

Article

Extraction of Mathematical Correlations Applied in the Aerodynamic Separation of Solid Particles

Emilian Mosnegutu ¹, Mirela Panainte-Lehadus ^{1,*}, Valentin Nedeff ^{1,2}, Claudia Tomozei ¹, Narcis Barsan ¹, Dana Chitimus ^{1,*} and Marcin Jasinski ³

¹ Department of Environmental Engineering and Mechanical Engineering, Faculty of Engineering, Vasile Alecsandri University of Bacau, 157 Calea Marasesti, 600115 Bacau, Romania; emos@ub.ro (E.M.); vnedef@ub.ro (V.N.); claudia.tomozei@ub.ro (C.T.); narcis.barsan@ub.ro (N.B.)

² Gheorghe Ionescu Sisesti, Academy of Agricultural and Forestry Sciences Bucharest, 61 Marasti, 011464 Bucharest, Romania

³ Institute of Vehicles and Construction Machinery Engineering, Warsaw University of Technology, Narbutta 84, 02-507 Warsaw, Poland; marcin.jasinski@pw.edu.pl

* Correspondence: mirelap@ub.ro (M.P.-L.); dana.chitimus@ub.ro (D.C.)

Abstract: This article describes the methodology used to identify the mathematical equation that describes the correlations between the input and output parameters of an experiment. As a technological process, aerodynamic separation was chosen to represent the behavior of a solid particle within an ascending vertical airflow. The experimental data were used to identify two parameters, namely the average linear velocity and the angular velocity. The Table Curve 3D program was used to develop a mathematical equation describing the dependence between the input parameters (the shape and size of the solid particle, as well as the velocity of the airflow) and the monitored parameters. A pyramid-type analysis (following a filtering system, a general equation was determined from a large number of equations that characterize an experimental set mathematically) was designed in order to determine a single mathematical equation that describes the correlation between the input variables and those obtained as accurately as possible. The determination of the mathematical equation started with the number of equations generated by the Table Curve 3D program; then, the equations with a correlation coefficient greater than 0.85 were chosen; and finally, the common equations were identified. Respecting the working methodology, one equation was identified, which has for the average linear velocity, a correlation coefficient r^2 of between 0.88–0.99 and 0.86–0.99 for the angular velocity.

Keywords: mathematical equation; Table Curve 3D; correlation coefficient



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1. Introduction

Regardless of the nature of the phenomenon or process, mathematics plays a crucial part in its understanding. Many researchers apply multiple mathematical programs to identify specific connections between the parameters analyzed, thanks to scientific advancements in hardware and software technology. This is why, regardless of the domain to which it refers, e.g., industry, agriculture, medicine, the environment, and so on, mathematical modeling has progressed [1–8]. As a result, in addition to traditional equations, such as those used in physics to explain specific events, many scientific articles have recently appeared in the literature that present mathematical correlations connecting the parameters under study. The authors of these articles want to find out if there are any dependencies that cannot be described using traditional physics, chemistry, or biology. It is important to note that the mathematical equations generated in these articles are specific to the study in question [9–12].

This article describes a methodological approach in which the major goal is to identify mathematical equations that may represent significant associations in a general way. This

article's mathematical equation identification methodology can be applied to a variety of experimental studies.

A set of experimentally obtained results are used to describe this method, which is taken up and explained summarily in this article (concerning the behavior of a solid particle in an ascending vertical airflow—more explanations can be found in the literature).

Within the process industry, there are several operations that involve the use of certain physical–mechanical characteristics of solid particles [13–16]. One of these is the aerodynamic behavior of solid particles, i.e., their aerodynamic separation [17–26].

Aerodynamics aims to study the dynamic interaction between fluid (respectively, the air) and various classes of solid particles, generically called aeromechanical structures.

Regardless of the scope of the practical research, in industry, agriculture (in the case presented, aerodynamic separation), medicine, or environmental protection, following a set of experimental determinations, it is advisable to design a mathematical equation, thus generating equations with which they can be tracked, analyzed, and optimized [27–35].

In order to create a mathematical equation corresponding to different experimental research, many works have been conducted and are presented in the specialized literature [27–30,32,36–39]. However, a rather difficult problem arises when it is desired to identify a mathematical equation that corresponds to several studies:

- Studies that were carried out at different times or in different locations but at the same time;
- Studies conducted by different authors but which have the same research field.

In this paper, the aim is to identify a common mathematical equation for a real case (practical case), using a pyramid system as the method of identification. In order to present this method, a study was used that aimed to monitor the behavior of a solid polystyrene particle (of different sizes), namely the study of the behavior of a solid particle in a vertical airflow [19]. It should be mentioned that the article aims to identify the mathematical equation that describes as accurately as possible the correlations between the input parameters used in the study and the parameters followed in this study, an equation that is valid for several parameters analyzed.

2. Materials and Methods

The study of the behavior of a solid particle in an ascending vertical airflow was performed using a laboratory stand, which is provided with an ascending vertical air channel and three chambers of soothing (Figure 1). To carry out this study, the laboratory stand was made of transparent material in order to allow visualization of the behavior of the solid particles in the air channel [20,23,40–42].

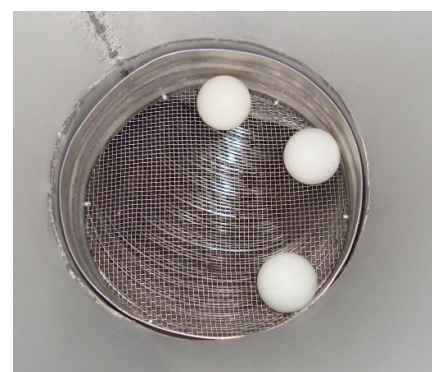


Figure 1. The image shows laboratory equipment and some of the particles that were utilized. [Reprinted/adapted with permission from Ref. [19]. 2020, Ristea M.].

The passage of the solid particle through the tracking area was very fast, and that is why it was chosen to film its behavior. For this purpose, a camera was used that could film a number of processes carried out quickly, namely a high-speed camera. The film thus obtained was subjected to analysis, and by means of video and image processing software, a series of parameters describing the behavior of the solid particles in the ascending airflow were determined [19,40,41].

The area in which the behavior of the solid particle was analyzed had a circular section, corresponding to the beginning area of the laboratory stand, an area in which the rooms of soothing are not located.

In order to be able to present the working methodology as previously mentioned, several sets of experimental determinations were made, and their initial parameters are presented in Table 1.

Table 1. Presentation of input parameters [Reprinted/adapted with permission from Ref. [19]. 2020, Ristea M.].

The Solid Particle Diameter	Sphericity *	Airflow Velocity (m/s)
27 mm	1	4.896 m/s; 5.775 m/s; 6.277 m/s
	0.90856	4.896 m/s; 5.775 m/s; 6.277 m/s
	0.81781	4.896 m/s; 5.775 m/s; 6.277 m/s
35 mm	1	5.775 m/s; 6.277 m/s; 7.784 m/s
	0.88118	5.775 m/s; 6.277 m/s; 7.784 m/s
	0.82946	5.775 m/s; 6.277 m/s; 7.784 m/s
47 mm	1	4.519 m/s; 4.896 m/s; 5.775 m/s
	0.94231	4.519 m/s; 4.896 m/s; 5.775 m/s
	0.90911	4.519 m/s; 4.896 m/s; 5.775 m/s
56 mm	1	5.775 m/s; 6.277 m/s
	0.94433	5.775 m/s; 6.277 m/s
	0.85499	5.775 m/s; 6.277 m/s

* Sphericity is a parameter that depends on the shape of the solid particle and was determined according to the literature [Reprinted/adapted with permission from Ref. [19]. 2020, Ristea M.].

For each size of the solid particles, a set of experimental determinations were performed, thus obtaining four sets of experiments, each of them corresponding to a value of sphericity and an airflow velocity:

- The values in set no. 1 correspond to the results for a solid particle with a diameter of 27 mm—there are 9 values;
- The values in set no. 2 correspond to the results for a solid particle with a diameter of 35 mm—there are 9 values;
- The values in set no. 3 correspond to the results for a solid particle with a diameter of 47 mm—there are 9 values;
- The values in set no. 4 correspond to the results for a solid particle with a diameter of 56 mm—there are 6 values;

The solid particles used in these experimental determinations are particles of polystyrene (Figure 1) [19].

The values of the airflow velocity in these experimental sets were chosen to be higher than the value of the floating velocity, allowing the particles in the air channel to move.

In the present work, the next parameters are taken into consideration:

- The average instantaneous velocity (m/s);
- Average angular velocity (rad/s).

3. Results

Following the analysis of the experimental results, it was possible to identify the dependence between the input parameters [19]:

- The sphericity parameter, which depends on the type of particle used in the experimental determinations;
- The value of the velocity of the airflow that passes through the vertical tubing depends on the operating mode of the installation used;
- and the output parameters:
- The average instantaneous velocity (Figure 2);
- The average angular velocity (Figure 3).

From the analysis of the graphical representations in Figure 2, it is observed that the average values of the instantaneous velocity vary directly in proportion to the variation of the airflow that crosses the working installation and inversely proportional to the variation of the sphericity of the particles used. The lowest obtained value of this parameter is 1.61 m/s, which corresponds to a velocity of airflow of 4.89 m/s for a solid particle with a diameter of 27 mm and sphericity of 1. The highest value is 4.97 m/s, which corresponds to an airflow velocity of 7.78 m/s for a solid particle with a diameter of 35 mm and a sphericity of 0.82 [19].

Figure 3 shows that the values of the average angular velocity are inversely proportional to variations in the sphericity of the solid particles and directly proportional to variations in the airflow passing through the laboratory stand. The lowest value of the average angular velocity obtained is 108.6 rad/s, which corresponds to a velocity of airflow of 4.51 m/s for a solid particle with a diameter of 47 mm and a sphericity of 1. In addition, the highest value is 424.6 rad/s, which corresponds to an airflow velocity of 6.27 m/s for a particle with a diameter of 27 mm and a sphericity of 0.81 [19].

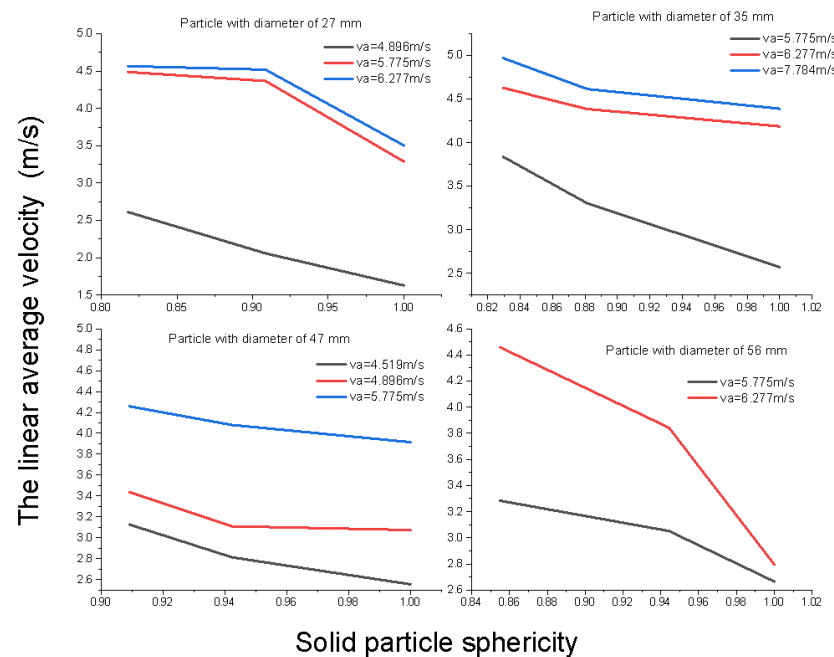


Figure 2. The variation of the linear average velocity on function by the variation of the airflow velocity and the variation of the solid particle shape for particles of different sizes [Reprinted/adapted with permission from Ref. [19]. Ristea M, 2020. [43]].

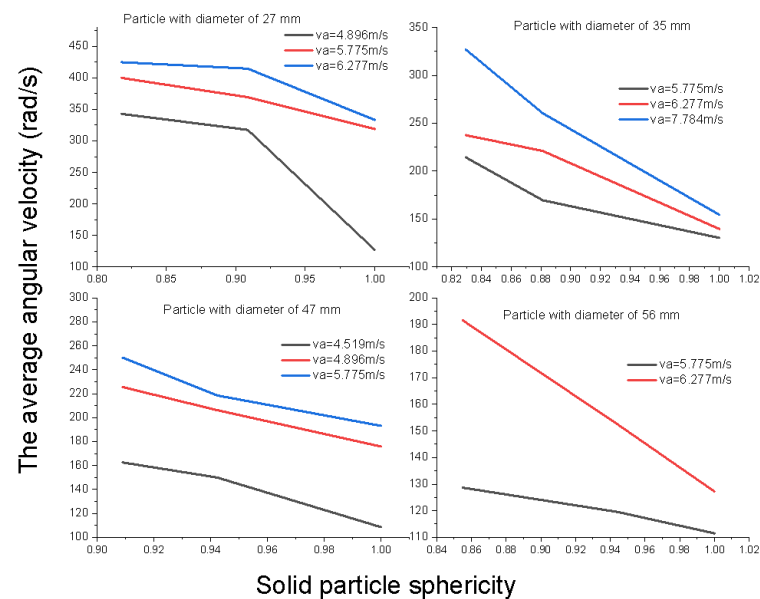


Figure 3. The variation of the angular average velocity on function by the variation of the airflow velocity and the variation of the solid particle shape for particles of different sizes [Reprinted/adapted with permission from Ref. [19]. Ristea M, 2020. [43]].

4. Identifying the Mathematical Equation

Table Curve 3D (V4, Systat Software Inc., London, UK Branch, 2019) software was used to construct mathematical equations that corresponded to the results. Table Curve 3D is a program that can generate various sorts of response surfaces. These surfaces correspond to the 450 million equations in the program database [44].

In order to derive the general mathematical equation for a n group of experiments (in our case, we have four experimental groups), the working stages shown in Figure 4 must be completed.

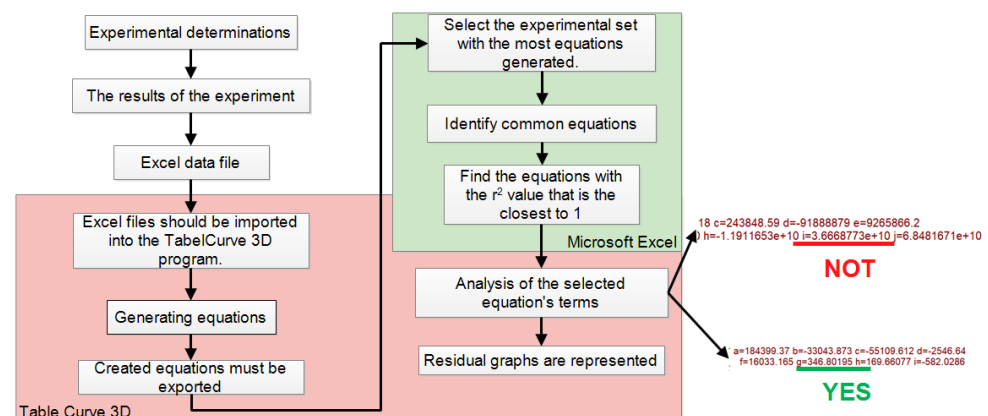


Figure 4. The steps involved in creating a mathematical equation.

The steps for determining the mathematical equation that corresponds to the present study are outlined below:

1. Experimentally obtained values are entered into an Excel 97-2003 file;
2. The Excel file was inserted into Table Curve 3D (the application allows for such an insertion [41]);
3. The three axes' parameters are chosen, the input parameters are entered on the OX and OY axes, and the tracked parameter is entered on the OZ axis;

4. The Table Curve 3D program [44] generates equations matching the values introduced. Their number is displayed in Figures 5 and 6 for all sets of experiments according to the value of the correlation coefficient r^2 , for linear and angular velocity, respectively.

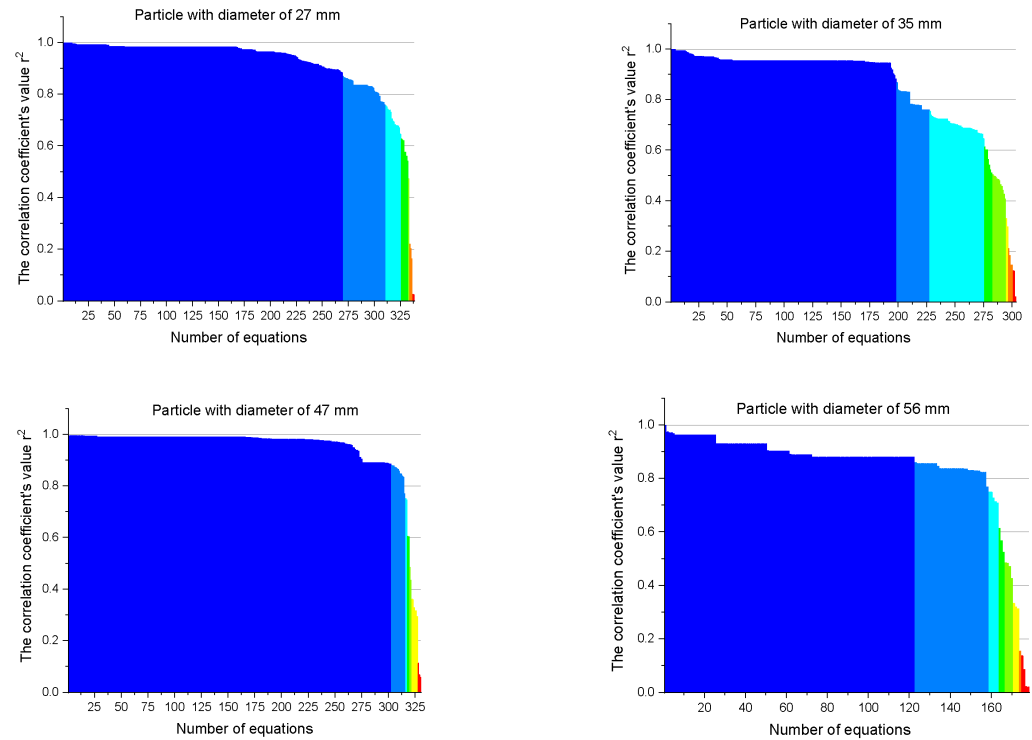


Figure 5. According to the value of the coefficient r^2 for the linear average velocity, the Table Curve 3D program generates a certain number of equations [43].

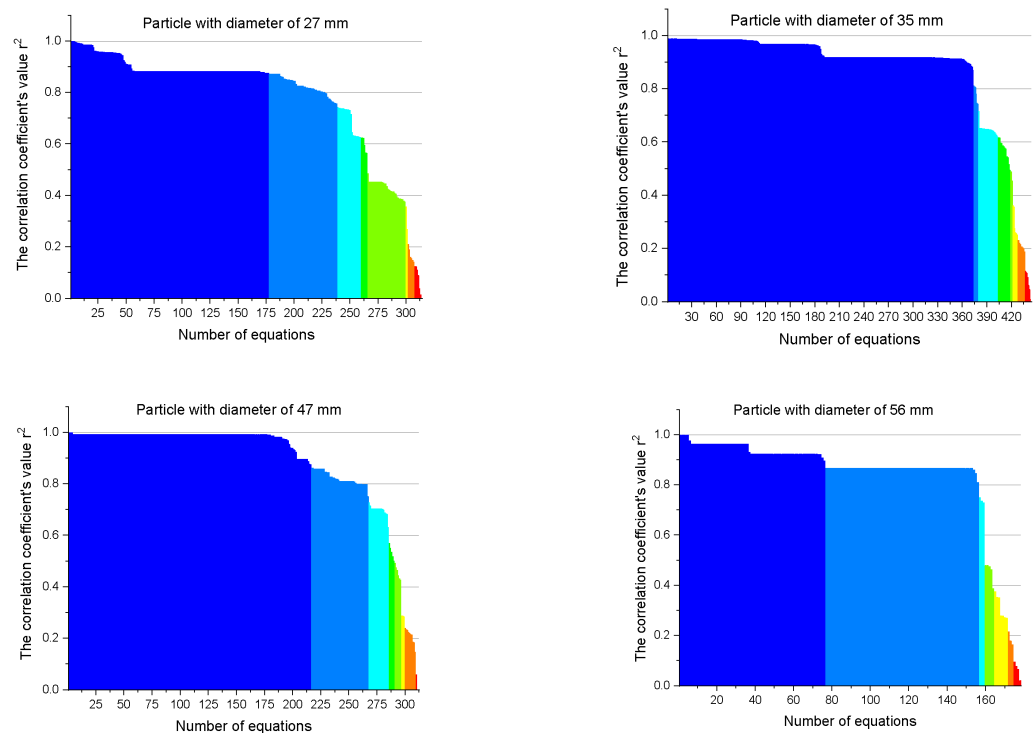


Figure 6. The number of equations generated by the Table Curve 3D program is represented as a function of the coefficient r^2 for the variation of the average angular velocity [43].

The Table Curve 3D application generated a large number of equations:

- A total of 338 equations were obtained for the average value of the instantaneous velocity for the particle with a diameter of 27 mm (maximum number of the equation), and 178 equations were generated for the particle with a diameter of 56 mm (minimum number of the equation);
 - In the case of average angular velocity, 444 equations were generated for the particle with a diameter of 36 mm (maximum number of equation), and 178 equations were generated for the particle with a diameter of 56 mm (minimum number of equation).
5. The resulting equations are categorized based on the r^2 correlation coefficient value. (Figure 7).

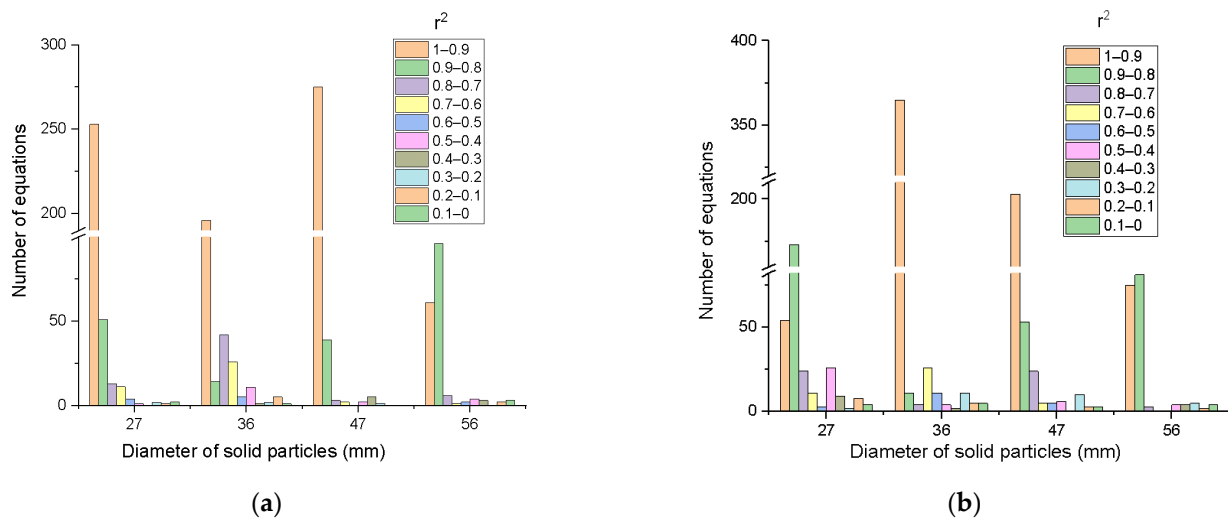


Figure 7. The r^2 coefficient is used to group the equations generated [43]: (a) average instantaneous velocity; (b) average angular velocity.

This sort of representation study, according to Figure 7, reveals that:

- The values of the coefficient r^2 are distributed as follows for the parameter average value of instantaneous speed:
 - The largest weighting, 74.8 percent, corresponds to r^2 variation in the range 0.9–1, and the smallest weighting, 0 percent, corresponds to r^2 variation in the range 0.3–0.4 for the particle with a diameter of 27 mm;
 - There are 196 equations developed for the particle with a diameter of 36 mm that belong to the interval 0.9–1, and the fewest number of equations are related to the interval r^2 equal to 0.3–0.4;
 - This parameter's maximum weighting is also for the interval 0.9–1, at 84.09 percent for the particle with a diameter of 47 mm, while no equations were found for the intervals 0.5–0.6, 0.1–0.2, and 0–0.1;
 - The maximum number of equations were formed for r^2 in the range 0.8–0.9, accordingly 96 equations, for the final dimension of the examined particle, the diameter of 56 mm, while no equations were generated in the range 0.2–0.3.
- The values of the coefficient r^2 are distributed as follows, for the value of the average angular velocity:
 - A maximum of 173 equations for the range of 0.8–0.9 and a minimum of 2 equations for the range 0.2–0.3 were created for the particle with a diameter of 27 mm;
 - The largest weighting, 82.2 percent, corresponds to r^2 variation in the range 0.9–1 for the particle with a diameter of 36 mm, while the smallest weighting, 0.45 percent, corresponds to r^2 variation in the range 0.3–0.4;

- A maximum of 205 equations corresponding to r^2 variation in the range 1–0.9 and a minimum of 0 equations corresponding to r^2 variation in the range 0.3–0.4 were discovered for the particle with a diameter of 47 mm;
 - A total of 81 equations for r^2 in the range 0.8–0.9 were developed for the particle with a diameter of 56 mm, which indicates the interval with the most equations. For r^2 between 0.6–0.7 and 0.5–0.6, no equations are generated in the intervals.
6. The next stage was to look for equations that are common (the COUNTIF function from Excel was used). The group corresponding to the experimental set with the greatest number of equations is identified at this step:
- a. There are 338 equations relating to the set of tests for the particle with a diameter of 27 mm, for the variation of the linear average velocity;
 - b. There are 444 equations relating to the set of experiments for the particle with a diameter of 36 mm, for the variation of the average angular velocity.

Each equation is assigned a number, which aids in the identification of common equations. As a result, an analysis is carried out with regard to the reference set of equations. Figure 8 shows the findings of the analysis. It should be mentioned in this representation that:

- No. 3 denotes that the reference set's equation can also be found in the other three sets of equations;
- No. 2 indicates that the reference set equation can only be found in two sets of equations;
- No. 1 indicates that the reference set equation can only be found in a set of equations;
- No. 0 indicates that the reference set's equation is not found in any other set of equations.

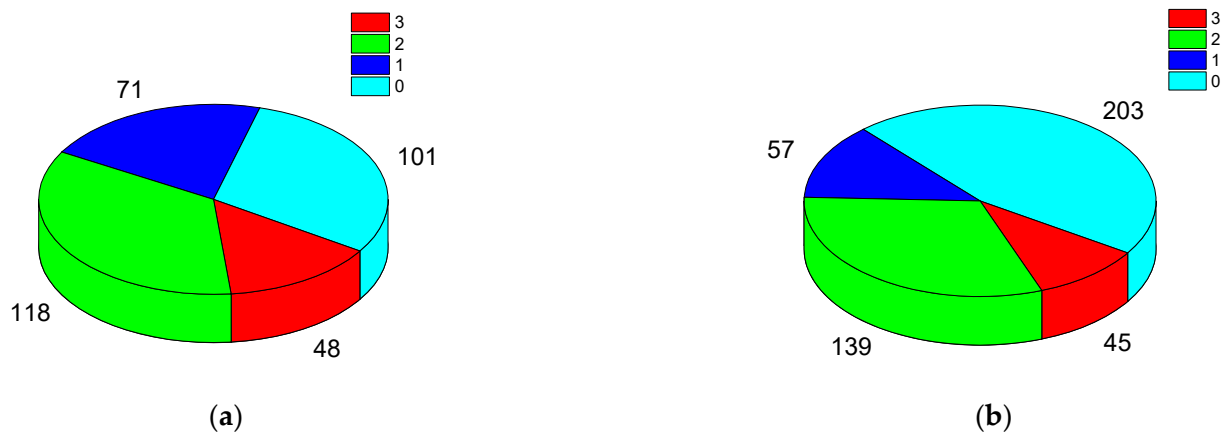


Figure 8. Identifying similar equations [43]: (a) average instantaneous velocity; (b) average angular velocity.

In this approach, a total of 48 common equations from a total of 338 equations could be discovered for variations in average instantaneous velocity, and a total of 45 common equations from a total of 444 equations could be identified for variations in average angular velocity.

7. An analysis of the common equations is carried out in order to choose the equations in which the correlation coefficient r^2 is as close to 0.99 as possible (for all sets of experiments). INDEX, SUM, and MAX functions from Excel were used to perform this filtering step (Figure 9). Only four equations were discovered at this point for both parameters studied.

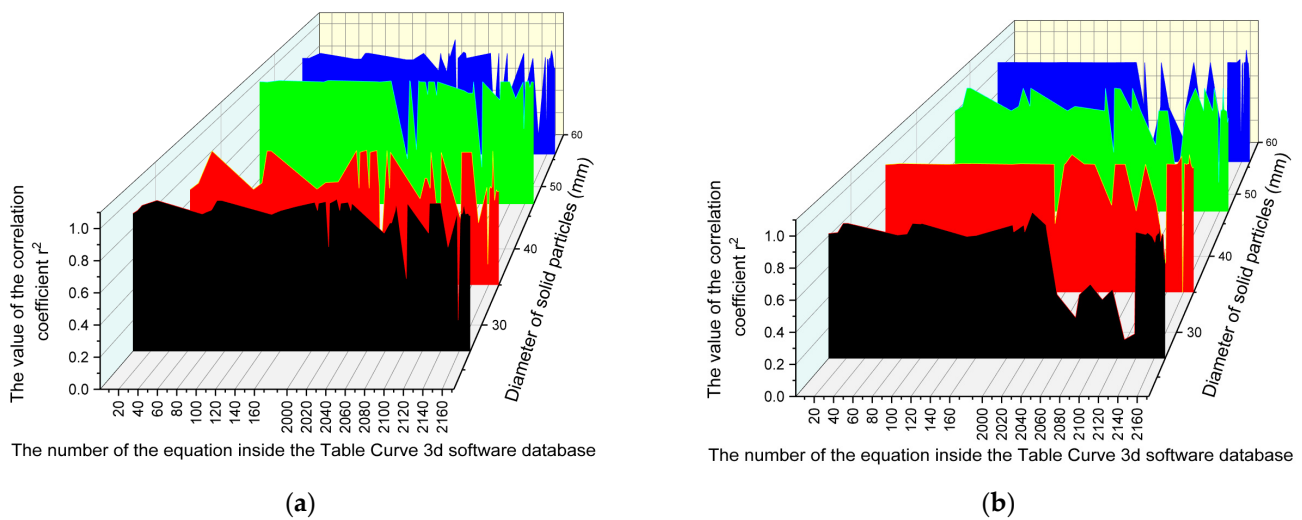


Figure 9. Analysis of common equations based on the value of the correlation coefficient r^2 [43]: (a) the average instantaneous velocity; (b) the average angular velocity.

8. Following that, a visual examination of each term of the mathematical equation will be carried out in accordance with the requirements shown in Figure 4.

At the end of this section, the graphical representation of the work stages described in this method is summarized briefly in Figure 10.

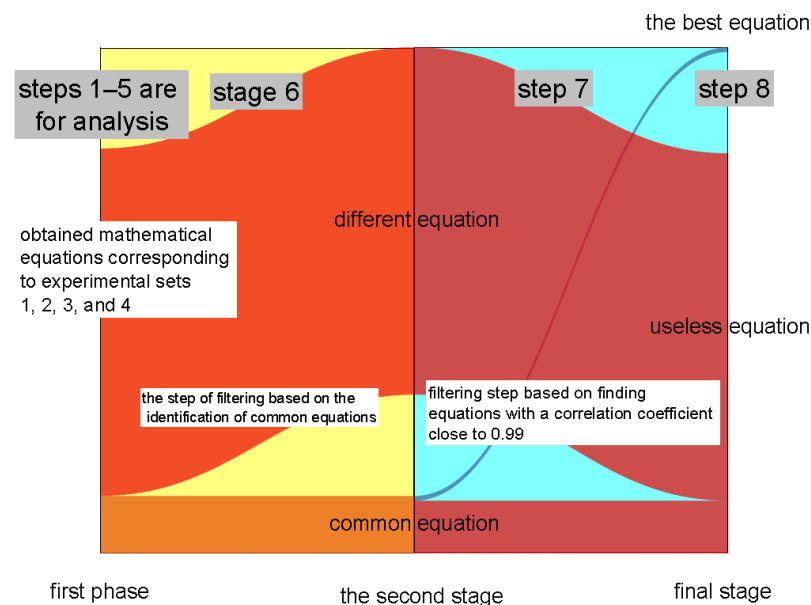


Figure 10. Summative graphical representation of the method used [43].

Figure 10 shows a graphical representation of the analysis of the average instantaneous velocity parameter (the same type of representation can be made for the second parameter—the average angular velocity—but it is considered that only this representation is enough). This image aims to illustrate the above-mentioned work steps even while providing a comparison of how to classify the mathematical equations generated by the Table Curve 3D software. The three steps of the methodology are presented:

- The number of equations identified in stage 4 is presented in the first stage;
- The common equations are highlighted in the second stage, according to stage 6 of the methodology (Figure 8, No. 3);

- After the filtering stage, there are a number of equations that match the criteria and may be used to describe the mathematical relationship between the input and output parameters.

5. Selecting the Best Mathematical Equation

A common equation was used for the final collection of tests, concerning both the variation of the average value of instantaneous speed and the variation of the average angular velocity (Equation (1)).

This equation is of the following form:

$$z = a + b \cdot \ln x + c \cdot (\ln x)^2 + d \cdot y + e \cdot y^2, \quad (1)$$

where x represents the variation in particle sphericity and y represents the variation in airflow speed. This is equation number 92 in the program's database [43].

The Table Curve 3D software created the graphical representations of the equation, which are shown in Figure 11 (an example is presented for each parameter studied).

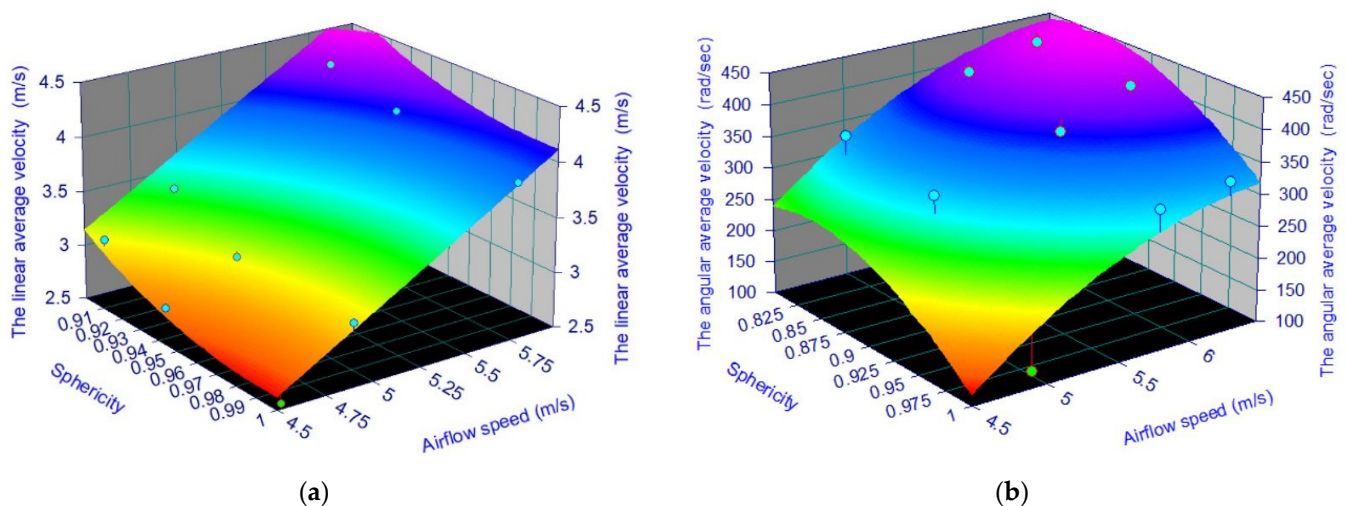


Figure 11. The response surfaces corresponding to the selected equation [44] are shown as follows: (a) for the average instantaneous velocity of a particle with dimensions of 47 mm; (b) for the average angular velocity of a particle with a diameter of 27 mm.

The values of the correlation coefficients r^2 are presented in Table 2 for the parameters analyzed, and the values of the coefficients corresponding to the mathematical equation are presented in Table 3.

Table 2. The correlation coefficients r^2 value for both speeds [44].

Diameter of Solid Particle (mm)	Source of Sampling	The Value of the Correlation Coefficients r^2
27	the average instantaneous velocity	0.98404352
35		0.954536506
47		0.991563069
56		0.8806499
27	the average angular velocity	0.883216778
35		0.918608489
47		0.992395157
56		0.868026975

Table 3. The numerical value of the terms in the mathematical equations [44].

Diameter of Solid Particle (mm)	The Constant Values				
	a	b	c	d	e
The average instantaneous velocity					
27	−50.23223724	−11.95975744	−34.97830761	17.47111956	−1.415462687
35	−49.20607684	−0.92288797	16.90007259	15.17783217	−1.067222164
47	−1.820559781	0.557052644	52.79511238	0.978623048	0.001785313
56	−28.8899824	−15.53346772	−52.68311297	9.116452615	−0.640957447
The average angular velocity					
27	−1559.120656	−1551.787458	−4519.318535	561.1160605	−41.90513018
35	−645.2588717	−524.764458	574.9907661	198.8608978	−11.88403605
47	−3171.846461	−519.4420102	436.8999213	1245.268354	−114.7711104
56	−999.2614963	−306.5043777	−297.4052482	297.6328447	−18.55319149

The value of the correlation coefficient r^2 is between 0.86 and 0.99, indicating that the values produced by the mathematical equation coincide with the real values utilized, according to the examination of the mathematical equation generated by the Table Curve 3D application.

The application enables the creation of a graphical representation known as the residual graph to show the difference between the two values, the real values, and the values generated by the mathematical equation. The difference between the surface created by the mathematical equation, the hatching surface that, in this case, coincides with the XOY plane, and the experimental values represented by dots is realized in this form of a graph. Figures 12 and 13 show these residual graphs [44].

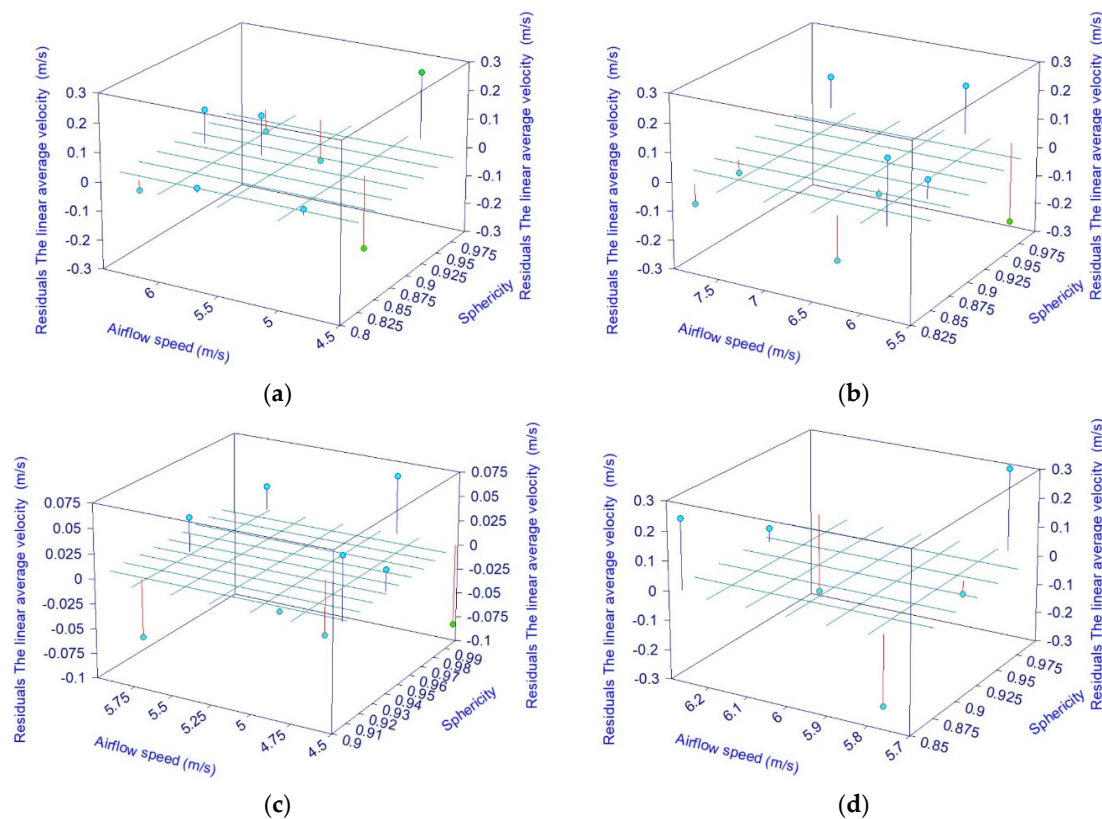


Figure 12. The residual graphs corresponding to the average instantaneous velocity [44]: (a) a particle measuring 27 mm in diameter; (b) a particle measuring 35 mm in diameter; (c) a particle measuring 47 mm in diameter; (d) a particle measuring 56 mm in diameter.

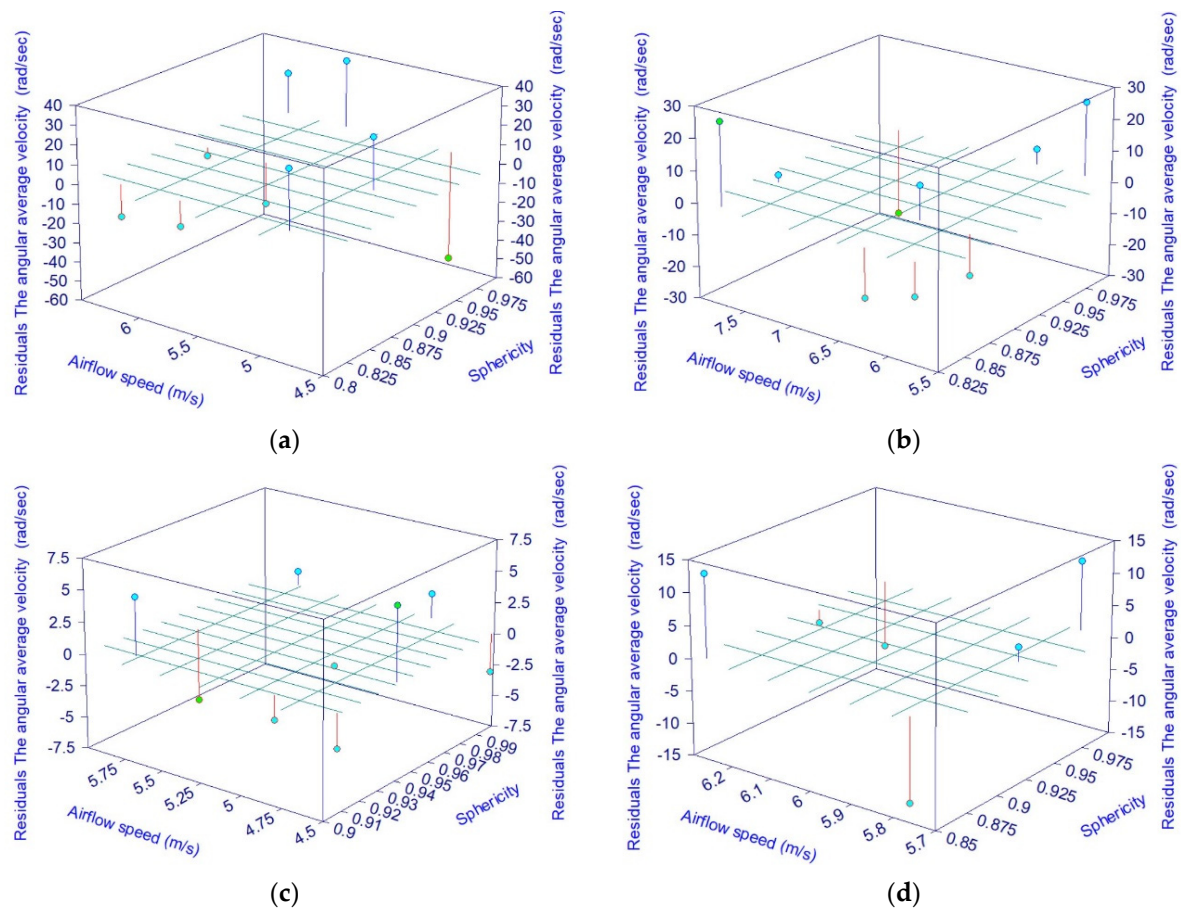


Figure 13. The residual graphs corresponding to the variation in the average angular velocity [44]: (a) a particle measuring 27 mm in diameter; (b) a particle measuring 35 mm in diameter; (c) a particle measuring 47 mm in diameter; (d) a particle measuring 56 mm in diameter.

By comparing the values obtained experimentally and those obtained from the identified mathematical equation (Equation (1)), a difference is obtained (described in the residual graphs), presented in Table 4.

Table 4. Minimum and maximum residual values [44].

Difference	Diameter of the Solid Particle (mm)			
	27	35	47	56
the average instantaneous velocity (m/s)				
maximum	−0.2541	−0.2841	−0.0838	−0.2843
minimum	0.2334	0.2199	0.0624	0.2843
the average angular velocity (rad/s)				
maximum	−56.3629	−28.2754	−5.7759	−12.8663
minimum	35.0704	26.07388	5.8351	12.8662

6. Discussion

The working approach described in this article aims to facilitate the identification of a mathematical equation formed from data obtained from multiple sets of experiments in a simple manner, regardless of the experimental area.

7. Conclusions

The process industry (and not only) involves a variety of processes in order to produce a set of goods. A series of experiences are performed to improve these processes, following

which a mathematical equation (for the purpose of optimization and comprehension) may be realized.

A mathematical equation was created utilizing a set of experimental data in this article. These dates were produced from studies on the influence of solid particle size, shape, and air current velocity on the behavior of a solid particle in an upward vertical airflow.

From a mathematical standpoint, there is a plethora of software available for the design and realization of dependencies between the input and output parameters of an experiment, ranging from standard software (for example, Excel) to software specifically designed for this purpose.

In this article, we used the Table Curve 3D software, which can generate mathematical equations involving three parameters (two inputs and one output), with a correlation coefficient close to one.

Using the Table Curve 3D application, experimental data were utilized to establish a general mathematical equation, valid for the two parameters under investigation (the average instantaneous velocity and average angular velocity).

The correlation coefficients r^2 , which relate to the mathematical equations selected and created by the Table Curve 3D software (in conformity with the experimental data), vary from 0.86 to 0.99.

Following the analysis of the common equations, a general mathematical equation that describes the dependence between the input and output parameters was identified.

The mathematical equation was verified by displaying the difference between the surface obtained with the help of a mathematical equation and the surface obtained with the help of real data, resulting in a residual graphical representation.

In regards to the case under discussion, it can be said that:

- An average of 287 mathematical equations were generated for the average instantaneous velocity parameter, and another 312 mathematical equations were generated for the average angular velocity parameter.
- For each parameter, only four equations could be identified using the process for selecting a generalized mathematical equation.
- After examining the differences between experimental and mathematical equation values, it was determined that:
 - The highest variation in the average instantaneous velocity parameter is 0.28 m/s, whereas the lowest difference is 0.003 m/s.
 - The highest variation in the average angular velocity parameter is 56.36 rad/s, and the smallest difference is 0.059 rad/s.

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