Experimental Application of the Process Industry Solid Particle's Displacement in a Vertical air Flow

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Abstract: In this article some experimental studies were performed in order to analyze some physical parameters specific for a solid particle during displacement in a vertical air flow. The analyzed parameters were the instantaneous average velocity value and the angular velocity value. To determine the two parameters, a laboratory stand was used for the aerodynamic separation of a mixture of solid particles and a high-speed video camera in order to be able to track the behaviour of the studied particles. At the same time, a working methodology has been designed, implying the use of multiple software, i.e. analysis, video, imagistic and date software, methodology that aims to convert a video file, where we have a 2D view, into a 3D interpretation. Following the analysis of the obtained results, we noticed that both the instantaneous average velocity value and the angular velocity value are closely linked to the sphericity of the solid particle, varying inversely proportional to it, and to the air flow velocity, which directly influences the analyzed parameters.

Keywords: vertical air flow, solid particle, instantaneous average velocity value, angular velocity value

1. Introduction

Within the process industry there are numerous operations involving direct and indirect actions on the raw material. In the case of solid raw material, these operations are reduced, the main ones remaining separation, mixing and size reduction [1-6].

In the case of separation of a heterogeneous mix of solid particles, we must take into account the physical properties of mix components [3, 4, 7-9]: floating velocity, geometrical dimensions, elasticity, surface condition, etc.

One of the oldest separation processes of solid particles mix is the aerodynamic separation, this being illustrated in different frescoes in the Egyptian pharaons' period [10-12], and it represents a separation method used in different industry fields [13-16].

Simple as it may seem this aerodynamic separation process, explaining it mathematically is more complicated. Therefore, the technical literature shows studies analyzing the behaviour of a solid particles mix in an air flow:
- By using numerical analysis [17-24].
- By using different software to carry our simulations [25-30].
- By carrying out experimental investigations for certain working conditions or for certain types of separation installations [24, 31-38].

This article aims to identify two parameters defining the behaviour of a one solid particle in a vertical ascending air flow, i.e. the instantaneous velocity and the angular velocity. Determining the values of the two parameters was possible due to modern working equipment, several analyses software and a complex working methodology.

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The methodology developed and presented in this article involves the analysis of a video recorded by using one video camera. Also, were used unconventional software methods to obtain a 3D representation of the solid particle and some parameters identifying. Similar paper identified put into evidence some studies related to [39-41] [42-45]:

- Analysis of the displacement of a particle or a mixture of particles by using of two or more video cameras, thus obtaining a 3D analysis.
- One video camera evaluation with a 2D analysis interpretation.
- Dedicated video software evaluations.
- Very small particle behaviour evaluation in similar working conditions.

2. Materials and methods

2.1. Laboratory technique

The study of the behaviour of a solid particle in a vertical ascending air flow was conceived, designed and achieved on a laboratory stand with a vertical ascending air flow and three stilling basins (Figure 1a). The laboratory stand was made of transparent material (Plexiglas) to allow the visualization of the behaviour of a solid particle in the vertical ascending air flow [35, 46, 47]. The Plexiglas was chosen because it does not create the lens effect, as in the case of glass, being easy to use, considering the constructive dimensions of the laboratory stand.

For the study of the behaviour of a one solid particle in the air channel we used only the circular section area of the laboratory stand (Figure 1b) [35, 46, 47].

For the variation the velocity of the air passing through the laboratory stand we used a frequency converter DF5 to allow the continual adjustment of the three-phase engine rotation speed.

Since the study of the behaviour of a solid particle in an air flow is a process to be achieved in very small time intervals, we used a HiSpec high speed camera placed, for the entire duration of the study, at the same distance to the laboratory stand (Figure 1b). The HiSpec high speed camera can record different types of processes taking place in a very short time (e.g. rapid movements or explosions), which can be recorded and stored continually, then displayed and analysed in detail right after the end of a work sequence.

The behaviour of a solid particle in the circular section channel crossed by the vertical ascending air flow was recorded by a high speed camera, with a 500 frames/s recording speed [35, 46, 47].
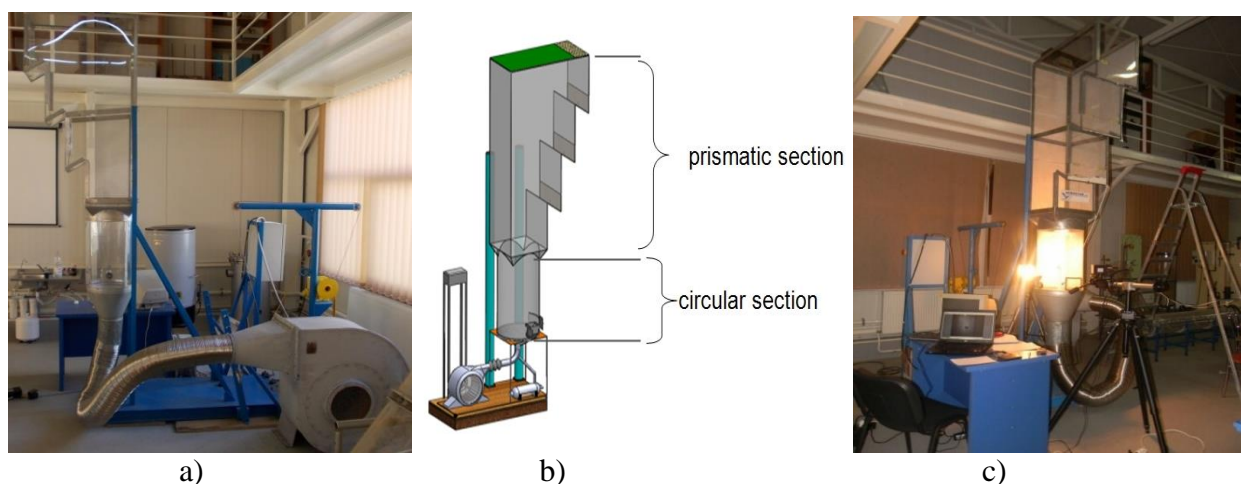

Figure 1. Experimental equipment's: a) Laboratory stand; b) Air channel sections,
c) High Speed Camera Hispec position

2.2. Working methodology

The materials used in this study were particles of different sizes: Φ 27, Φ 35, Φ 47 and Φ 56, made of polystyrene of 15 kg/m^3 density [46]. For a complex study, part of the used particles was deformed to have variable sphericity, parameter that was calculated by using the equation (2). The results obtained are presented in Figure 2 [1, 37, 46]:

$$\Phi_s = \sqrt[3]{\frac{l \cdot b \cdot c}{l^3}} \tag{1}$$

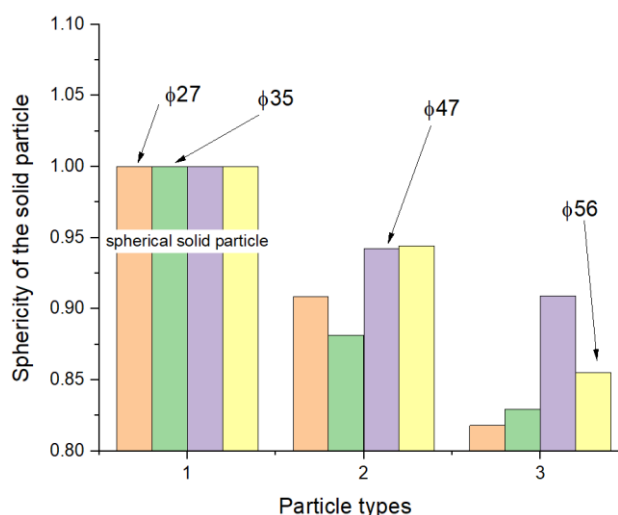where l, b and c represent the particle dimensions.

Figure 2. Sphericity of the solid particles [39]

According to solid particles size, several values of the speed of the air crossing the vertical channel of the laboratory stand (Figure 3), values that are greater than or equal to the value of the floating speed of the particles used.
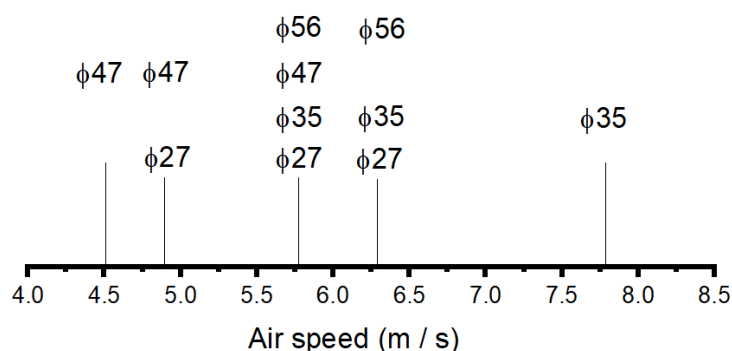

Figure 3. Air flow speed value [46]

Following the experimental determinations, by using the working methodology, we intended to determine the following parameters [46]:

- The instantaneous average velocity value – the average value of the solid particle displacement velocity between two frames.
- The average angular velocity – average value of angular velocity of the solid particle displacement velocity between two frames.

To determine the two parameters on the surface of the solid particle undergoing the study, we made different marking elements (point no. 2 in Figure 4) in order to monitor the rotation speed and to determine the linear velocity, to obtain the angular velocity. For the linear displacement we chose as guiding mark the higher or lower part of the solid particle (point no. 1 in Figure 4) [46, 47].
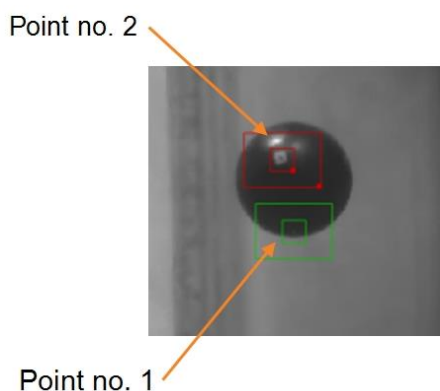

Figure 4. Marking points [46, 47]

Besides the equipment and materials used in this study, to determine the searched parameters we also used the working methodology showed in Figure 5 [46].
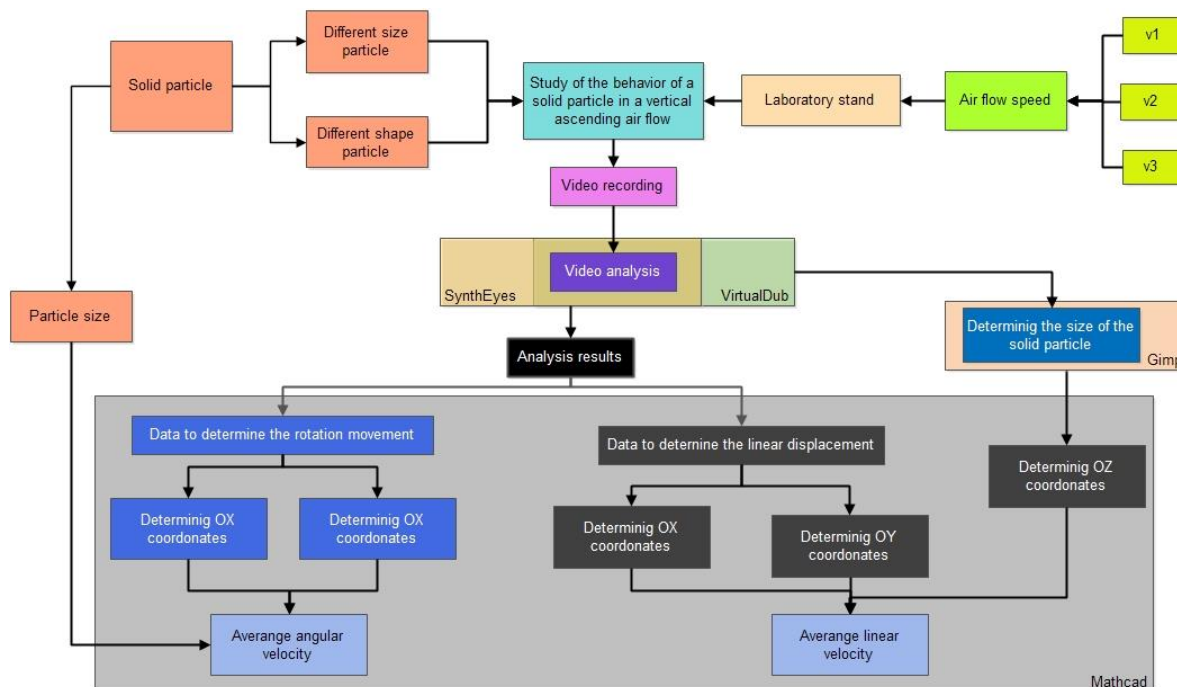

Figure 5. Working methodology

The working methodology implies the observance of certain work stages and using software [46]:
-    For the video analysis we used two software:
o   SynthEyes software used to obtain the coordinates corresponding to OX and OY axes (Figure).
o   VirtualDub software used to obtain different frames for subsequent analyses (Figure 7).
-    For the imagistic analysis we used Gimp software, which can determine a size within a picture, value that can be subsequently used to conceive a mathematical pattern and to determine the coordinated corresponding to OZ axis.

- for the processing the obtained data and to determine the studied parameters, we used Mathcad software to easily import data files and for the easy way to process the obtained data.
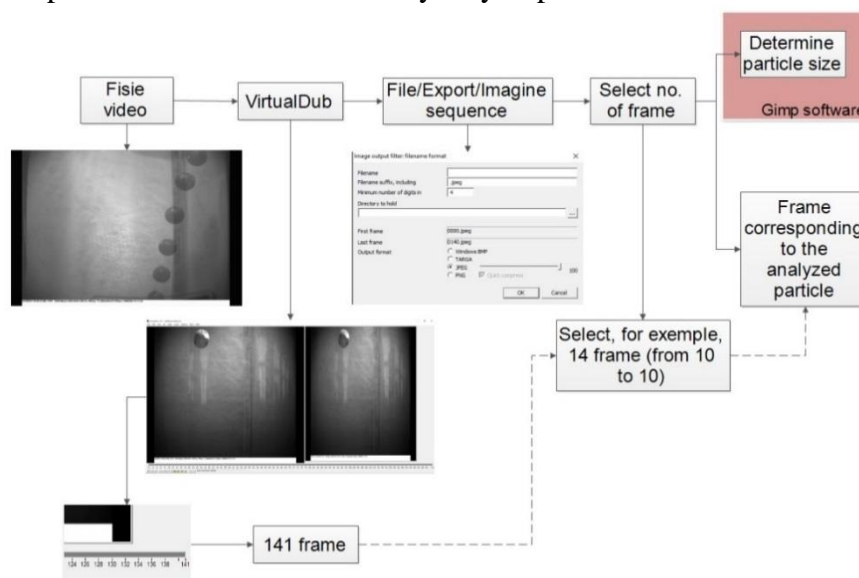
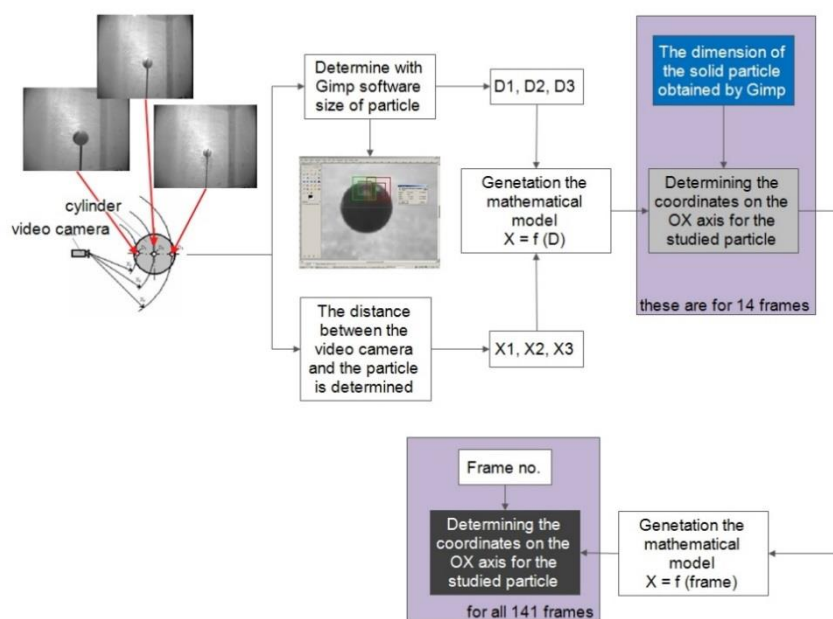**Figure 6.** Determining the solid particle size

Figure 7. Determining OX axis coordinates

These software programs define the modality of obtaining and processing data for the purpose of determining the two parameters. Thus, we can identify:
- Two methods to obtain the data:
o Automatically, in the case of generating the data obtained within the process of monitoring the solid particle to obtain the OX and OY coordinates.
o Manually, in the case of generating the data used to determine the OZ axis coordinates.
- One method of processing the generated data:
o generating mathematical patterns.
o data processing.

The mathematical models generated were linear models, such as:

$$y = a + b \, x \qquad (2)$$

where the parameters a and b are specific for each experiment.

3. Results and discussions

Following the experimental determinations and the analysis of the obtained data we could determine the average value of the instantaneous displacement velocity of a solid particle in the vertical ascending air flow and the value of the average angular velocity corresponding to the rotation of the particle (Figure 8 and 9).

Figure 8. Variation of the average value of the instantaneous velocity corresponding to the studied particle according to its sphericity and to the value of the air flow crossing the vertical ascending air channel [46]: a) Φ 27; b) Φ 35; c) Φ 47; d) Φ 56

By analyzing the obtained results regarding the variation of the average value of the instantaneous velocity, we can notice that (Figure 8):
- Regardless of the size of the particle, it is noted that:
o Average value of the instantaneous velocity varies directly proportional to the variation of the air flow velocity crossing the air channel.

o   Average value of the instantaneous velocity varies indirectly proportional to the variation of the sphericity of the solid particle.

-    The lowest value of the instantaneous velocity was obtained for the particle with the smallest size, Φ 27, of spherical shape, carried over by an air flow with a velocity value of 4.896 m/s.

-    The highest value of the instantaneous velocity was obtained for the Φ 35 particle, and a sphericity of 0.82, and for a value of the air flow of 7.784 m/s;

-    Analysing the variation of the average instantaneous linear velocity for the Φ 27 particle (Figure 8a) it is noted that [46]:

o   The value of average linear instantaneous velocity shows a gradual increase as following: for a value of sphericity of 1 it increases from 1.61 m/s to 3.58 m/s, from 1.94 m/s to 4.6 m/s for a sphericity of 0.9, and for the last value of sphericity of 0.81, we obtained an increase of this parameter from 2.38 m/s to 4.61 m/s. These values are obtained for the three values of the air flow velocity.

o   For he sphericity values used in this experimental study, it is observed that the value of the average linear instantaneous velocity significantly increases by 2 m/s corresponding to the lowering of sphericity value by 0.09, followed by a smooth increase of approximately 0.2 m/s corresponding to the lowering of sphericity value by 0.09, compared to previous value.

-    In the case of the Φ 35 diameter particle (Figure 8b), the average linear instantaneous velocity varies as following [46]:

o   For the value of sphericity of the solid particle of 1, we obtained the lowest values of the average linear instantaneous velocity, i.e. for an air flow velocity of 5.775 m/s we obtain 2.59 m/s, for an air flow velocity of 6.277 m/s the value of the analysed parameter increases by 1.61 m/s, and for an air flow velocity of 7.784 m/s the value of the average linear instantaneous velocity increases to 4.97 m/s.

o   For an air flow velocity of 5.775 m/s we notice that, for a sphericity value of 1, the value of the analysed parameter is 2.56 m/s. Lowering the sphericity value of the solid particle from 1 to 0.82, we observe that the value of the average linear instantaneous velocity increases by 0.73 m/s, and for the 0.82 sphericity we notice a slower increase reaching 3.83 m/s.

o   For an air flow velocity of 6.277 m/s the value of the average linear instantaneous velocity increases gradually by an average of approximately 0.2 m/s for each the value of sphericity starting from the spherical particle and ending with the 0.82 sphericity particle.

o   For the last value of the air flow velocity of 7.784 m/s it is also noticed an increase of the value obtained for an average linear instantaneous velocity from 4.389 m/s to 4.615 m/s ending with 4.97 m/s, values corresponding to the particles with sphericity of 1.00, 0.88 and 0.82.

-    By analysing the graphical representation of the variation of average linear instantaneous velocity corresponding to the Φ 47 solid particle (Figure 8c), the following conclusions can be drawn [46]:

o   For both spherical particle and that with different shapes we observed that the average linear instantaneous speed varies directly proportional to the variation of the air flow velocity.

o   In the case in which we consider constant the value of the air flow velocity and we very the shape of the particle used in the experimental determinations, we notice that the value of the average linear instantaneous velocity increases with the lowering of the value of sphericity.

-    By analysing the graphical representation of the variation of average linear instantaneous velocity corresponding to the Φ 56 solid particle (Figure 8d), the following conclusions can be drawn [46]:

o   For the spherical particle at an air flow velocity of 5.775 m/s the average linear velocity is 2.795 m/s, and for an air flow velocity of 6.277 m/s we notice an increase of 0.13 m/s.

o   In the case of the 0.94 sphericity particle we notice an increase of the average linear velocity from 3.05 m/s to 3.84 m/s, values corresponding to an air flow velocity of 5.775 m/s and 6.277 m/s.

o For the 0.85 sphericity particle, the difference between the two values obtained of the average linear instantaneous velocity is 1.17 m/s, the lowest value corresponds to the air flow velocity of 5.775 m/s and it is 3.28 m/s.

o By analysing the studied parameter, the average linear instantaneous velocity, from the point of view of the variation of the air flow crossing the piping of the laboratory stand, we notice that for an air flow speed of 5.775 m/s the average linear instantaneous velocity of the solid particle displacement in the piping increases with the lowering of the sphericity of the solid particle, and we obtained the following values: 3.28 m/s, 3.05 m/s and 2.66 m/s for the following sphericity values: 0.85, 0.94 and 1. The same pace of dependence is observed when the piping is crossed by an air flow with a speed of 6.277 m/s, and the average value of the linear instantaneous velocity is 4.45 m/s; 3.84 m/s and 2.79 m/s corresponding to the same types of particles.

With regard to the results corresponding to the variation of the average angular velocity (Figure 9) [46] it is found that:

- Value of the average angular velocity is closely linked to the shape of the solid particle and it is observed that lower the sphericity value, the highest the value of the average angular velocity:

o The lowest sphericity corresponds to the Φ 27 particle and it is 0.81, and for this value we obtained the highest values of the average angular velocity, regardless of the value of the air flow crossing the laboratory stand.

o The lowest value of the average angular velocity of 108.6 rad/s corresponds to the Φ 47 spherical particle and to an air flow value of 4.52 m/s.

- The relationship between the input parameters of the study, sphericity and air flow speed, as well as the value of the average angular velocity is the same as in the case of the variation of average instantaneous velocity.

- By analysing the variation of the values of the average angular velocity corresponding to the Φ 27 particle, we can ascertain that (Figure 9 a) [46]:

o In the case of the spherical particle, for an air flow speed of 4.896 m/s we obtained an angular velocity of 127.24 rad/s, for the velocity of 5.775 m/s we obtained an increase of the angular velocity by 191.6 rad/s compared to the first value, and for an air flow speed of 6.277 m/s the increase was of 205.9 rad/s still compared to the first value.

o For the particle of a different shape than spherical, i.e. with a sphericity of 0.9, we obtain, just like in the case of sphericity 1 particle, for an air flow speed of 4.89 m/s, a minimal value of the angular velocity of 317.39 rad/s, the next value being by 51.76 rad/s higher and corresponding to an air flow speed of 5.775 m/s, and the last value is by 45.3 rad/s higher than the previous one.

o For the 0.81 sphericity particle, the angular velocity shows a linear increase, thus obtaining a minimal value of 342.39 rad/s corresponding to an air flow speed of 4.896 m/s and a maximal value of 424.6 rad/sec for the air flow speed of 6.277 m/s. For an air flow speed of 5.775 m/s we obtained a value of the studied parameter of 8 rad/s.

o For an air flow speed of 4.895 m/s in the case of the spherical particle we obtained an angular velocity of 127.24 rad/s, value increased by 250 % for the 0.9 sphericity particle, so that the 0.81 sphericity particle the increase was 269.3 % compared to the first value.

o For an air flow speed of 5.772 m/s we obtained a value of the minimal angular velocity of 333.2 rad/sec, corresponding to the spherical particle, and the maximal value of 424.6 rad/s, corresponding to the 0.81 sphericity, with an average pace of approx. 40.49 rad/s between the obtained values.

o In the case of an air flow speed of 6.277 m/s we observed the same direct relationship between the angular velocity and the sphericity of solid particles.
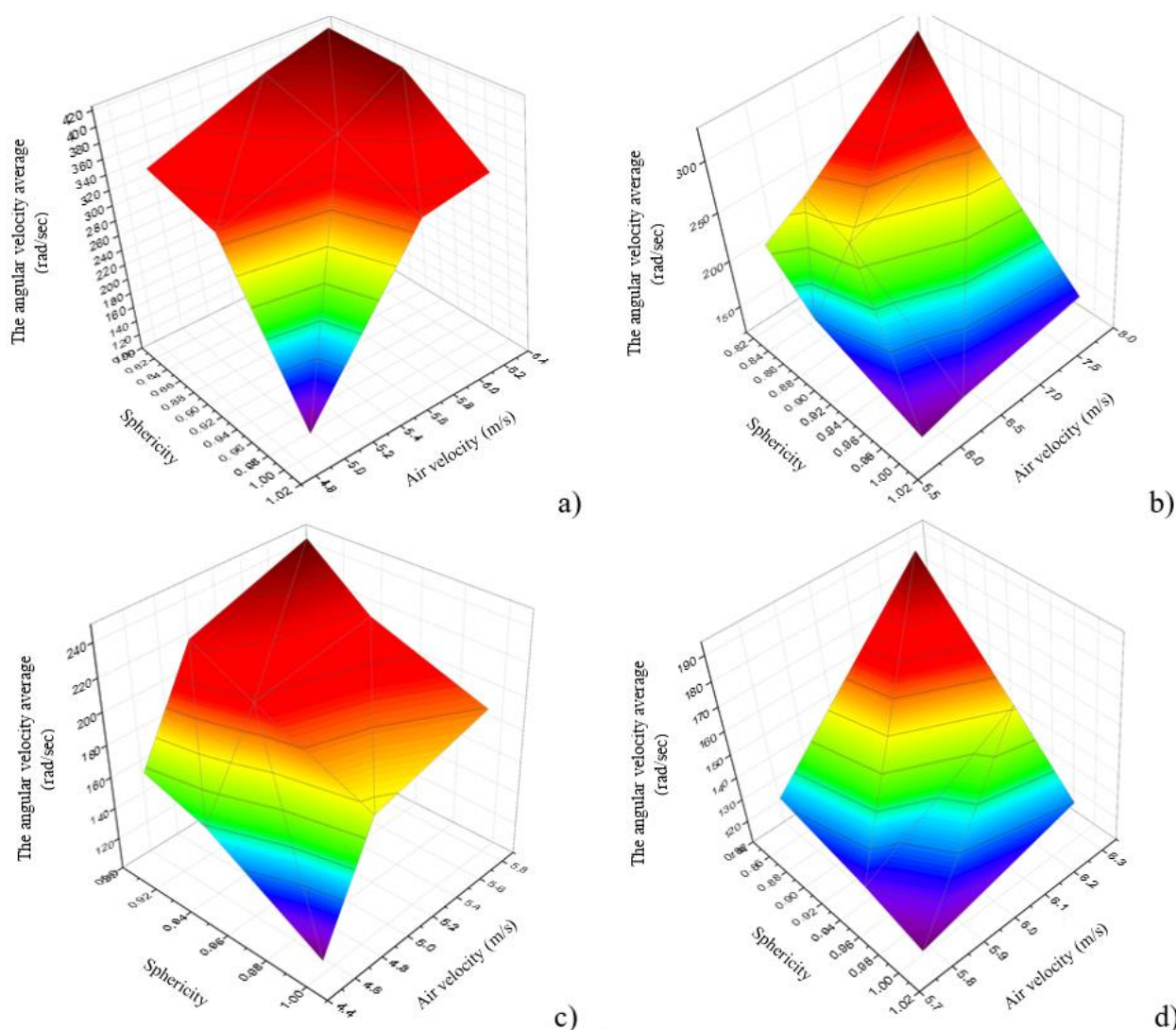
Figure 9. Variation of average angular velocity corresponding to the studied particle according to its sphericity and to the value of the air flow crossing the vertical ascending air channel: a) Φ 27; b) Φ 35; c) Φ 47; d) Φ 56

- Following the analysis of the experimental results in Figure 9b, corresponding to the Φ 35 mm particle, we observed that [46]:

o The value of the angular velocity increases with the air flow speed, regardless of the shape of the particle.

o The value of the angular velocity increases with the increase of the difference of the solid particle shape compared to the spherical particle, regardless of the value of the air flow speed.

- From the graphical representation of the results obtained following the determination of the average angular velocity corresponding to the Φ 47 solid particle (Figure 9c) it can be ascertain that [46]:

o For the spherical particle, in the case of air flow speed values of 4.519 m/s, 4.896 m/s and 5.775 m/s we obtained the following values of the studied parameter: 108.62 rad/s, 175.78 rad/s, and 193.04 rad/s.

o In the case of the 0.94 sphericity particle, for an air flow speed of 4.519 m/s we obtained an angular speed value of 149.98 rad/s, for an air flow speed of 4.896 m/s we have 206.17 rad/s and 218.52 rad/s for 5.775 m/s.

o   In the case of the 0.9, for the lowest value of the air flow speed we obtained an angular velocity of 162.48 rad/s, for the angular velocity of 4.896 m/s the value of the studied parameter became 225.39 rad/s, and in the case of the maximal air flow speed, corresponding to this experimental lot, the value of the angular velocity increased 1.1 times compared to the previous value.

o   Analysing the obtained results from the point of view of the variation we obtained the lowest value of the angular velocity of 108.62 rad/s for the spherical particle, and the maximal value of the studied parameter is 162.48 rad/s for the 0.9 sphericity particle. For the 0.94 sphericity particle, the value of the angular velocity increased by 32.85 rad/s compared to the minimal value of this parameter.

o   For the other values of the air flow speed crossing the piping, there is the same relationship between the sphericity of the solid particle and the value obtained for the angular velocity.

-    For the Φ 56 particle (Figure 9d) we obtained a variation of the average angular velocity as following [46]:

o   For an air flow speed of 5.775 m/s the obtained angular velocity is 111.52 rad/s for the spherical particle, of 119.54 rad/s for the 0.94 sphericity particle and for 0.9 sphericity particle the value of the studied parameter increased by 9.12 rad/s compared to the previous value.

o   For an air flow speed value increased from 5.775 m/s to 6.277 m/s we observe an increase of the angular velocity by 14.1 % for the spherical particle, by 27.48 % for the 0.94 sphericity particle and by 48.8 % for the 0.85 sphericity particle.

o   In the case of the spherical particle, the difference between the first and the second value of the angular velocity is 15.73 rad/s, the minimal value being 111.52 rad/s corresponding to an air flow speed of 5.775 m/s.

o   For the 0.94 sphericity particle it is observed that the angular velocity increased by 32.85 rad/sec for an air flow speed of 6.277 m/s compared to the value of the studied parameter of 119.54 rad/s, value obtained for the air flow speed of 5.775 m/s.

o   For the last type of particle, the one of 0.85 sphericity, the value of the angular velocity is 128.66 rad/s for an air flow speed of 5.775 m/s, and for an air flow speed of 6.277 m/s the value of the angular velocity increased by approx. 1.5 times compared to the initial value.

4. Conclusions

Considering the obtained results, corresponding to the carried-out study, the following conclusions can be drawn:

-    Monitoring the behaviour of a solid particle in an air flow aims to optimize the installations used in the process industry to carry out different complex industrial operations.

-    Because in the specialized literature most of the studies aimed at analyzing the behavior of a mixture of particles and not a single particle, no comparative conclusions can be generated.

-    The present study combines two methods for analysis, analysis frame by frame but also an continuous analysis of the particle trajectory.

-    To achieve the aerodynamic separation of a heterogeneous solid particles mix, we need to determine a series of working parameters for the installation used for this process, but also the parameters in relationship with the behaviour of the solid particle in the air flow.

-    Determining the monitored parameters implies the use of different complex installations and equipment, video editing and imagistic software, as well as a working methodology to transform the obtained data in real values.

-    The average value of the instantaneous velocity varies directly proportional to the variation of the air flow crossing the installation and inversely proportional to the variation of the sphericity of the particles. The lowest value obtained corresponding to this parameter is 1.61 m/s corresponding to an air flow speed of 4.89 m/s in the case of Φ 27 solid particle and a sphericity of 1, and the highest value is 4.97 m/s in the case of Φ 35 solid particle and 0.82 sphericity for an air flow speed of 7.78 m/s.

- The values of the average angular velocity vary inversely proportional to the variation of the sphericity of solid particles and directly proportional to the variation of the air flow crossing the laboratory stand. The lowest value, corresponding to the average angular velocity of 108.6 rad/s, corresponding to an air flow speed of 4.51 m/s in the case of the Φ 47 solid particle and 1 sphericity, and the highest value is 424.6 rad/s in the case of an air flow speed of 6.27 m/s for a Φ 27 solid particle.

- It is ascertained that the two analyzed parameters have the same relationship to the input parameters (sphericity of the solid particle and the air flow speed).

- Although all particles used in this study have been introduced in the air channel crossed with the same vale of the air flow speed, i.e. 5.77 m/s, we could not determine a pace of the studied parameters since the solid particles did not have the same position in the air channel, nor the same trajectory.

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