shows an image recorded by the camera of the liquid with seeding particles.

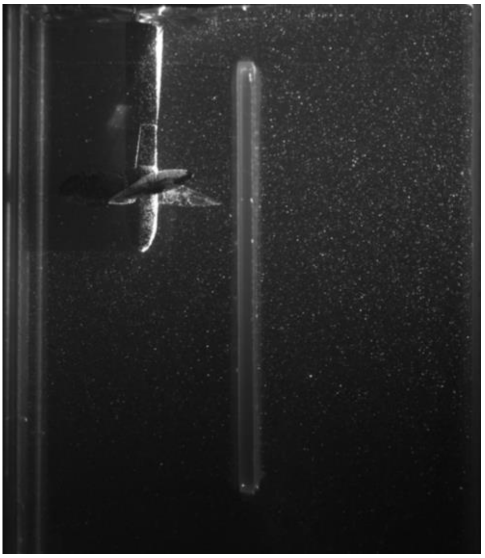

Fig. 4. Image of the mixture of liquid and seeding particles (glass powder) taken by the camera.

Ideally, the contrast between the seeding particles and the black background is high, and the particles are in focus, so the image's overall clarity is high. Most of the defects in our case are probably caused by the refraction of plexiglass, which could be mitigated by using clear glass.

For the CCD camera we used, it was possible to control the focal length and aperture diameter of the lens. Prior to recording, these two parameters always had to be set for the respective seeding particle, as they had different light reflection and geometric properties (diameter). When adjusting the focal distance, the goal was to change the sharpness of the images, while changing the aperture diameter was to change the depth of field of the images. Experience has shown that by increasing the aperture diameter, the intensity of the laser light also had to be increased to obtain high quality images.

In our experiments, eight types of seeding particles were compared using the described equipment. Selection was based on availability, adequate light reflectance, and presumed flow properties (size, density – particles need to be able to move with the flow). The available particles and their characteristics are listed in Table 1.

Table 1. Investigated seeding particles.

ID	Composition, characteristics, features
T1	Al_2O_3 - 100-200 μm size range
T2	Al_2O_3 - 40-60 μm size range
T3	Glass powder - 0-50 μm size range; grinding material for nanotechnological grinding
T4	Talcum powder - commercially available
T5	„Light powder" – commercially available glitter powder with aluminium content
T6	Styrofoam powder – made by coffee grinder, from standard Styrofoam board, with a characteristic particle size of ~500 μm
T7	„Mica powder" –commercially available glitter powder, ground mica shale and titanium oxide
T8	Glitter powder – commercially available, small particle size glitter powder

4 Results

The applicability of the previously listed seeding particles in an aqueous medium was investigated using the described equipment (container with stirrer) and measurement technique (PIV). Changing the speed of the propeller of the stirrer was made possible by a frequency controller. Experiments were performed at the lowest speed, and by placing an equal volume of seeding particles in the water every time. The examination of the region shown in Figure 5 was the primary goal, and the vector field of this area was determined and evaluated during subsequent post-processing.

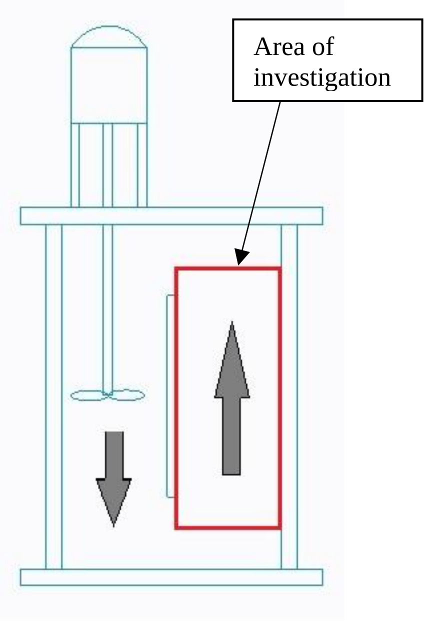

Fig. 5. The area of investigation.

To obtain an accurate relation of the location of particles compared to the measurement domain, a calibration procedure is needed. During the process, a target with a pattern of equidistant dots is placed in a way that its plane is parallel with the laser light sheet. The parameters and the exact location of the calibration target are well known; hence the recording and post processing software (*Insight 3G*) can be calibrated.

Images resulting from the eight measurements series were processed, and evaluated for three interrogation zone sizes, and for each of the three evaluations, the average velocities, and the velocities at a fixed point of each seeding particle were determined. Control velocities were measured to validate the obtained results using ultrasound ultrasonic velocity measurements and by adding 6, relatively big pearls to the system, and calculating their displacement using MATLAB.

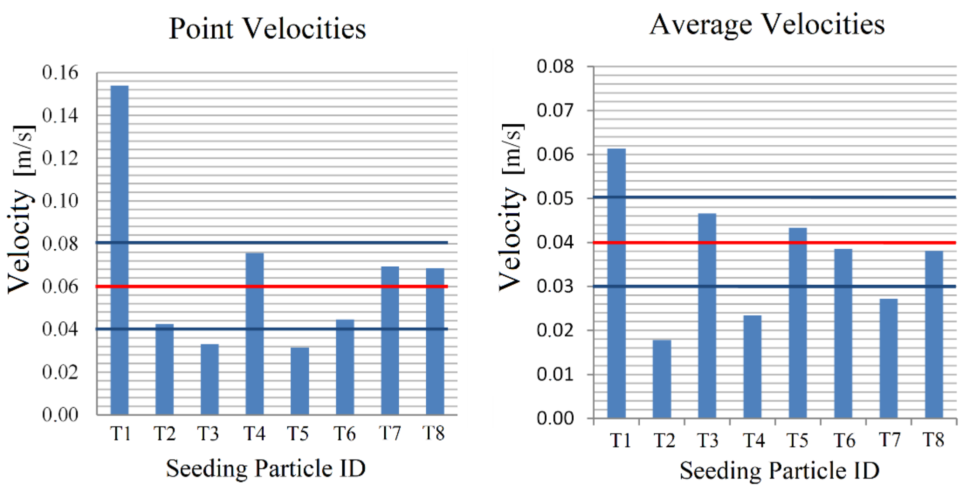

Fig. 6. Fixed point and average velocities of different seeding particles in case of a 64x64 pixel sized computational area, with the control velocity at a fixed point (red horizontal line) and average control velocity region (between blue horizontal lines).

The diagrams show that both the average and fixed-point velocity values of particle T1 (Al_2O_3, 100-200 μm) are outside of the control velocity range, so this seeding particle was declared unsuitable, and no further studies were performed with it. Both the fixed-point and average velocities of T6 (Styrofoam powder) and T8 (glitter powder) fell within the control range, hence under the given conditions, based on our investigations, the flow was followed best by these two seeding particles. In addition, the fixed-point velocity values of T2, T4 and T7, and the average velocity values of the T3, proved to be adequate, so further studies were performed for these seeding particles.

A statistical analysis of the suitable seeding particles followed. Five subsequent image-pairs form a measurement series, and a vector field was created based on each image pair. The variance of the vector components u and v are known. The variance values of the five vector fields were averaged and plotted for the seven different tracer particles (Fig. 7).

We are trying the find the seeding particles that produce the lowest variance values, as measurements performed with them should provide the most reliable results. The trends in Figure 7 show that the variance in velocities for component v are always greater than that of component u, which is expected since the flow is mostly vertical (v direction). This implies a greater degree of variation in values. Seeding particles with the smallest variance values were T2, T3, T7 and T8, for these the cross-correlation procedure using *Insight 3G* software proved to be successful.

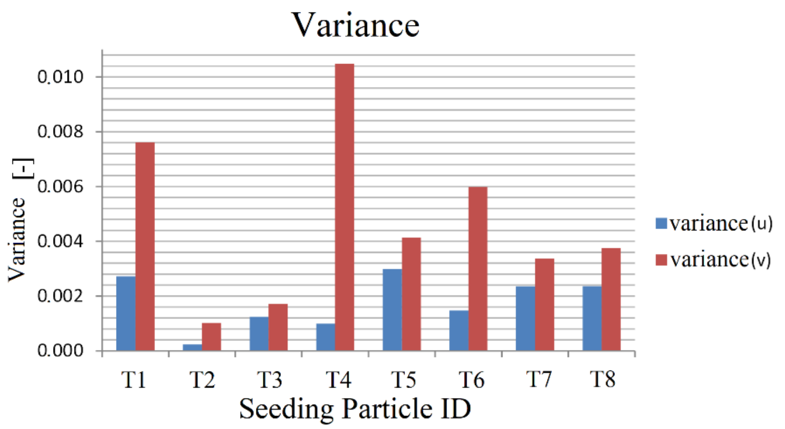

Fig. 7. Variance values for different seeding particles.

T8 (glitter powder) passed well in both control phases (velocity and statistical), and particles T2, T3 and T7 also showed good results in the statistical test, so flow visualization was performed for these four seeding particles.

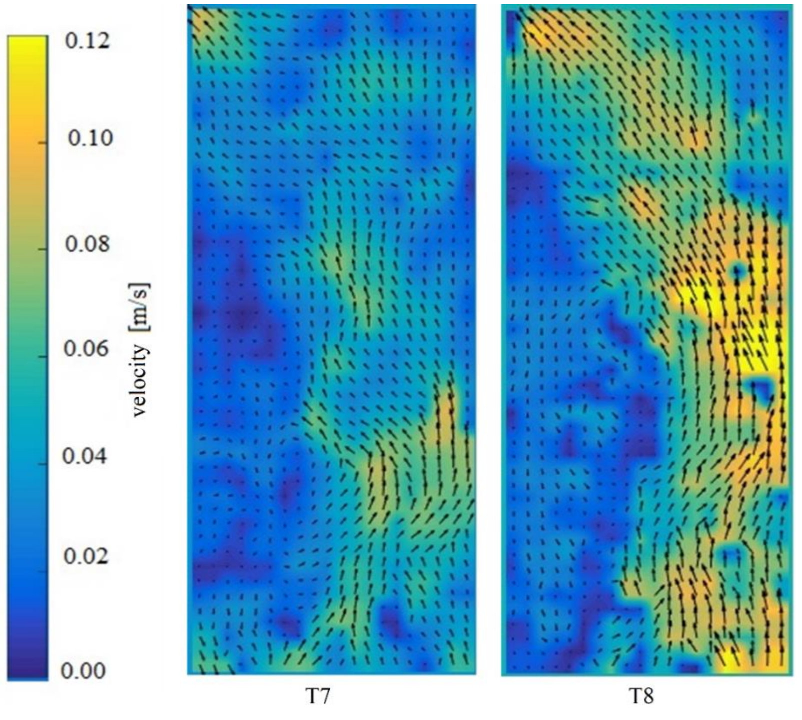

Fig. 8. Velocity field with vectors obtained by using mica powder (T7), glitter powder (T8).

5 Conclusion

The applicability of different seeding particles in a container designed for the qualification of heat treatment media according to the ISO 9950 standard has been investigated. Eight – mostly commercially available – materials were investigated as seeding particles for PIV measurements. Seeding particles must meet to prerequisites: they should follow the flow well, so their size should be adequately small, and their average density should not differ greatly from the density of the medium. They must also reflect the light emitted by the light source effectively to provide clear, relatively high contrast images for the PIV processing software to avoid spurious results. The continuous flow of the mixture of medium and seeding particles were granted by a propeller stirrer placed inside the container.

Post-processing of the images taken during the measurements was performed using the *Insight 3D* software. The size of the computational area was optimized by checking the velocity values after processing. At this time, a 64x64 pixel computational area proved to be the most efficient, so we performed further data processing according to this.

During the evaluation of the resulting vector fields, we compared the fixed point and average velocities of the validation measurements (executed prior to PIV investigations using MATLAB and ultrasonic velocity measurement) with the velocities obtained by the use of different seeding particles. Some seeding particles with false results were filtered. Under the given conditions, T6 (Styrofoam powder) and T8 (glitter powder) performed the best at following the flow. It is likely that their effectiveness is due to their density being similar to that of water. The density of styrene (raw material of Styrofoam) is ρ=1040 kg/m^3. If a sufficiently fine powder is produced from it, most of the air bubbles are removed, so it can be used effectively as a tracer particle in aqueous media. The base material of the glitter powder we obtained was polyethylene terephthalate (PET), density of which is ρ=1380 kg/m^3, which is slightly higher than the density of water.

The appropriate reflectance of the investigated particles was inferred from the variance of the velocity vector files. The lowest variance values were produced by T2 (Al_2O_3) and T3 (glass powder). T7 (mica powder) and T8 (glitter powder) particles also showed adequate variance values. Based on these results, it can be stated that by using these four seeding particles, the cross-correlation procedure during data processing created a correct vector field with few errors.

Overall, four of the eight seeding particles were found to be suitable for the current scenario during data processing. These are Al_2O_3 (T2), glass powder (T3), mica powder (T7) and glitter powder (T8). Using these four seeding particles, the velocity distribution of the area of investigation was obtained as shown in Figure 8. Based on obtained the images, it can be said that although the Al_2O_3 (T2) powder gave the smallest values of standard deviation and variance during the statistical evaluation, it created an insufficient vector field in the lower part of the investigated area. The images also show that the generated flow nonhomogeneous, a high velocity region occurs. This flow pattern will, of course, be altered if the specimen is inserted, but it is likely that the visible trend will remain, resulting in a higher velocity flow along one side of the rod. This causes the specimen to cool asymmetrically, resulting in thermal stresses and other structural defects. In the future, velocity fields obtained during the cooling of the rod can be examined in a similar manner, using the experience of the present research to our advantage. Although mica powder and glitter powder have proven to be the most suitable under the current circumstances, introducing a specimen of 850 °C into the water during the heat treatment will massively alter the whole filter process. Seeding particles can melt, air bubbles can form around the specimen, and a whole set of new factors should be considered. Glass powder with a particle fraction of 0-50 μm can provide a viable alternative that has shown good properties in our studies and is also resistant to high temperatures.

Acknowledgements

The authors are grateful to the Hungarian-German Intergovernmental S&T co-operation programs TKA-DAAD (160552), for the financial support of this research.

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