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ORIGINAL RESEARCH PAPER

THE INFLUENCE OF AIR VELOCITY ON THE BEHAVIOR OF A SOLID PARTICLE DISPLACEMENT IN A VERTICAL PATH

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Abstract: This article presents an experimental study regarding the behavior of a ball-shaped polyethylene solid particle in vertical air channel. To this effect, we used a laboratory stand, an aerodynamic screen with vertical air flow, and a high-speed camera to study the behavior of the solid particle. The recoding speed of this measurement was 500 frames·sec^{-1}. During this assessment, the movement direction of the solid particle within the vertical air flow was not taken into account, i.e. the particle moved either in the same direction with the air flow or in the opposite direction. After the video recording analysis, a series of physical data of the solid particle have been identified, such as: average travelling speed, distance covered by the solid particle, tracing time, angular speed of the solid particle and its rotation. It has been observed that aforementioned data are in strict accordance with the variation of the speed of the air flow passing through the ascending vertical air channel.

Keywords: *ball-shaped solid particle, behavior of the solid particle, vertical air flow*

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INTRODUCTION

The behavior of a particle mixture in a fluid has been carefully studied and presented in different treatises, as it is a key element within many industrial processes (screening, transport), being applied in the chemical industry, food industry, energetic, but also in the protection of the environment [1 – 8].
The rotation of solid particles is a common phenomenon in the behavior of a solid particle in a fluid flow (air or water) [9]. From the dynamics point of view, the reason for the rotation of a solid particle in a fluid flow is the variation of the distribution of forces on its surface. The rotation of the solid particle plays an important part in various aspects, with regard to the mechanism of the behavior of the solid particles in the fluid flow, i.e. gas-solid mixture.
Moreover, the behavior of the solid phase, as well as of the distribution of the lines of the fluid flow, may be affected by the rotation of particles, according to several published simulation projects [10 – 15]. Several theoretical investigations have showed that the effect of the rotation of solid particles may appear also if these are in gas flow [16 – 19].
However, there are several experimental assessments highlighting the difficulties that may appear within the process of measuring the rotation speed of a solid particle during its movement, regardless of the environment. Some of these assessments have been made in order to determine the rotation of a solid particle during its movement, and they have been carried out using the following methods: photography of the particles [20, 21], photography using a stroboscope [22], Laser-Doppler anemometry (LDA) [23] or video camera recording [24]. Within these measurements, the particles have been of the order of millimeters or centimeters, compared to typical particles to be found in gas-solid flows. In order to analyze their behavior, the particles have been marked on the surface with special lines or spots [25 – 27].
This article presents a series of experimental results having the purpose of finding some physical data that can be determined following the analysis of a video recording, by using ball-shaped expended polystyrene particles. Within the analyzed videos, we followed the behavior of a single solid particle in a vertical ascending air flow.

MATERIALS AND METHODS

The experimental measurements have been carried out in the Process Equipment Laboratory of the Faculty of Engineering, “Vasile Alecsandri’’ University, Bacau, Romania, on a laboratory stand specially designed to visualize the behavior of a solid particle in a vertical ascending air flow. This is why the laboratory stand was made out of Plexiglas (Figure 1) [3].
The stand has two sections, a cylindrical one and a rectangular one. The study presented in this article refers to the behavior of a solid particle in a vertical air channel with a constant section. In order to avoid the influence of the channel section on the behavior of the particle, a circular section channel was chosen [6].
Within these experiments, the tracing of the behavior of the solid particle was carried out only for the circular section of 400 mm diameter and 700 mm height.

Figure 1. *Laboratory stand*

Figure 2. *Position of the HiSpec high-speed camera*

Figure 3. *The HiSpec high-speed camera*

In order to be able to determine the behavior of a solid particle in a vertical air channel, we used a HiSpec high-speed camera (made in USA by Fastec Imaging Company) (Figure 2) placed at 410 mm from the exterior wall of the vertical air channel with cylindrical section. The speed registered by the high-speed camera was 500 frames·sec^{-1} (Figure 3) [4].

During the experimental measurements, we used full expended polystyrene balls of 27 mm diameter, density of 15 kg·m^{-3}, particle mass of 0.225 g and a floating speed [4, 5] of 3.176 m·s^{-1} [6].

In order to determine the influence of the air flow on the behavior of the solid particle in the vertical ascending air channel, the speed of the air flow passing through the vertical air channel varied from 4.896 m·s^{-1} to 5.775 m·s^{-1} and to 6.277 m·s^{-1} respectively. This speed was determined using a TESTO 425 anemometer (made in USA by TESTO Company), the measurement being carried out in the middle of the air channel at the level of the manway.

Theoretical considerations

In order to determine, from theoretical point of view, the behavior of a solid particle in a vertical ascending air channel, the floating velocity of the solid particle must be determined. Therefore, to calculate the value of this parameter, the following calculation is used:

$$v_p = \sqrt{\frac{4 \cdot d_p \cdot \rho_p \cdot g}{3 \cdot k}} \qquad [\text{m}\cdot\text{s}^{-1}] \qquad (1)$$

where: d_p - the diameter of the solid particle [m];

ρ_p - the density of the solid particle [kg·m^{-3}];

g - gravitational acceleration [m·s^{-2}];

k - drag coefficient which is determined by the particle shape (for the spherical particle is between 0.47 (for the smooth surface particle) and 1.17 (for the ruby surface particle) [28].

It must keep in mind that aerodynamic separation process is achieved due to solid particle behavior by an upward vertical air current, behavior that comes from the different forces acting on the solid particle. The particle displacement velocity in the air channel, where the solid partition is entrained by the air flow, is given by the relation:

$$v = u - v_p \cdot \frac{\left(e^{\frac{2 \cdot g \cdot t}{u}} + \frac{u - v_p}{u + v_p} \right)}{\left(e^{\frac{2 \cdot g \cdot t}{u}} - \frac{u - v_p}{u + v_p} \right)} \ [\mathrm{m \cdot s^{-1}}] \qquad (2)$$

where: u - the velocity of the air flow [m·s^{-1}];

t - time to determine the displacement speed of particle [sec].

Working methodology

The working methodology used in this experimental lot is showed in the flowchart at Figure 4 [3].

It has been designed in order to determine the following data:

- Three-dimensional trajectory of the solid particle in the ascending vertical air channel;
- Variation of linear speed of the solid particle in the ascending vertical air channel;
- Variation of angular speed, i.e. number of rotations of the solid particle in the ascending vertical air channel.

All these data are determined only for the time period when the solid particle moves in front of the camera.

The working methodology implies using several software [2, 3]:

1. Video camera software - to adjust the settings for the recording speed and the resolution of the recording. Software produced by Fastec Imaging Company, USA;
2. SynthEyes software - to extract the facts necessary to determine the studied data. Software produced by Andersson Technologies LLC, USA;
3. Virtual Dub software - to extract from the footings certain frames necessary for the analysis (Free Software - virtualdub.org);
4. Gimp software - to determine the coordinate on the OX axis (Free Software-gimp.org, GNU Image Manipulation Program);
5. Mathcad software - to make all accurate calculations necessary for data processing. Software produced by PTC Company;
6. Originlab software - for the graphical plotting. Software produced by Originlab Corporation, USA.

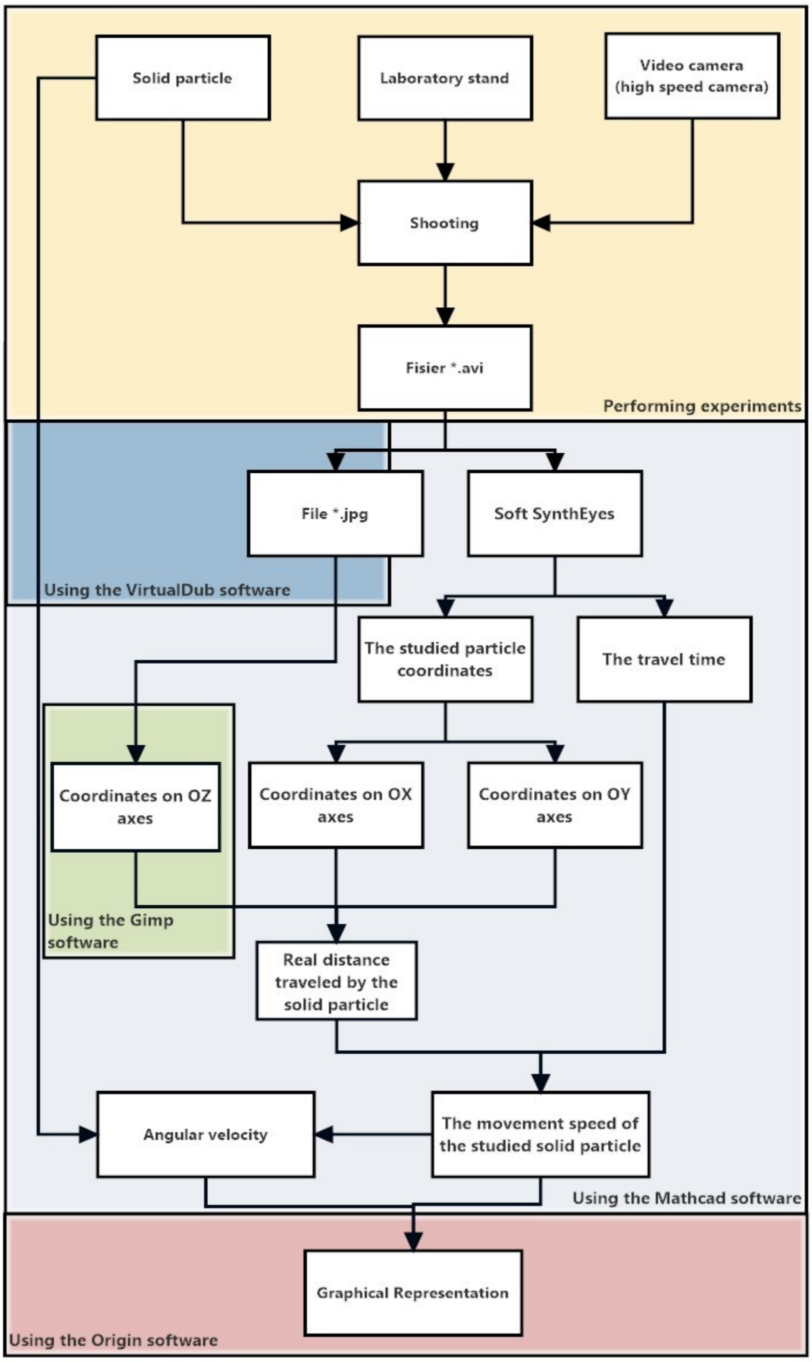


Figure 4. *Working methodology*

RESULTS AND DISCUSSION

The high-speed camera recordings have been processed according to the aforementioned working methodology, the data files being exported and imported in the working software, in order to avoid data corruption. During these experiments 15 films between 0.086 and 0.53 sec. have been processed. Overall, 1263 frames have been used.

Following the data analysis, a series of results have been obtained.
By analyzing the 15 trajectories obtained, it showed that for each experimental lot in which the air flow speed was varied, the movement of the particle is linear, ascending or descending. For all 3 air flow speeds, 3 ascending trajectories and 2 descending trajectories have been obtained, according to Figure 5.

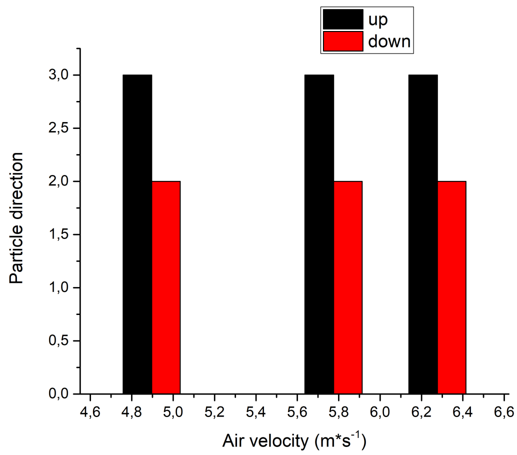
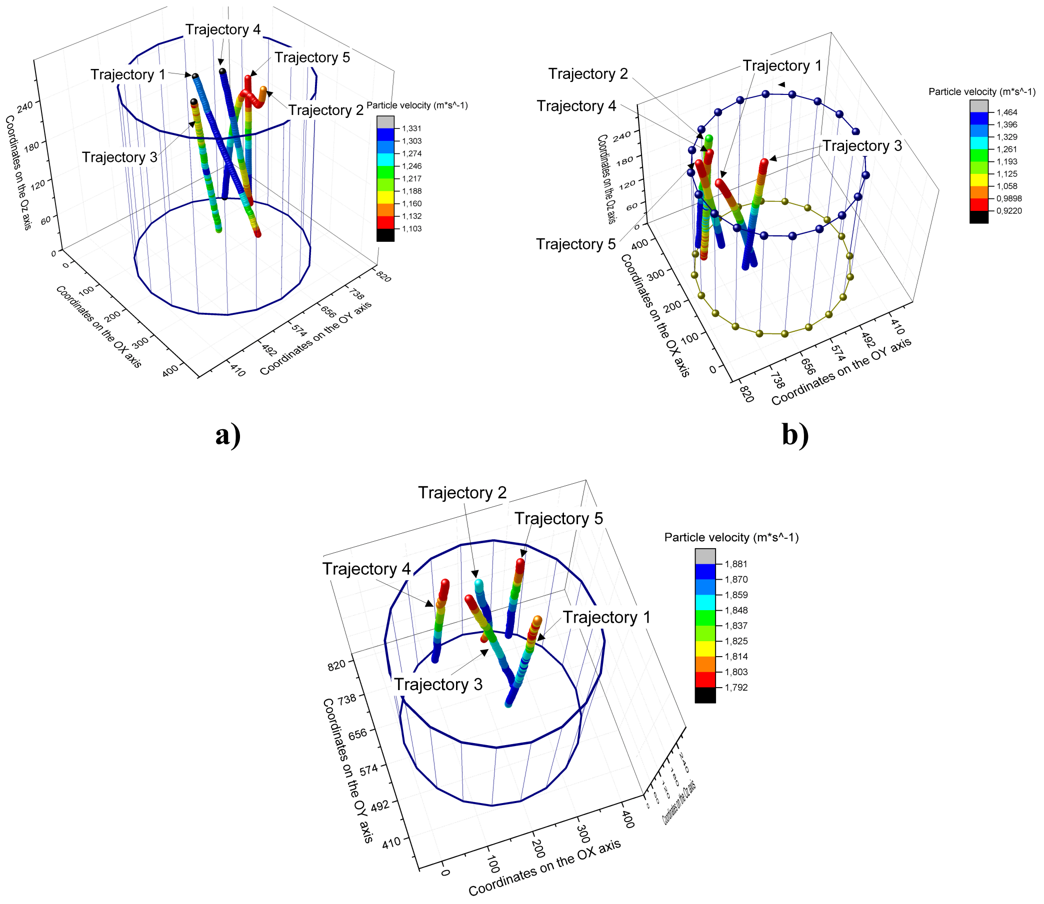


Figure 5. *Identifying the direction of movement of the solid particle*

By individual analysis of the 15 trajectories (Figure 6) it is observed that:

- most of trajectories obtained are straight trajectories, except for trajectory no. 2 corresponding to an air flow average velocity of 4.896 $m \cdot s^{-1}$;
- in the case of the channel crossed by an air flow with the velocity of 4.896 $m \cdot s^{-1}$, the maximum moving speed of the solid particle was 1.331 $m \cdot s^{-1}$, for an air flow with the velocity of 5.775 $m \cdot s^{-1}$, the maximum moving speed of the solid particle was 1.881 $m \cdot s^{-1}$, and for an air flow with the velocity of 6.277 $m \cdot s^{-1}$ the maximum moving speed of the solid particle was 1.464 $m \cdot s^{-1}$;
- most of the maximum moving speed values of the solid particle have been recorded when this one was placed at the lower part of the air channel, regardless of the trajectory type, ascending or descending;
- the highest values of the moving velocity parameter have been obtained for the case where the trajectory of the solid particle is placed near the center of the air channel and this trajectory is ascending.



c)

Figure 6. *Trajectories of solid particles and variation of their velocity [3]:*
a) *air flow velocity of 4.896 m·s*$^{-1}$*;* ***b)*** *air flow velocity of 5.775 m·s*$^{-1}$*;*
c) *air flow velocity of 6.277 m·s*$^{-1}$

Moreover, determined to analyze the behavior of a solid particle in a vertical ascending air flow, a series of data have been determined:

a) from an experimental point of view:

- distance travelled by the solid particle (Figure 7);
- the time spent by the solid particle during the tracking process (Figure 8);
- number of rotations during the tracking process (Figure 9);

b) from a mathematical point of view:

- average particle displacement velocity (Figure 10);
- average rotational speed (Figure 11);
- average angular velocity (Figure 12).

If analyzed the variation of the distance travelled by the solid particle in the air channel crossed by a vertical ascending air flow, it can observe that the distance reduces in direct ratio with the reducing of the air flow velocity (Figure 7) [3]. The same thing can be said regarding to the variation of the tracking time of the solid particle in the air channel, in the monitored area (Figure 8) [3].
Regarding to the number of rotations (Figure 9) performed by the solid particle in the air channel, it can observe that, for this parameter also, there is an increment from 2.96

rot·s^{-1}, value corresponding to an air flow with the velocity of 4.896 m·s^{-1}, a value of 3.407 rot·s^{-1} for an air flow speed of 5.775 m·s^{-1}, and for an air flow speed of 6.277 m·s^{-1} it can observe a decrease of this parameter with 0.045 rot·s^{-1} in relation to the previous value. These values have been obtained for the time period when the solid particle was tracked in the air channel, corresponding to the monitoring area.

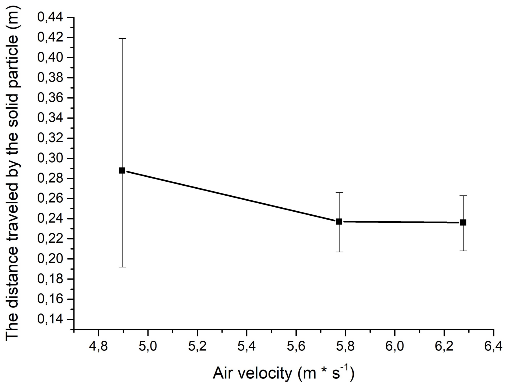


***Figure** 7. Variation of distance travelled by the solid particle according to air velocity*

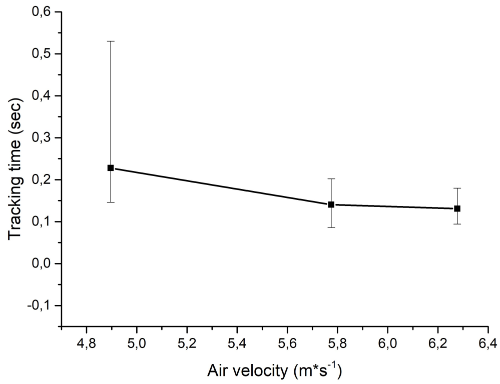


***Figure 8.** Variation of tracking time of the solid particle according to air velocity*

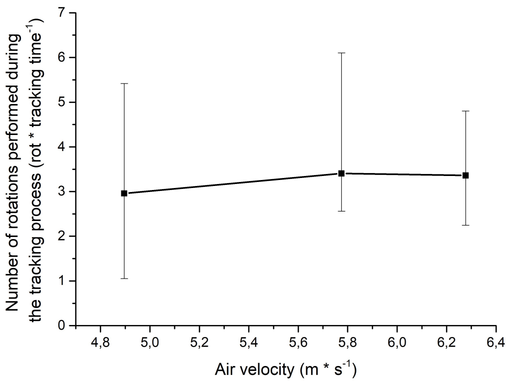


***Figure 9.** Variation of number of rotations performed during the tracking process according to variation of air velocity*

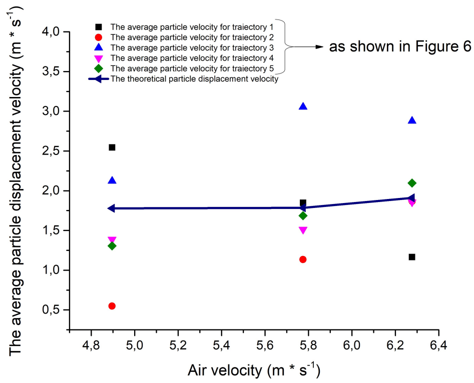


***Figure 10.** Variation of average particle displacement velocity according to air velocity*

Based on these conclusions, it is observed that the variation of the average particle displacement velocity in the air channel increases from 1.58 m·s^{-1}, corresponding to an air flow of 4.896 m·s^{-1}, to 1.97 m·s^{-1} in the case of the air channel crossed by a 6.27 m·s^{-1} flow (Figure 10) [3]. Also in Figure 9, besides the experimental values are presented the values obtained theoretically using equation 2, taking into account the average time value. It has been achieved, for an air velocity of 4.896 m·s^{-1}, a speed of movement of the solid particle of 1.779 m·s^{-1}, the value increasing as it reaches an air velocity of 6.277 m·s^{-1} to 1.911 m·s^{-1}.

Taking into account that, during the experiments it used ball-shaped particle of 27 mm diameter can be determined the number of rotations performed by the solid particle, the average rotation velocity and the angular velocity.

After analyzing the average rotation velocity (Figure 11) it can observe that, for the case when the air channel is crossed by an ascending vertical air flow of 4.896 m·s^{-1}, an average rotation velocity of 15.77 rot·sec^{-1} has been obtained, and for an air velocity of 6.277 m·s^{-1} it is obtained an average rotation velocity of 26.72 rot·sec^{-1}.
In Figure 12 it is present the variation of the average angular velocity of the solid particle in the air channel according to the variation of the air velocity, and following the flowchart analysis it can notice that, for a value of the air velocity of 4.896 m·s^{-1} it is obtained an average angular velocity of 99.29 rad·sec^{-1}, value the increases by 61 rad·sec^{-1} and by 69 rad·sec^{-1} in relation to the first value of the analyzed parameter, values corresponding to an air velocity of 5.77 m·s^{-1} and 6.277 m·s^{-1} respectively.

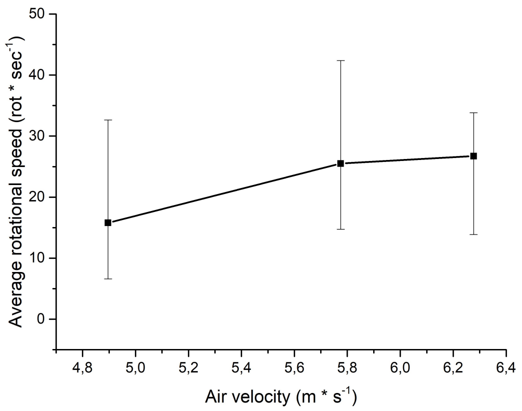


Figure 11. *Variation of average rotational speed of the solid particle in the air channel according to the variation of the air velocity*

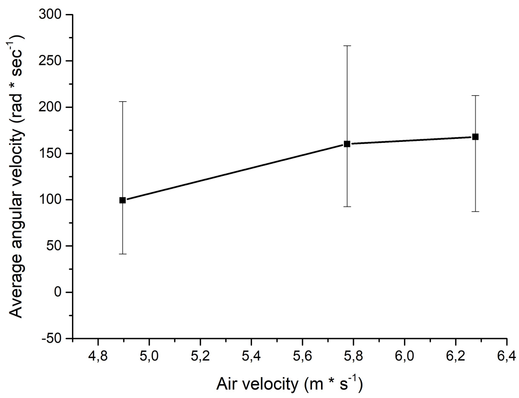


Figure 12. *Variation of average angular velocity of the solid particle in the air channel according to the variation of the air velocity*

CONCLUSIONS

After analyzing the obtained results, the following conclusions are detached:

- The aerodynamic sorting process of solid particles is a complex process, influenced by a series of factors that depend on the particles features that make up the mixture and the characteristics of the air flow;
- In order to determine the trajectory of a solid particle into a vertical ascending air flow, linear and angular velocity, a laboratory equipment has been designed and constructed, coinciding with the industrial equipment used in the aerodynamic separation process;
- A high-speed video camera of the HiSpec3Kit type with a recording speed of 500 frames·second^{-1} was used to monitor the behavior of the solid particle in the upward vertical air channel;
- A working methodology has been designed so that we can obtain the following parameters for different values of the average velocity of the air flow passing through the laboratory cervical air channel, respectively for 4.896 m·s^{-1}, 5.775 m·s^{-1} and 6.277 m·s^{-1};

- Following the processing of the experimental data, obtained for 5 trajectories of the solid particle, at different airflow values and the 3D trajectory, but also the variation of the linear velocity parameters and the angular velocity;
- It has been observed that the average distance travelled by the solid particle decreases from 0.2878 m for the air velocity of 4.896 $m \cdot s^{-1}$ to 0.2362 m for an air velocity of 6.277 $m \cdot s^{-1}$;
- It has been observed that the mean value of the distance travelled, by the solid particle, decreases from 0.2878 m for the air flow rate of 4.896 $m \cdot s^{-1}$ to 0.2362 m at an air flow velocity of 6.277 $m \cdot s^{-1}$;
- The same conclusion can be drawn from the analysis of the variation of the tracking time of the solid particle, namely a decrease from 0.2278 sec for the air flow rate of 4.896 $m \cdot s^{-1}$ to 0.1308 sec at an air velocity of 6.277 $m \cdot s^{-1}$;
- Taking into account the two parameters presented above, the average displacement velocity of the solid particle into the airflow channel increased from 1.5818 $m \cdot s^{-1}$ corresponding to an air flow rate of 4.896 $m \cdot s^{-1}$ at 1.973 $m \cdot s^{-1}$ corresponding to an air flow rate of 6.277 $m \cdot s^{-1}$;
- Analyzing the experimental values of the displacement velocity of the solid particle in the air channel with the theoretical values, of the same parameter, using the relations 1 and 2, there is obtain a maximum difference of 0.197 $m \cdot s^{-1}$ and minimum of 0.062 $m \cdot s^{-1}$;
- Regarding the number of rotations made by the solid particle upward in the vertical air channel, during its tracking period the particle ranged between 2.959 - 3.3612 rot· tracking time^{-1};
- When analyzing the angular velocity parameter, we notice an increase proportional to the variation of the airflow velocity, respectively from 99.29 $rad \cdot sec^{-1}$ for 4.896 $m \cdot s^{-1}$ to 167.92 $rad \cdot sec^{-1}$ for 6.277;
- The next phase of this study is to determine the influence exerted by the solids particular impact with the wall, and between two solid particles, on the solid particle trajectory, but also over the parameters presented in this article.

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