

Article

Computational Fluid Dynamics Analysis of Erosion in Active Components of Abrasive Water Jet Machine

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Abstract: This study presents a comprehensive three-dimensional computational fluid dynamics (CFD) analysis of abrasive fluid flow and its erosive effects on the active components of the WUXI YCWJ-380-1520 water jet cutting machine. The research investigates the behavior and impact of abrasive particles within the fluid, determining the erosion rates for particles with diameters of 0.19 mm, 0.285 mm, and 0.38 mm (dimensions resulting from the granulometry of the experimentally established sand), considering various abrasive flow rates. The methodology includes a detailed granulometric analysis of the abrasive material, identifying critical particle sizes and distributions, with a focus on M50 granulation (average particle size of 0.285 mm). Additionally, the study employs the Wadell method to determine the shape factor ($\Psi_i = 0.622$) of the abrasive particles, which plays a significant role in the erosion process. Experimental determination of the abrasive flow rate is conducted, leading to the development of a second-order parabolic model that accurately predicts flow variations based on the control settings of the AWJ machine. The maximum erosion occurs at the entry surface of the mixing tube's truncated zone, with a higher intensity as the particle size increases. For the 0.19 mm particles, the erosion rates range from $1.090 \times 10^{-6} \text{ kg/m}^2 \cdot \text{s}$ to $2.022 \times 10^{-6} \text{ kg/m}^2 \cdot \text{s}$ and follow a parabolic distribution. The particles of 0.285 mm show erosion rates ranging from $2.450 \times 10^{-6} \text{ kg/m}^2 \cdot \text{s}$ to $6.119 \times 10^{-6} \text{ kg/m}^2 \cdot \text{s}$, also fitting the second-order parabolic model. The largest particles (0.38 mm) exhibit erosion rates ranging from $3.646 \times 10^{-6} \text{ kg/m}^2 \cdot \text{s}$ to $7.123 \times 10^{-6} \text{ kg/m}^2 \cdot \text{s}$, described by a third-order polynomial. The study concludes that larger particle sizes result in higher erosion rates due to their increased mass and kinetic energy. Therefore, the present investigation demonstrates a significant relationship between particle size, abrasive flow rate, and erosion rate, highlighting critical wear points in the machine's components. The findings contribute to optimizing the design and operational parameters of water jet cutting machines, thereby enhancing their efficiency and lifespan.

Keywords: abrasive water jet machine; active component; computational fluid dynamics (CFD); erosion rate; particle diameter; abrasive flow rate



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1. Introduction

Abrasive water jet (AWJ) machining is a non-traditional manufacturing process that utilizes a high-velocity jet of water mixed with abrasive particles to cut materials. This method is prized for its ability to machine a wide variety of materials, including metals, ceramics, and composites, without inducing significant thermal damage or stress on the workpiece [1–6]. However, a critical challenge associated with AWJ machining is the erosion of active components, such as nozzles and mixing tubes, which are exposed to the high-speed abrasive-particle-laden water jet. Understanding and reducing this erosion is essential for improving the durability and performance of AWJ machines.

The effectiveness of the AWJ cutting process is significantly influenced by the size and distribution of abrasive particles. Recent research has demonstrated that the disintegration intensity of abrasive materials during jet formation plays an essential role in determining

cutting performance. For instance, one study [7] evaluated the grain distributions of different abrasive materials, including alluvial garnet, recycled garnet, corundum, and olivine, after their formation in the cutting head. Using the geometric and logarithmic Folk and Ward method, the study assessed how abrasive concentration impacts grain distribution and, consequently, the effectiveness of the cutting process.

The various abrasives used in abrasive waterjet machining include garnet, aluminum oxide, olivine, silica sand, and silicon carbide, among others [8–11]. Among the various abrasives used in AWJ machining, corundum-based abrasives are particularly notable for their ability to cut extremely hard materials, such as ceramics. A recent study [12] explored the mass loss factor and geometrical changes in focusing tubes when using corundum abrasives, comparing their results with the more commonly used garnet abrasives.

In recent years, computational fluid dynamics (CFD) has emerged as a powerful tool for analyzing the complex fluid flows and erosion patterns within AWJ systems [13,14]. By simulating the interactions between the high-velocity abrasive particles and the machine components, CFD can provide detailed insights into the mechanisms of erosion and help in designing components that are more resistant to wear. In addition to experimental validation, CFD simulations can aid in the optimization of AWJ machine components by allowing engineers to test various design modifications in a virtual environment before implementation. This can significantly reduce the time and costs associated with experimental testing. For example, modifications in nozzle design and material selection can be simulated to predict their impact on erosion rates and machine longevity.

Previous studies have employed CFD to examine the multiphase flow-induced sand erosion in pipes [15–17], pipe bends [18–20], and complex geometries [21–23]. However, studies exploring erosion in AWJ components remain quite limited [24–27].

For instance, to better understand the role of abrasive grit interaction in the erosion process in AWJ machining, experiments were conducted in [24], using abrasive grits of varying shapes and mechanical properties, followed by a visual analysis and residual stress measurements. This study uncovered the key mechanisms necessary for the accurate modeling of AWJ machining operations.

Recent advancements in fluid-induced vibration sensing and multi-field coupling modeling, such as those presented in the works [28–30] on multiphase sink vortex-induced vibration, further emphasize the importance of understanding the complex interactions in fluid systems.

In AWJ machining, the nozzle is a vital component that directly impacts the process's performance, precision, and cost efficiency. Due to continuous exposure to high-speed jets and abrasive particles, the nozzle is highly susceptible to wear and erosion, necessitating frequent replacements. To address this challenge, one study [27] aimed to simulate nozzle wall erosion using CFD under various operating conditions. The findings demonstrated that different operating conditions significantly affect the erosion rates and interactions between water, air, and abrasive particles. Similarly, the investigation performed by Mostofa et al. [31] employed CFD to optimize the mixing of water, air, and abrasives in a multi-phase system. By modeling these interactions and tracking particles, the study showed that nozzle length and waterjet velocity significantly impacted the erosion rates at the nozzle wall. The $k-\epsilon$ turbulence model revealed that erosion was highest near the nozzle's initial zone and increased with nozzle length. Deepak et al. [32] utilized ANSYS software to study the impact of inlet pressure on the skin friction coefficient and jet exit kinetic energy. Their findings revealed that increasing the inlet pressure significantly raised the skin friction coefficient and enhanced the jet's kinetic energy. The performed analyses indicated that increasing the abrasive volume fraction led to notable reductions in both the skin friction coefficient and jet kinetic energy. Furthermore, research on the optimization of water jet nozzles, such as work focused on self-propelled water jet nozzles, underscores the significance of nozzle design parameters in influencing the jet flow field [33]. In this study, the authors utilized SolidWorks and CFD to simulate the effects of different nozzle sizes and arrangements on the jet flow within a pipeline. Their findings demonstrated that

nozzle inclination angles and aperture sizes significantly affected jet velocity attenuation and vortex formation, which are critical factors in optimizing nozzle performance.

To address the existing research deficiencies and emphasize the innovations of this study, it is important to note that, while previous investigations have primarily focused on isolated aspects of erosion in AWJ machining, they have often overlooked the complex interdependencies between the various factors that affect erosion rates and component durability. Prior studies have typically examined single variables, such as nozzle design or abrasive particle properties, without integrating these elements into a complete analysis that reflects the real-world conditions encountered in AWJ systems. This research fills this gap by conducting a comprehensive three-dimensional CFD analysis that not only simulates the behavior of abrasive particles within the fluid flow, but also quantifies the erosive effects on the critical components of the water jet cutting machine under varying abrasive flow rates and particle sizes. By identifying the critical wear points and establishing a clear relationship between particle size, abrasive flow rate, and erosion, this research offers a more integrated and thorough understanding of the factors influencing erosion in AWJ machining. This approach not only addresses the limitations of previous studies, but also contributes to optimizing the design and operational parameters of water jet cutting machines, thereby enhancing their efficiency and lifespan.

2. Materials and Methods

2.1. Granulometry of Abrasive Material

To study the influence of sand grain size on the erosion processes within water jet processing, it is necessary to analyze the granulometry of the sand and establish its degree of uniformity. In order to establish the average size of sand grains, it is necessary to undergo some steps presented below.

According to [34], the leachable component represents the part of the sand made up of very fine particles, which are found in the form of dust between sand grains or in the form of a film on their surface. In general, the leachable component consists of clay or bentonite.

As a working principle for the determination of the leachable component, the same method described in [35] was used. The method's principle for determining the leachable component in the case of garnet-type sand used being in the water jet cutting machine consists of washing with water a quantity of 20 g of sand and removing the dirty water by siphoning. In a Berzelius glass of at least 600 cm³, the amount of dry sand at 105 °C and about 475 cm³ of water was poured, after which, the mixture was boiled for about 4 min using an electric stove, as shown in Figure 1a. The mixture was stirred with a magnetic stirrer for 5 min. After stirring, the liquid was left to stand for 10 min after the dirty water was removed by siphoning, with this operation being repeated until the liquid became completely clear. According to the procedures presented in [34,35], the leachable component is determined with Relation (1), and the masses are expressed in grams.

$$C_{lev} = \frac{m_{1i} - m_1}{m_{1i}} \times 100, [\%] \quad (1)$$

where m_{1i} represents the mass of the initial sand sample [g], and m_1 represents the mass of the sand sample after separating the leachable component, [g].

It was found that, after the first washing of the sand, the amount of water in the glass was quite clear, leading to the conclusion that the sand was very clean. Since it would be almost impossible to determine the difference in mass between the washed and the original sand, a value for the leachable component of less than 0.02% was estimated.

To determine the granulation, sand was sifted (from which the leachable component had been removed) using a device called a granulometer, which had in its composition a set of sieves arranged in ascending order from the tray, as shown in Figure 1b. The mesh lining was chosen according to [36,37] with the following mesh side dimensions in mm: 1; 0.8; 0.5; 0.315; 0.25; 0.1; and 0.063. A sample of 50 g of washed and dried sand was used, which was subjected to sieving for about 10 min. The remaining sand on each sieve, including

the tray, was weighed using an analytical balance (Figure 1c). Since the leachable part was very small (below 0.02%), it was not taken into account in the granulation calculation.

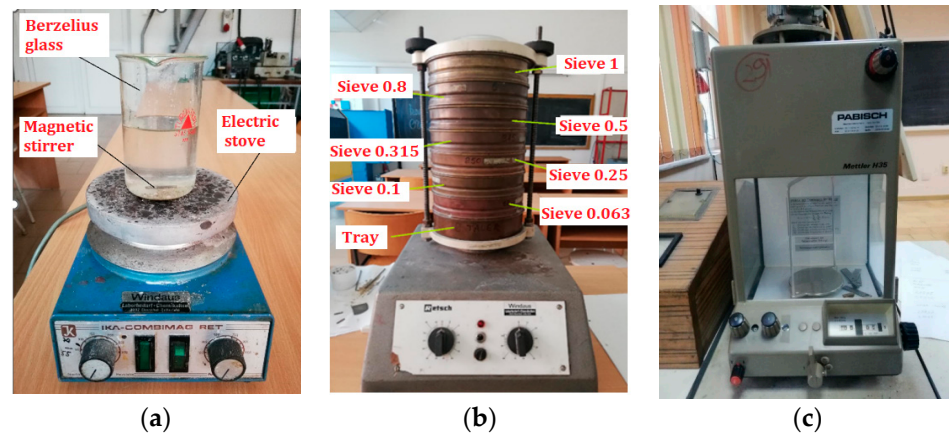


Figure 1. Granulometric equipment: (a) electric stove; (b) granulometer; and (c) analytical balance.

The remaining sand on each sieve (expressed as a percentage) was calculated, according to [34], with the formula:

$$\text{Residue on the sieve} = \frac{m_s}{m} \times 100 \quad (2)$$

where m_s represents the mass of the residue on the sieve, [g], and m represents the mass of the sample in work, including the leachable part. In the analyzed case, $m = 50$ g.

2.2. Determination of Sand Particles Shape Factor

The shape of the abrasive grains is an important factor in the erosion process, with different and significant influences on the materials subjected to erosion, as well as the process itself. Regarding the water jet processing method, the shape of the abrasive particles has an influence on the quality of the surfaces of the processed parts, the erosion rate, and the processing time, as well as on the active elements of the water jet processing installation, leading to a change in their degree of wear.

There are three notions that geometrically characterize an abrasive grain: configuration, roundness, and surface texture [38]. The configuration of the particle refers to its default shape, and from this point of view, particles can be spherical, prismatic, or blade-shaped. Roundness or angularity is a measure of particle smoothness or deviation from a circular shape. Surface texture refers to the presence or absence of small variations in shape, such as scratches or pinches, that appear on the surface of the particle. Surface texture has minor influences on the erosion process and will not be addressed in this study.

The configuration of a particle can be described in two ways [38]:

- ✓ Through three-dimensional (3D) analysis, in which a three-dimensional scan of the particle is performed;
- ✓ By two-dimensional (2D) analysis, where the abrasive particle is projected into a plane.

A 3D analysis of a particle requires a quite complex equipment to create a three-dimensional image, and this analysis is not recommended for small particles such as grains of sand. To establish the form factor, it is much easier to perform a 2D analysis due to the simplicity of the equipment for capturing images of sand grains. In a 2D analysis, it is assumed that the particle settles in the plane along two axes (generally along the longest and intermediate dimensions), and the shortest dimension of the particle will be along the axis perpendicular to the observation plane.

A study of the shape factor that characterizes the abrasive material particles used in the WUXI YCWJ-380-1520 water jet cutting machine is conducted after a 2D analysis using

the method presented by Wadell (1932), where the shape factor (sphericity) is defined as the ratio of the two surfaces characterizing the analyzed particle, as shown in Figure 2 [38].

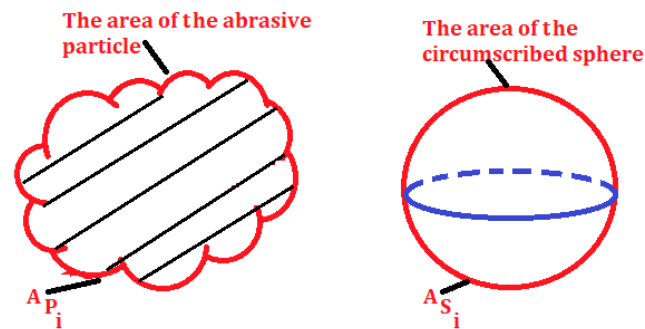


Figure 2. Determination of sand particles' shape factor.

The analytical expression for the calculation of the form factor according to the method developed by Wadell is given by expression (3) [38]:

$$\Psi_i = \frac{A_{Pi}}{A_{Si}} \quad (3)$$

where Ψ_i —shape factor of the particle, [-]; A_{Pi} —area of an abrasive particle measured in the plane, [μm^2]; and A_{Si} —area of the circle that inscribes the abrasive particle, [μm^2].

2.3. Determination of Abrasive Flow Rate

In finite element modeling of the abrasive fluid flow, it is necessary to impose some conditions related to the amount of abrasion that the machine generates. In this sense, the flow rate of the abrasion needed to process the materials must be evaluated. The determination of this flow rate was conducted through experimental tests. The water jet processing machine was equipped with an abrasive dispenser, as shown in Figure 3. The sand was transported from the abrasive tank and collected in the container (1), from where it flowed by gravity onto the roller (2). This roller was connected to a mechanical transmission system (3), and its speed can be set from the graduated potentiometer present on the machine controller, as shown in Figure 4.

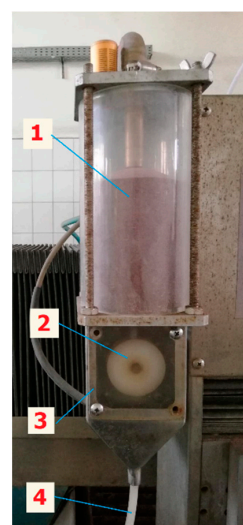


Figure 3. Abrasive material dosing system: 1—container; 2—roll; 3—the enclosure of the mechanical transmission system; and 4—drainage tube.



Figure 4. Abrasive control system.

Depending on the gradation of the potentiometer and, implicitly, on the speed of the roller, a flow of abrasion flowing by gravity is established through the tube (4). The sand is collected in a container and its filling time (t_u) is recorded for each experimental trial. The effective values of the abrasive mass flow rate are calculated using Relation (4):

$$Q_{abr,i} = \frac{m_{ai}}{t_u} \quad (4)$$

where m_{ai} represents the mass of the abrasive sample, [g], and t_u represents the sand filling time [s].

2.4. Abrasive Fluid Modeling by Active Elements of AWJ Machine

In this part of the study, a three-dimensional analysis of the abrasive fluid flow through the active elements of the WUXI YCWJ-380-1520 water jet cutting machine is performed. To create this model, the bibliographic references [39,40] are consulted, using the CFD type program from Ansys-Fluent APDL 2010, taking into account the standard $k-\omega$ mathematical flow model, as well as the SST model (Shear Stress Transport model). Within these two models, the turbulent viscosity is calculated with Relation (5), and ω is given by Relation (6), representing the specific dissipation rate [41].

$$\mu_t = \rho_a \frac{k}{\omega} \quad (5)$$

where k represents the kinetic energy of turbulence and ρ_a represents the density of the fluid.

$$\omega = \frac{\varepsilon}{C_\mu \cdot k} \quad (6)$$

where ε —turbulent kinetic energy dissipation rate and C_μ —constant related to fluid turbulence.

A geometric model of the three-dimensional flow analysis is presented in Figure 5, where only the liquid part of the cutting head of the water jet cutting machine is considered. This geometric model shows two entry zones, namely: the zone where the water enters the ruby hole under pressure and the entry zone of the abrasive particles entrained by the air flow. These two fluid parts are mixed and discharged through the orifice of the mixing tube, where the ambient pressure is considered.

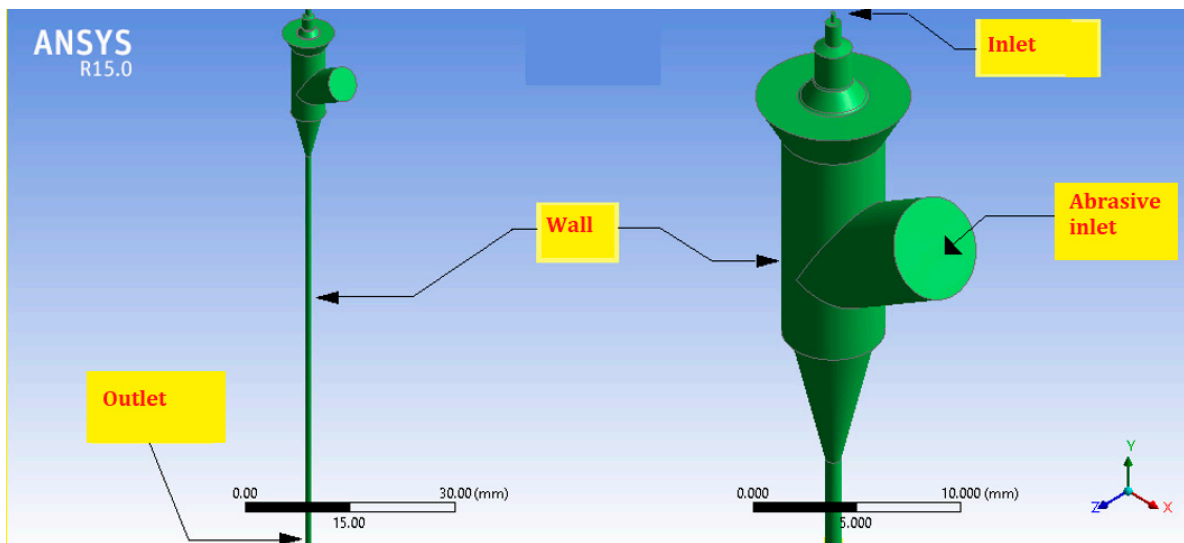


Figure 5. The geometric model of the liquid part made in Ansys-Fluent.

Figure 6 shows the meshing of the geometric model of the flow, performed with the “program controlled” option. Since three-dimensional analysis requires a more laborious calculation algorithm, the meshing must be chosen in such a way as to optimize the analysis time of the program. The program-controlled meshing option is used as it provides an efficient and effective means of generating a high-quality mesh tailored to the complex geometry of the flow domain. This method is selected based on its successful application in our previous study [42], where it yielded accurate and reliable results. Following this operation, 48,797 nodes and 244,831 elements are created.

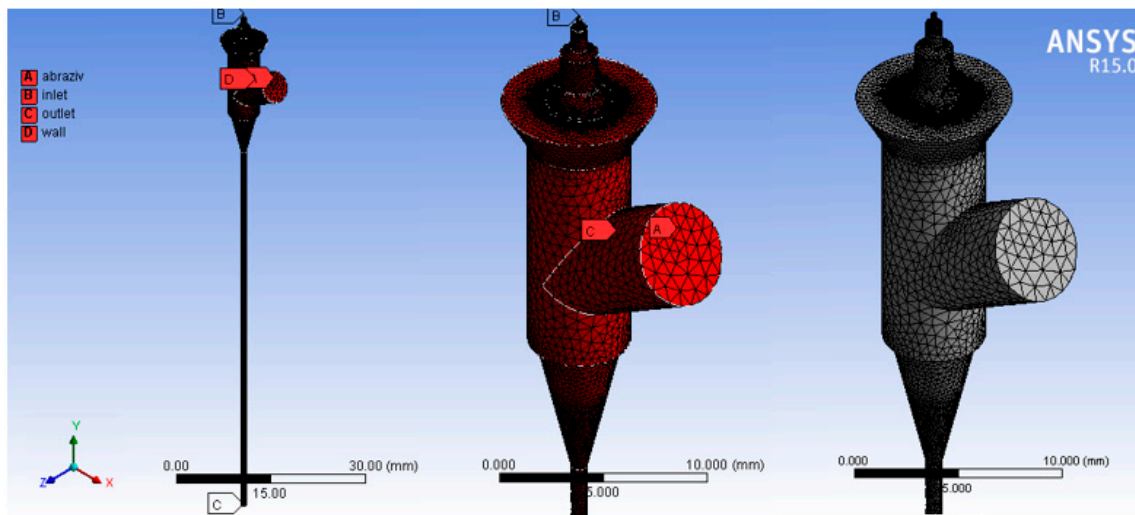


Figure 6. The geometric model of the liquid part.

Table 1 shows the data considered in the program to simulate the multiphase flow through the active elements of the water jet cutting installation. These data were entered based on experimental evaluations, within the limits of the means provided by the Ansys-Fluent program. The CFD simulation was performed for three sizes of sand particles with a form factor resulting from the abrasive analysis.

The CFD analysis of the active components of the cutting plant was conducted considering five abrasive flows in the range of divisions 0...20 on the machine controller. The numerical values of these flows are presented in Table 2.

Table 1. Data input to CFD simulation in Ansys-Workbench.

• Model:	- Multiphase flow	
	- Viscous—SST; k -omega	
• Abrasive material:	- Particle material: quartz [43,44];	
	- Particle diameter: $(190; 285; 380) \times 10^{-6}$ m	
	- Abrasive flow rate: according to Table 2, [kg/s]	
	- Form factor of the particle: 0.62	
• Fluid phases:	- Primary phase: water	
	- Secondary phase: air	
• Terms of connection:	- Abrasive input:	- Speed: 2.542 m/s [6]
	- Water inlet:	- Speed: 622.35 m/s [14]
	- Exit conditions:	- Pressure: 101,350 Pa [14]
• Notions related to calculation:	- Time: constant;	
	- Maximum number of iterations: 50	

Table 2. Sand flow through TA inlet.

Gradation Machine, x_a	0	5	10	15	20
Abrasive flow rate, Q_{abr} [g/s]	3.1807	4.8180	6.0110	6.7580	7.0600

In order to be able to create some theoretical models regarding waterjet processing, it is necessary to know some physical characteristics of the abrasive material used in the waterjet cutting machine. These characteristics are presented in Table 3, taking into account the data from [45,46].

Table 3. Physical characteristics of abrasive material.

Property	Density 10^3 [kg/m ³]	Specific Density	Hardness Mohs	Melting Point [°C]
Value	3.2...4.3	3...4	7.5...8	1250

3. Results and Discussion

3.1. Results Regarding the Granulometry of Abrasive Material

As mentioned above, a 50 g sample of washed and dried sand was used, which was subjected to sieving for about 10 min, and the remaining sand on each sieve, including the tray, was weighed, with their values shown in Table 4.

Table 4. AWJ sand granularity.

Sieve Number/Mesh Side, [mm]	Granule Size, [mm]	Remain on the Sieve		The Sum of the Cumulative Percentages (Passing through the Sieve)
		[g]	% vs. Working Quantity (50 g)	
1	0.63–0.1	0	0	100
0.8	0.4–0.63	0	0	100
0.5	0.315–0.4	0.886	1.772	98.228
0.315	0.25–0.315	4.7294	9.4588	88.7692
0.25	0.16–0.25	44.1804	88.3608	0.4084
0.1	0.1–0.16	0.1972	0.3944	0.014
0.063	0.063–0.1	0.007	0.014	0
Tray	0–0.063	0	0	0

The remaining sand on each sieve was calculated, according to Formula (2), using the data obtained from Table 4.

The granularity of AWJ sand is graphically expressed in Figure 7 by directly representing the percentages of granular fractions obtained by sieving.

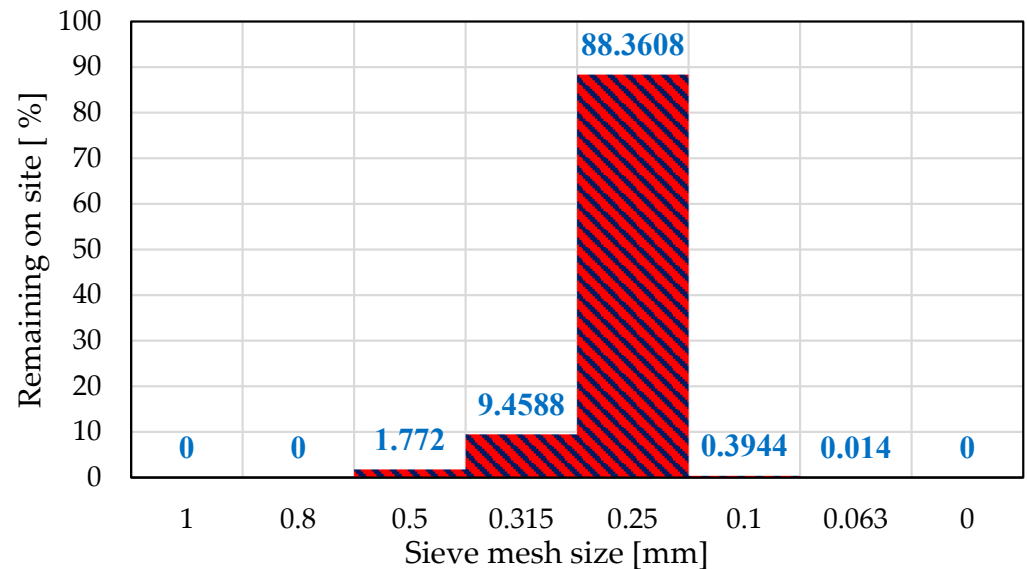


Figure 7. Abrasive material grain size histogram.

According to [34], medium grain size (M50) means the theoretical size of the sieve mesh through which 50% of the assessed amount of sand passes (excluding the leachable part). The average grain size M50 was determined from the grain size cumulative curve of the sand obtained by sieving, as represented in Figure 8. For the representation of this curve, a coordinate system was taken with the size of the mesh used on the abscissa and the cumulative passage through the sieve in percentage on the ordinate. On this curve, the average grain size M50 can be read, and in the analyzed case, this was a value of 0.285.

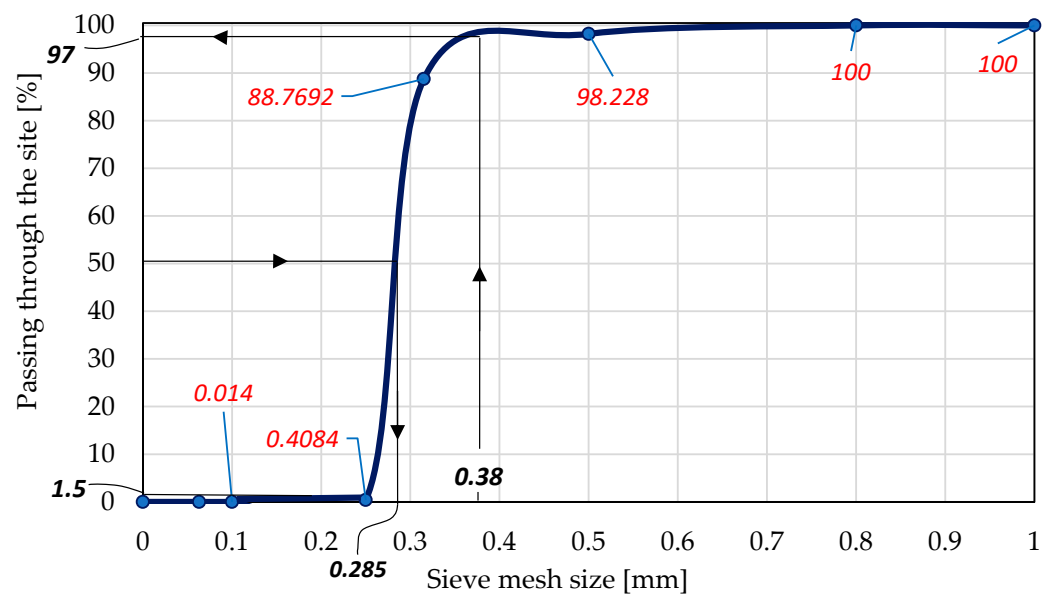


Figure 8. Cumulative abrasive material grit curve.

The degree of uniformity is calculated according to the average grain size M50 and is given by Relation (7) [34]:

$$GU = \frac{4}{3}M50 - \frac{2}{3}M50 \quad (7)$$

The values of the terms in Relation (7) are:

$$\frac{4}{3}M50 = \frac{4}{3} \cdot 0.285 = 0.38 \quad (8)$$

$$\frac{2}{3}M50 = \frac{2}{3} \cdot 0.285 = 0.19 \quad (9)$$

From the curve presented in Figure 8, it can be deduced that, through the sieve with the mesh side size of 0.38 mm, a quantity of sand of 97% passes, and through the sieve with the mesh size of 0.19 mm, the quantity of sand that passes through is 2%. With Relation (10), the value of the degree of uniformity is determined in the case of the analyzed sand:

$$GU = 97 - 2 = 95\% \quad (10)$$

The value of the degree of uniformity is 95%, so it can be concluded that the garnet-type sand used in water jet processing is very uniform [37].

From the cumulative granulation curve, it can be seen that the sizes of the sand grains are in the range of 0.25 mm. . . 0.32 mm. This can lead to the conclusion that, in the subsequent analyses that take into account the dimensional characteristics of the sand, values included in this range will be taken.

From the granulation curve, it can be concluded that there is no sand grain size greater than 0.8 mm, and in the size range 0.5 mm. . . 0.8 mm, the percentage value of the remaining sand on the sieve is 1.772%. Taking this into account, as well as the fact that the usual diameter of the mixing tube is 0.76 mm, it can be concluded that there is a small probability that a sand particle of a size that could lead to clogging will appear during processing the mixing tube and, of course, to the damage of the active components of the machine.

3.2. Determination of Sand Particles Shape Factor

The realization of the images of the sand grains, in order to establish their form factor, was achieved using an SEM-type microscope. An overview of the particle sample can be seen in Figure 9. The images were taken on a sample of twelve particles from an abrasive material sample, and these images are shown in Figure 10.

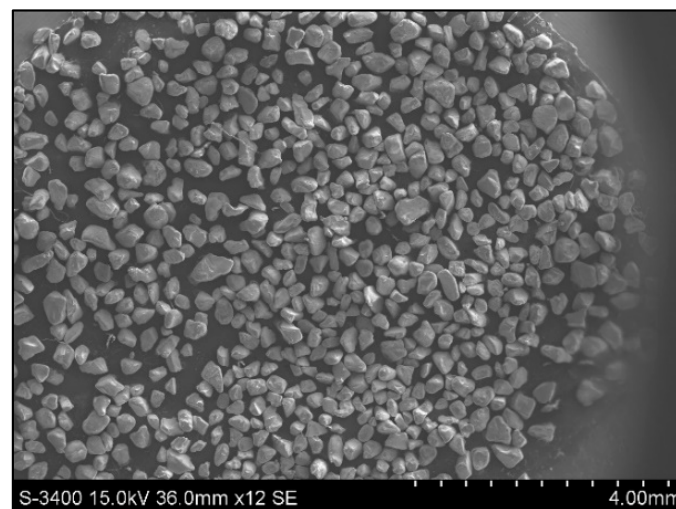


Figure 9. SEM images of the sand particles.

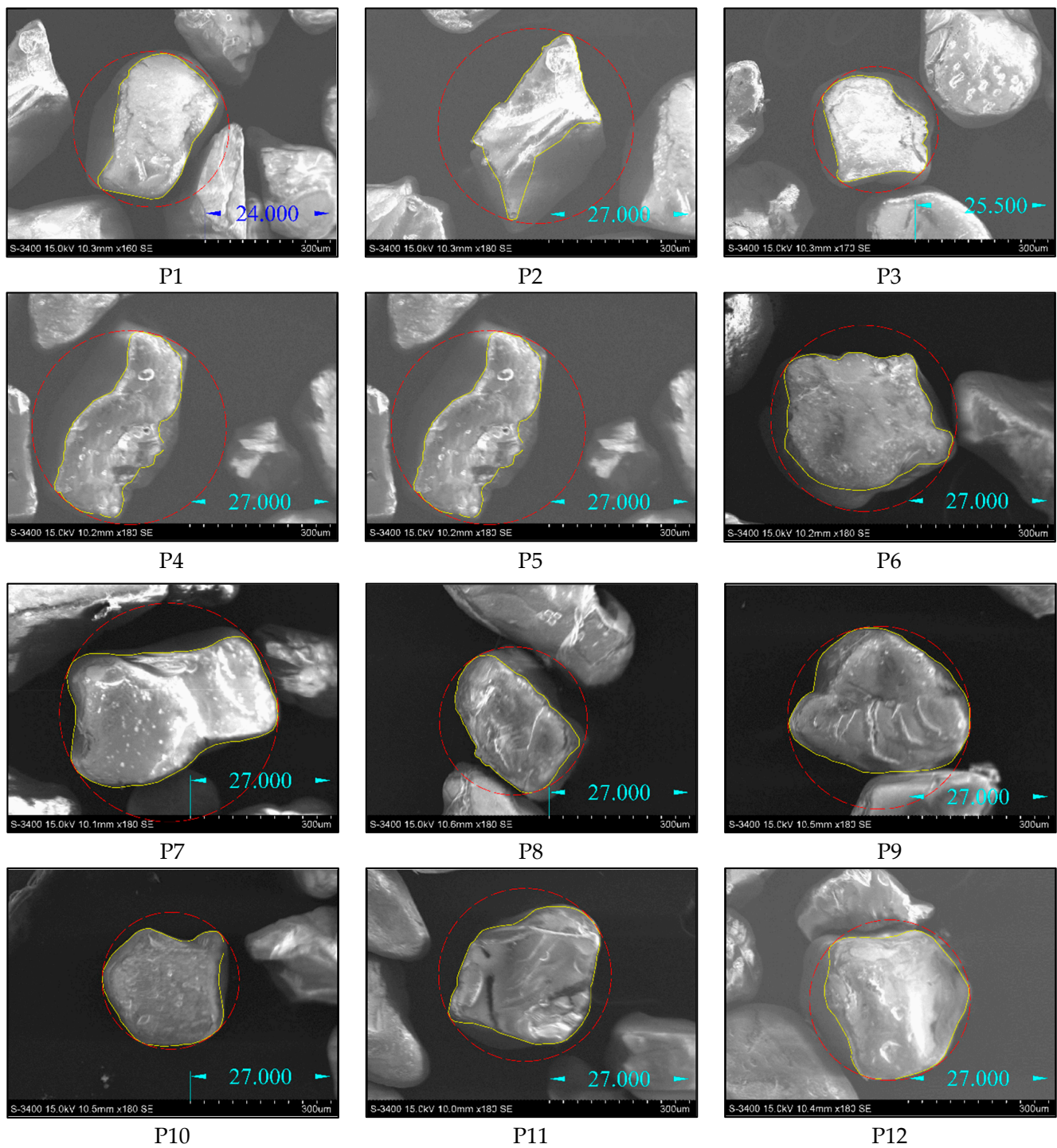


Figure 10. Sand particles analyzed for determination of shape factor.

Images were captured on a batch of particles with sizes between 200 and 300 μm . Determinations of the surface area of the sand particle (A_{pi}) and the area of the circle that inscribes the particle (A_{Si}) in the considered plane were made using the images taken on with SEM inserted in the AutoCAD graphic representation program. The surface characteristics actually calculated for the particle images presented in Figure 10, as well as the form factor calculated using Expression (3), are presented in Table 5.

Table 5. Shape characteristics of sand particles.

No. Image Particle	Particle Area, $A_P \times 10^5 [\mu\text{m}^2]$	Area Circumscribed by the Particle, $A_S \times 10^5 [\mu\text{m}^2]$	Form Factor, Ψ_i
P1	0.64917	1.10037	0.590
P2	0.46045	1.37234	0.336
P3	0.42821	0.64071	0.668
P4	0.59066	1.35736	0.435
P5	0.38884	0.66525	0.585
P6	0.81574	1.24621	0.655
Q7	1.04665	1.71943	0.609
P8	0.47862	0.79153	0.605
Q9	0.88192	1.20744	0.730
P10	0.52431	0.67682	0.775
P11	0.71004	1.07936	0.658
P12	0.74291	0.93088	0.798

The global shape factor that will be considered in the finite element simulations of the water jet flow was established as the arithmetic mean of the shape factors for each individual abrasive particle Ψ_{ii} , using Relation (11).

$$\Psi_i = \frac{\sum_{i=1}^{10} (\Psi_{ii})}{n} = 0.6202 \quad (11)$$

In conclusion, it can be said that the Wadell method used to determine the shape factor of sand particles is the most suitable and easy to apply in the case of small particles. This method performs the analysis in one plane of the particle and does not take into account its third dimension.

From the images captured with SEM, it can be seen that the edges of the particles are quite rounded, which leads to the conclusion that the erosion process on the machined part can be influenced by this factor, in the sense that the machine time needed to process the part can be changed.

From the expression of the global shape factor, it can be concluded that the shape factor was evaluated at the value of 0.62, meaning that the sand particles have a deviation of about 38% from a spherical shape. This form factor will be considered in all finite element simulations of the flow and erosion models in this study.

In Figure 11, the chemical analysis of the sand used in the water jet processing process is presented, performed using SEM.

From the chemical analysis conducted with SEM, it can be seen that the main component element is oxygen with a percentage weight between 30.7% (spectrum 5) and 56.2% (spectrum 1), from which we can draw the first conclusion that this sand is mainly made up of oxides. The second component element in the sand structure is Si, with a percentage weight between 13.5% (spectrum 5) and 18.5% (spectrum 3). The third component element is Al, with a percentage weight between 8.2% (spectrum 5) and 12.1% (spectrum 3), followed by Fe between 5.4% (spectrum 1) and 33.6% (spectrum 5). From the analyses carried out on the SEM microscope, it is possible to identify metals such as: Ti, in an amount of approximately 0.4%, Mn (1.4 . . 2.2)%, Ca (0.5 . . 2.9)%, and Mg (1.3 . . 5.3)%, and these metals can, in turn, form different oxides from the composition of sand crystals.

The chemical composition of the garnet-type abrasive material used in the water jet cutting machine is presented in Table 6, according to [47] and the images from Figure 11.

From the spectral analysis presented in Figure 11, as well as from the data presented in Table 6, it can be concluded that the abrasive material is mainly composed of silicon oxide (SiO_2), followed by iron oxide III (Fe_2O_3).

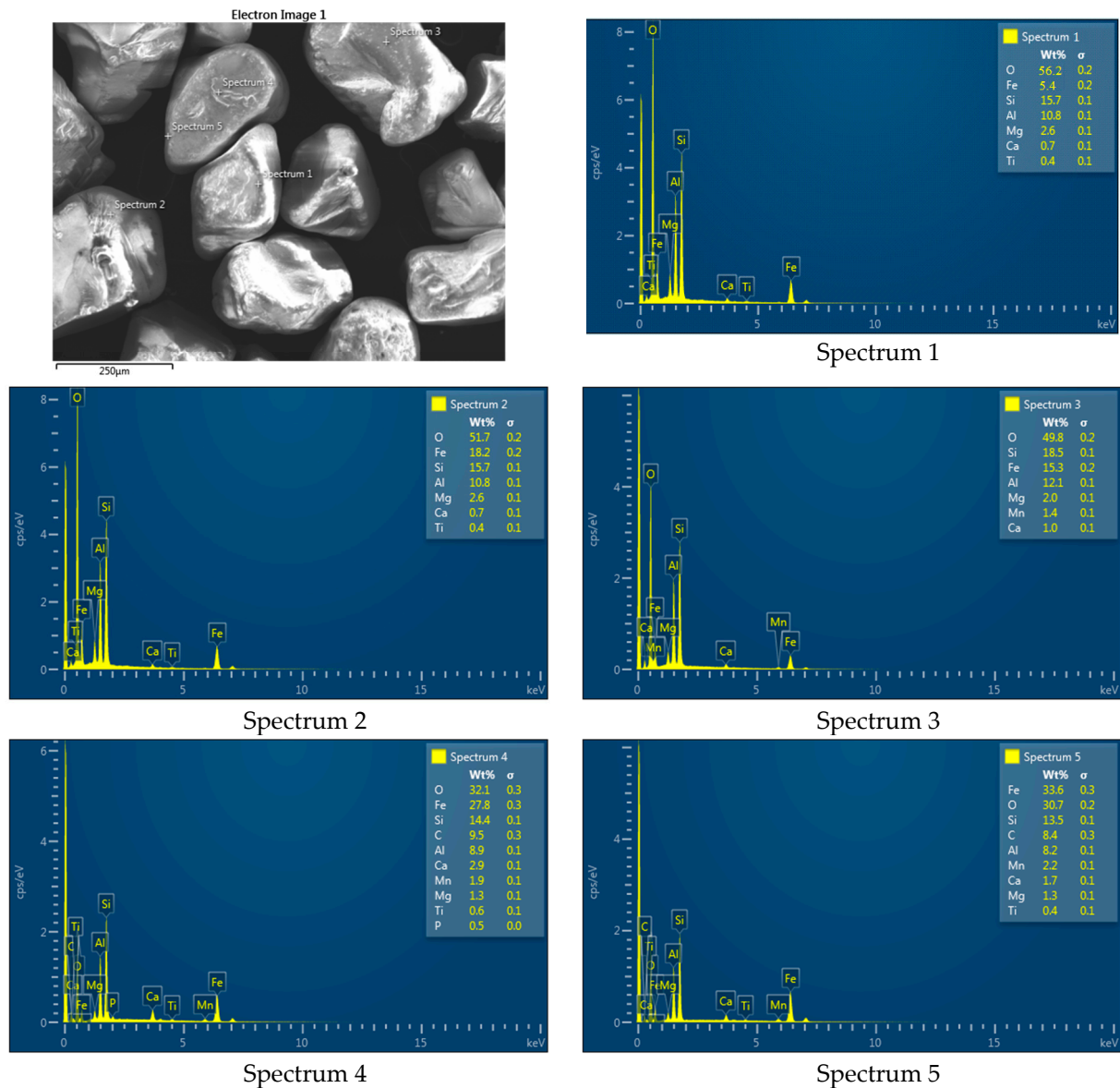


Figure 11. SEM spectral analysis of abrasive material.

Table 6. Chemical composition of abrasive material.

Chemical Compound	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	CaO	TiO ₂	P ₂ O ₅	MnO
Content [%]	37.20	27.80	16.60	4.70	4.95	2.5	0.05	0.5

3.3. Results Regarding the Abrasive Flow Rate

The variation in the sand flow depending on the grade of the machine is represented in the diagram in Figure 12. With Excel application, it was possible to approximate this flow through a theoretical curve.

The experimental curve from Figure 12 was generated considering a machine gradation range between 0 and 20 divisions. From some experimental tests, it was observed that an abrasive flow rate value above this limit can lead to an unnecessary consumption of abrasive material, with it being deposited on the surface of the processed part, leading to the shielding phenomenon and, implicitly, to defective processing of the material; energy is lost through particle–particle interactions.

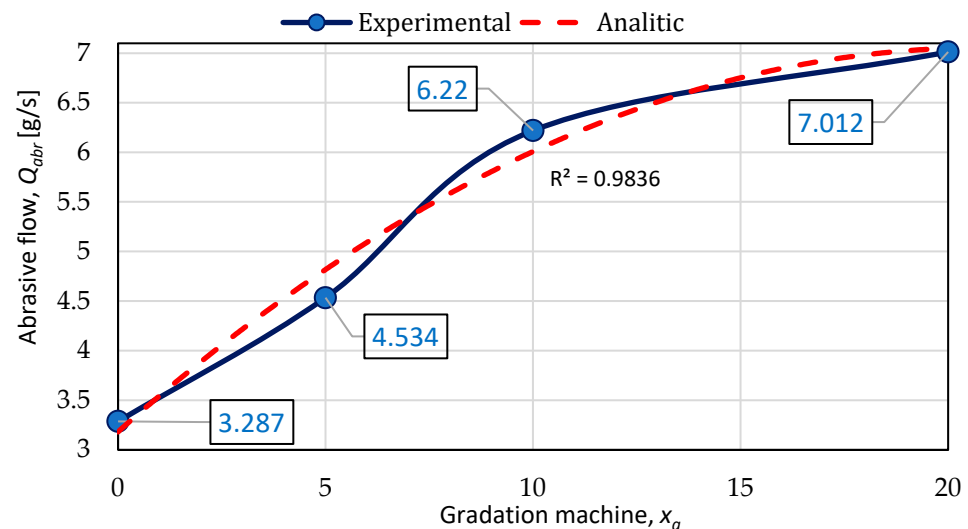


Figure 12. Graphical representation of abrasive flow.

The experimental curve can be approximated, most precisely, with a theoretical curve of order II with the mathematical form given by Relation (12). This parabolic approximation is only valid in the gradation interval 0–20, and in order to establish a distribution law for the abrasive flow over the entire gradation interval of the machine, experimental tests carried out for each division of the machine are necessary.

$$Q_{abr}(x_a) = -0.0089 \cdot x_a^2 + 0.372 \cdot x_a + 3.1807 \quad (12)$$

where Q_{abr} represents the abrasive mass flow rate, [g/s], and x_a represents the number of the division in the gradation of the machine corresponding to the flow of abrasive material actually consumed, [-].

3.4. Results of CFD Simulation

During the flow of the abrasive fluid through the mixing nozzle of the water cutting installation, two fluid circuits appear, whose flow lines are shown in Figure 13. It is observed that the maximum water flow velocity occurs along the ruby orifice and has a value of 633 m/s, decreasing in value as the water jet leaves the ruby nozzle, reaching values below 100 m/s inside the cylindrical steel body of the cutting head. Along the mixing tube, the water jet increases its velocity due to the narrowing of the flow section to around 160 m/s. From samples taken using the CFD-Post program mode along the mixing tube, values of the water jet velocity are obtained in the range from 183 m/s to 210 m/s. Also, in Figure 13, turbulence can be observed in the exit area of the liquid from the water nozzle, leading to the conclusion that the material of the part is affected by wear.

Since the fluid flows at different speeds along the CH of the water discharge installation, different pressure zones appear, whose distributions are shown in Figure 14. According to this analysis, it is observed that the maximum pressure has a value of 63.61 MPa, decreasing as the water jet leaves the mixing tube. At the exit from the ruby hole, a pressure value of 38.73 MPa is recorded (green area on the pressure map), and the difference between these two values is 24.88 MPa.

Figure 15 shows the air circuit developed inside the mixing head of the water jet processing machine. It is observed that the air enters the mixing head enclosure at a low speed (below 5 m/s), after which, it is directed by the high-speed water jet through the mixing tube cone and driven to speeds around 160 m/s. Figure 16 presents the trajectories of the sand particles obtained after the simulation.

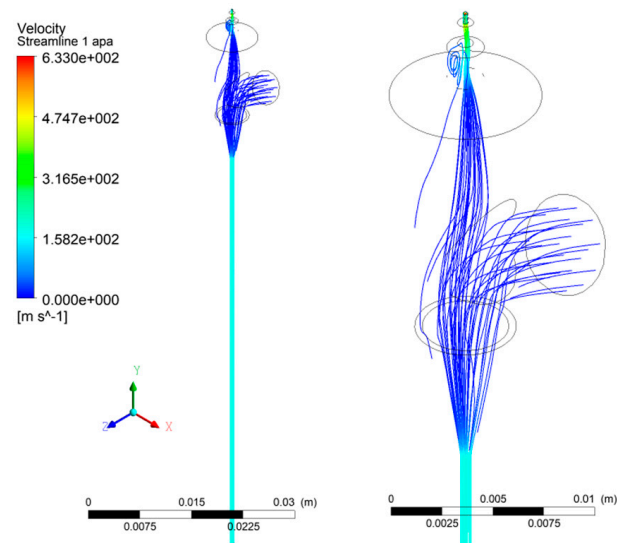


Figure 13. Streamlines of the abrasive mixture.

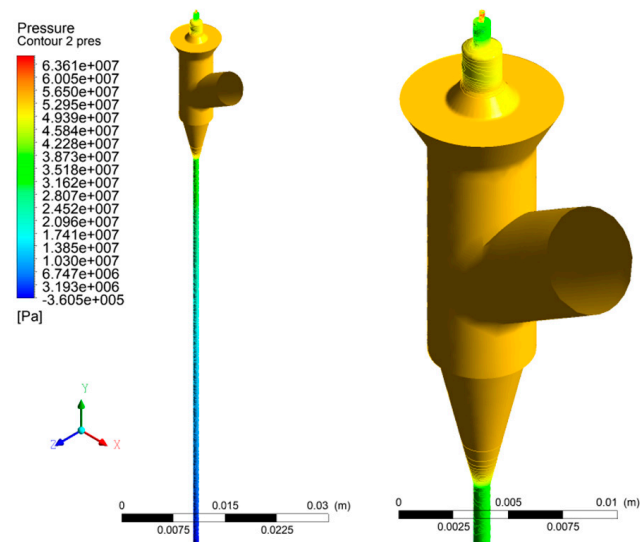


Figure 14. Pressure drop inside CH.

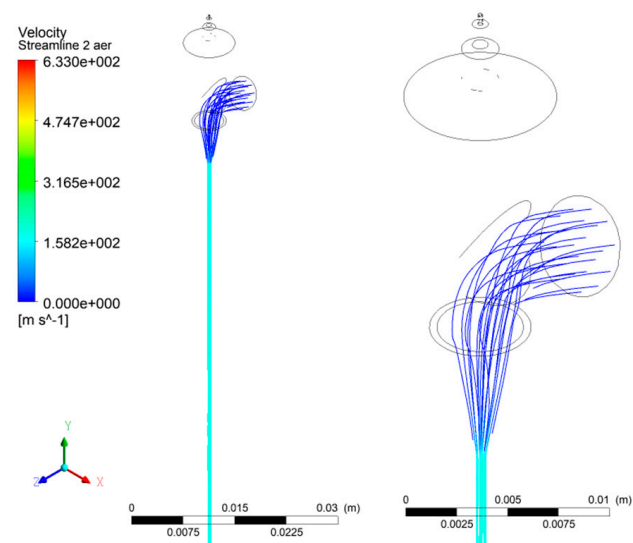


Figure 15. Streamlines of air inside the CH.

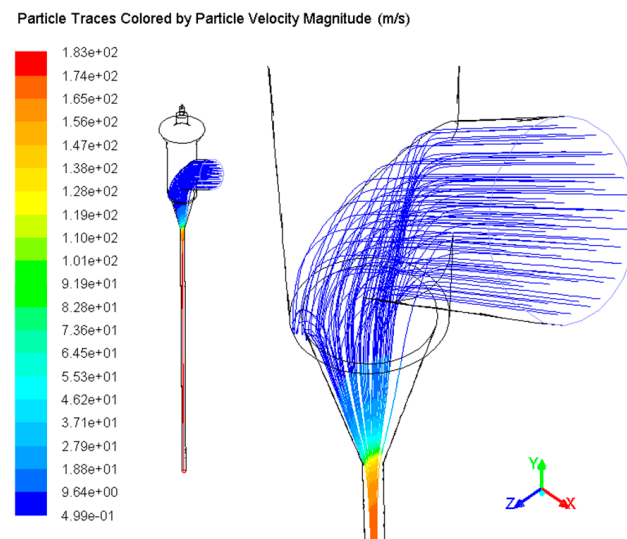


Figure 16. The trajectories of the abrasive particles inside the CH.

As can be seen, the abrasive particles are carried by the air current to the inside of the mixing head of the machine and driven by the water jet through the mixing tube up to a speed of 183 m/s, meaning that the sand particles are carried by the jet of water as if they are solidly linked to the movement of the liquid. Also in this figure, it can be observed that some particles deviate from their path and hit the annular surface at the base of the mixing cone, leading to the phenomenon of wear due to the erosion of the active elements of the machine.

3.4.1. Evaluation of the Erosion Rate (ER) Produced by Particles with 0.19 mm Diameter

The results obtained from the CFD analysis of the erosion produced by the particles with a diameter of 0.19 mm on the active components of the WUXI YCWJ-380-1520 water jet cutting machine are presented in Table 7. The contour of the erosion rate obtained in this case of particle size for each of the five values of the abrasive flow are presented, in ascending order of flow, in Figure 17.

Table 7. Erosion produced by particles with 0.19 mm diameter.

Gradation Machine, x_a	0	5	10	15	20
Erosion rate, $ER_{19} (\times 10^{-6})$ [kg/m ² ·s]	1.092276	1.308244	1.493233	1.652131	2.022878

In the images from Figure 17, it can be seen that the maximum values of the erosion rate are between $1.09 \cdot 10^{-6}$ kg/m²·s (Figure 17a) and $2.022 \cdot 10^{-6}$ kg/m²·s (Figure 17b), and appear in two isolated points located at the entrance to the conical zone of the mixing tube, while the minimum values appear towards the peripheries of these two zones.

It can be observed that, near these two points of maximum erosion, there are some areas whose maximum values are included in the range of $(3.43 \dots 5.76) \cdot 10^{-7}$ kg/m²·s. These secondary areas appear on the inner surface of the steel body of the cutting head, and these secondary zones increase in area and intensity with an increasing abrasive flow. This phenomenon can be attributed to the fact that particles with a smaller mass can be more easily diverted from their path by the currents developed in the fluid medium.

The diagram in Figure 18 shows the erosion rate as a function of the abrasive flow for the case when abrasive particles have an average diameter of 0.19 mm. On the experimental curve, an almost linear increase in the erosion rate can be observed up to the value of $1.652 \cdot 10^{-6}$ kg/m²·s, corresponding to an abrasive flow rate of 6.758 g/s (grade 15 on the

machine controller). After this value, the erosion rate suddenly increases to the value of $2.022 \cdot 10^{-6} \text{ kg/m}^2 \cdot \text{s}$, corresponding to an abrasive flow rate of approximately 7 g/s.

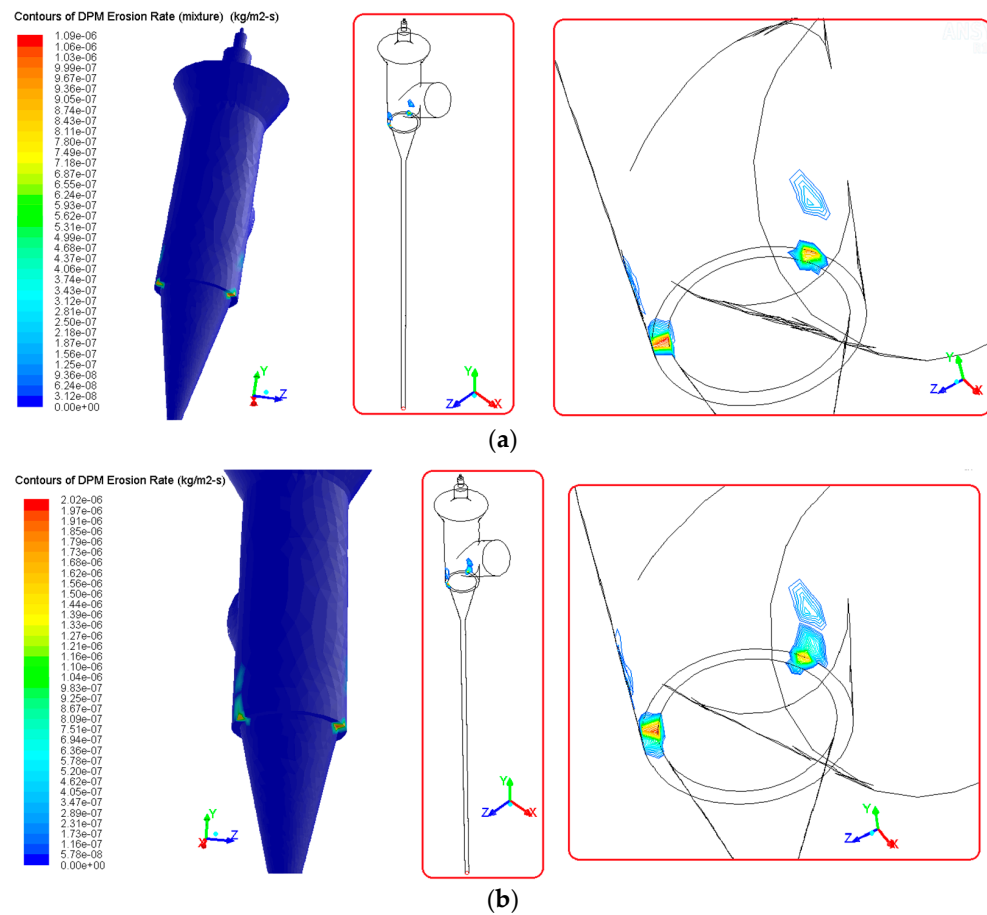


Figure 17. The erosion produced by particles with 0.19 mm diameter: (a)—gradation $x_a = 0$ and (b)—gradation $x_a = 20$.

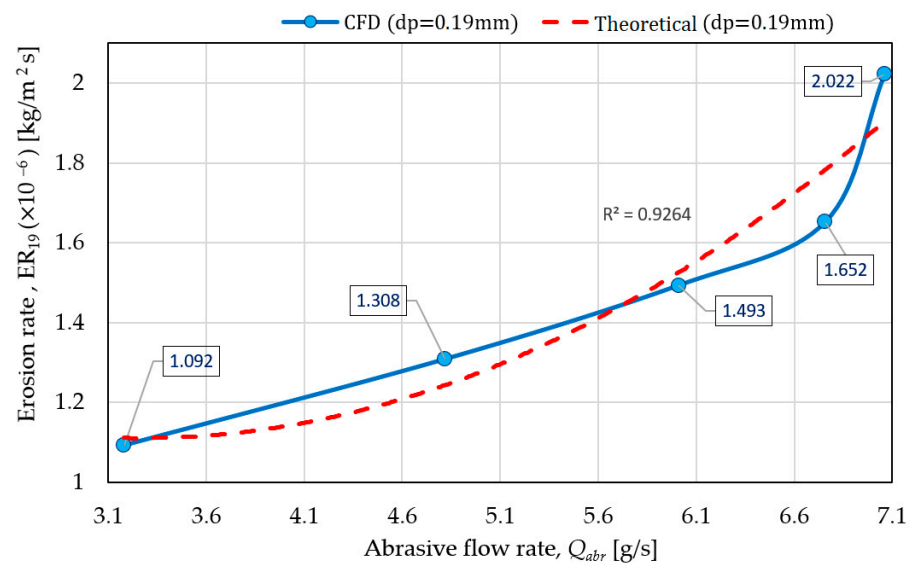


Figure 18. The ER graph produced by particles with 0.19 mm diameter.

For a better interpretation of this graph, a theoretical model was built, and the closest curve to the experimental graph was a parabola of the second order, whose expression is given by Relation (13).

$$ER_{19} = 0.0553 \cdot Q_{abr}^2 - 0.3612 \cdot Q_{abr} + 1.7004 \quad (13)$$

where ER_{19} represents the erosion rate produced by particles with an average diameter of 0.19 mm, [kg/m²·s], and Q_{abr} represents the abrasive flow rate of the machine in the range of divisions 0...20, [g/s].

Since the experimental graph has a linear dependence with a small slope over the largest range of abrasive flow rate, and a sharp increase occurs over a fairly narrow range, the erosion rate produced by the particles 0.19 mm in diameter can be approximated on the active elements of the cutting machine as having a linear dependence on the range of divisions between 0 and 20 (corresponding to the machine controller).

3.4.2. Evaluation of the ER Produced by Particles with 0.285 mm Diameter

The results obtained from the CFD analysis of the erosion produced by the particles with a diameter of 0.285 mm on the active components of the WUXI YCWJ-380-1520 water jet cutting machine are presented in Table 8. The contour of the erosion rate obtained in this case of particle size for each of the five values of the abrasive flow are presented, in ascending order of flow, in the images in Figure 19.

Table 8. Erosion produced by particles with a diameter of 0.285 mm.

Gradation Machine, x_a	0	5	10	15	20
Erosion rate, ER_{285} ($\times 10^{-6}$) [kg/m ² ·s]	2.456068	2.955192	4.456159	5.524016	6.119593

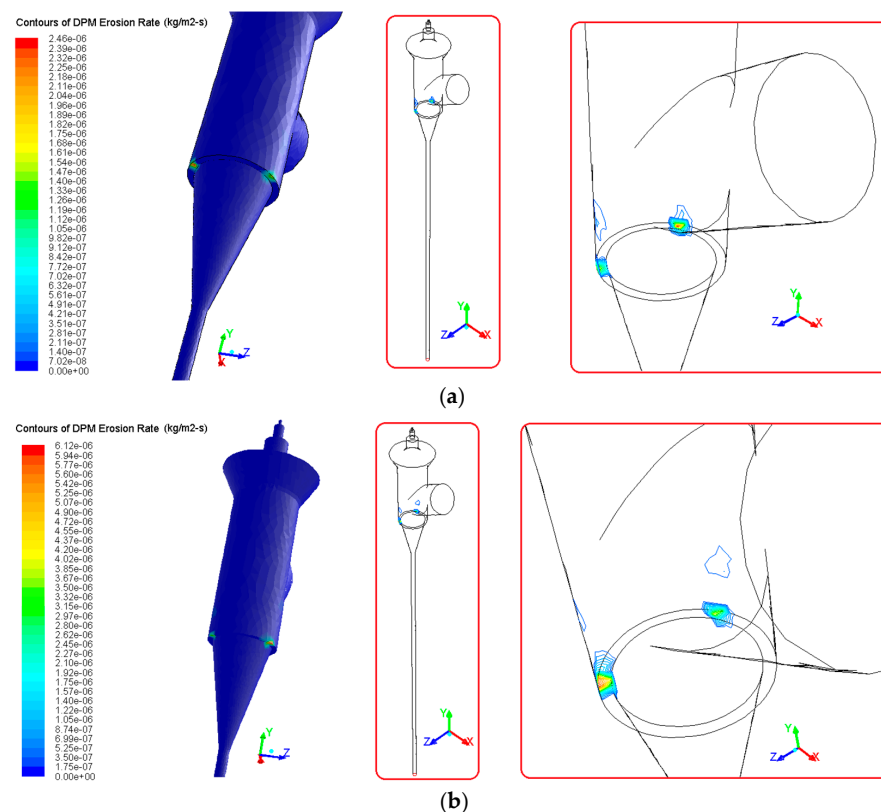


Figure 19. The erosion produced by particles with 0.285 mm diameter: (a)—gradation $x_a = 0$ and (b)—gradation $x_a = 20$.

In Figure 19, it can be seen that the maximum values of the erosion rate are between $2.46 \cdot 10^{-6}$ kg/m²·s (Figure 19a) and $6.12 \cdot 10^{-6}$ kg/m²·s (Figure 19b). As in the previous case, the points of maximum erosion occur in two isolated areas from the entrance of the fluid to the conical surface of the mixing tube. It is also observed that some erosion areas located on the inner wall of the steel body of the machine's cutting head appear near these two points. These secondary erosion zones have maximum values in the range of $(1.4 \dots 3.5) \cdot 10^{-7}$ kg/m²·s, with a lower intensity compared to the previous case, as well as a smaller expansion surface.

The diagram in Figure 20 represents the erosion rate produced by particles with a diameter of 0.285 mm on the active elements of the water jet cutting machine, depending on the abrasive flow rate. On the curve, an increase in the erosion rate can be observed with a smooth slope between a 3.1 g/s and 4.8 g/s abrasive flow rate, with the difference in the erosion rate being approximately $5 \cdot 10^{-7}$ kg/m²·s. On the second interval, there is a quicker increase in the erosion rate up to the value of $6.12 \cdot 10^{-6}$ kg/m²·s, corresponding to the gradation interval of the abrasion between 5 and 20.

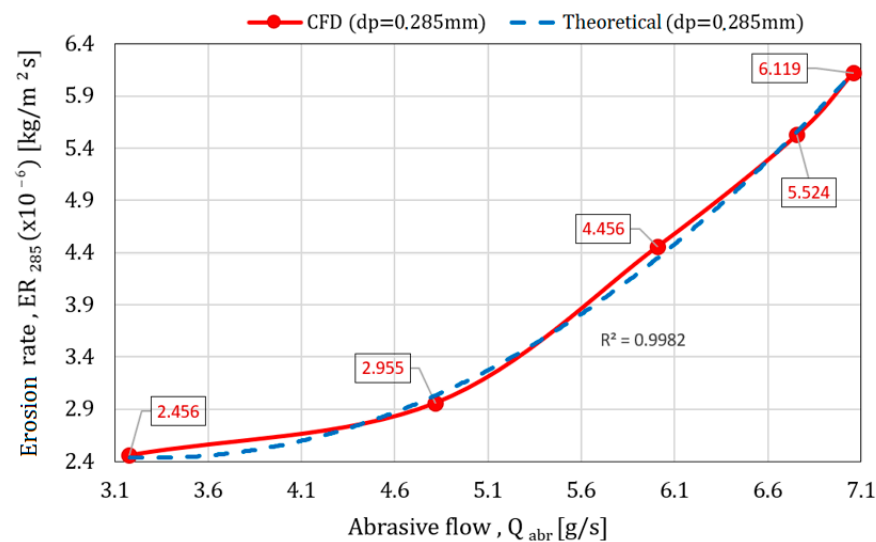


Figure 20. The graph of ER produced by particles with a diameter of 0.285 mm.

The experimental curve in the case of erosion produced by this particle size can be approximated with a second-order parabola, whose expression is given by Relation (14).

$$ER_{285} = 0.2635 \cdot Q_{abr}^2 - 1.7467 \cdot Q_{abr} + 5.3282 \quad (14)$$

where ER_{285} represents the erosion rate produced by particles with an average diameter of 0.285 mm, [kg/m²·s], and Q_{abr} represents the abrasive flow rate of the machine in the range of divisions 0...20, [g/s].

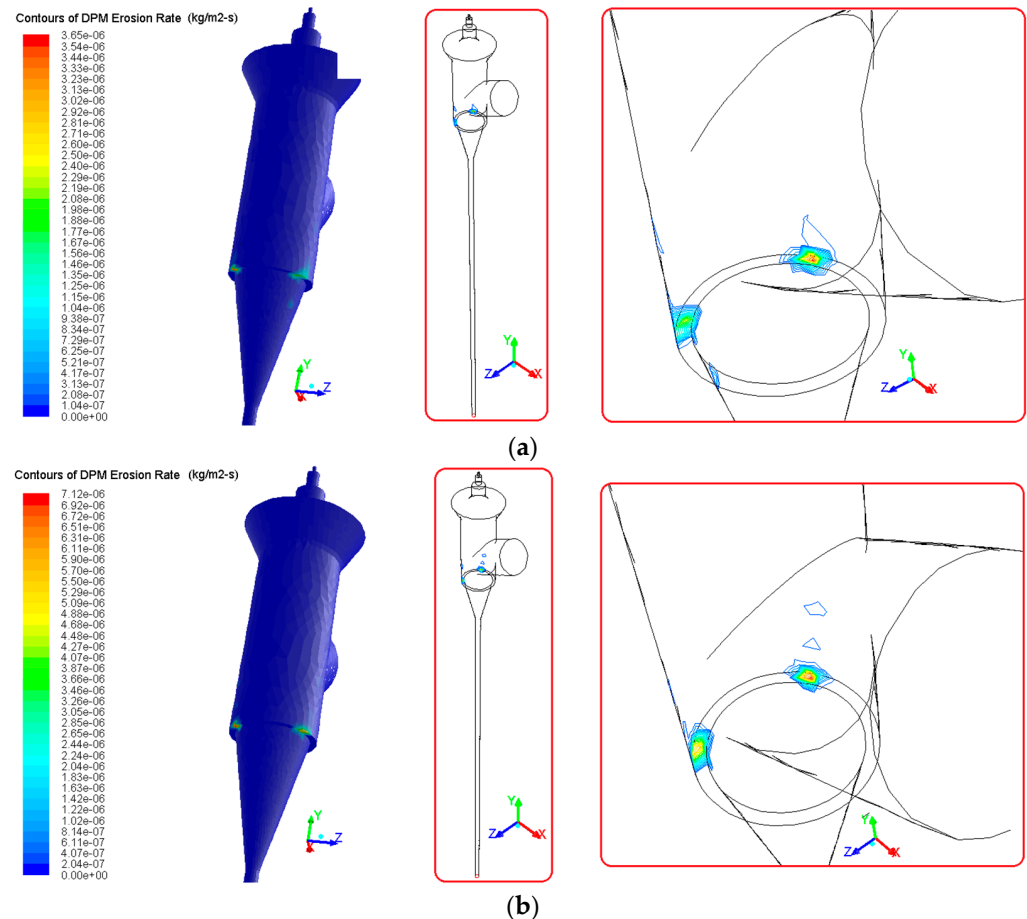
It is observed that this theoretical curve represented by a parabola is very close to the real model, which means that, in the case of particles with an average diameter of 0.285 mm (corresponding to the degree of uniformity), the erosion rate has a parabolic dependence up to an abrasive material flow rate of 7.06 g/s, i.e., up to 20 divisions on the controller. During most of the cutting process, erosion occurs with particles of 0.285 mm in diameter.

3.4.3. Evaluation of the ER Produced by Particles with a Diameter of 0.38 mm

The results obtained from the CFD analysis of the erosion produced by the particles with a diameter of 0.38 mm on the active components of the WUXI YCWJ-380-1520 water jet cutting machine are presented in Table 9. The contour of the erosion rate obtained in this case of particle size for each of the five values of the abrasive flow are presented, in ascending order of flow, in the images in Figure 21.

Table 9. Erosion produced by particles with a diameter of 0.38 mm.

Gradation Machine, x_a	0	5	10	15	20
Erosion rate, ER_{38} ($\times 10^{-6}$) [$\text{kg}/\text{m}^2\cdot\text{s}$]	3.646755	5.465438	6.715589	6.495351	7.123866

**Figure 21.** The erosion produced by particles with 0.38 mm diameter: (a)—gradation $x_a = 0$ and (b)—gradation $x_a = 20$.

In the images from Figure 21, it can be observed that the maximum values of the erosion rate are between $3.65 \cdot 10^{-6} \text{ kg}/\text{m}^2\cdot\text{s}$ (Figure 21a) and $7.12 \cdot 10^{-6} \text{ kg}/\text{m}^2\cdot\text{s}$ (Figure 21b), varying increasingly with an increase in the abrasive flow rate. As in the other two cases, around the two points of maximum erosion, several isolated areas appear, whose maximum values are in the range of $(1.04 \dots 1.82) \cdot 10^{-6} \text{ kg}/\text{m}^2\cdot\text{s}$. These secondary zones appear on the inner surface of the steel body of the machine's cutting head, but also on the inner conical surface of the mixing tube, as can be seen in Figure 21. This phenomenon occurs because larger particles produce a stronger but isolated impact, implicitly having a higher kinetic energy. That is, particles with a greater mass are more difficult to be deflected from their path by the currents developed during the erosion process.

In the diagram in Figure 22, a graphic representation is shown of the erosion rate produced by sand particles with a diameter of 0.38 mm on the active elements of the water jet cutting machine, depending on the abrasive flow rate. In this diagram, an increase in the erosion rate can be seen up to the value of $6.715 \cdot 10^{-6} \text{ kg}/\text{m}^2\cdot\text{s}$, corresponding to an abrasive flow range between 3.1 and 6 g/s. Next to division 15 on the car's controller, a decrease in the erosion rate is observed next to the value of $6.495 \cdot 10^{-6} \text{ kg}/\text{m}^2\cdot\text{s}$, after which it increases, to the value of $7.123 \cdot 10^{-6} \text{ kg}/\text{m}^2\cdot\text{s}$. This behavior leads to a theoretical

curve represented by a third-order polynomial function, whose expression is given by Relation (15).

$$ER_{38} = -0.0173 \cdot Q_{abr}^3 + 0.1218 \cdot Q_{abr}^2 + 1.0221 \cdot Q_{abr} - 0.2904 \quad (15)$$

where ER_{38} represents the erosion rate produced by particles with an average diameter of 0.38 mm, [kg/m²·s], and Q_{abr} represents the abrasive flow rate of the machine in the range of divisions 0–20, [g/s].

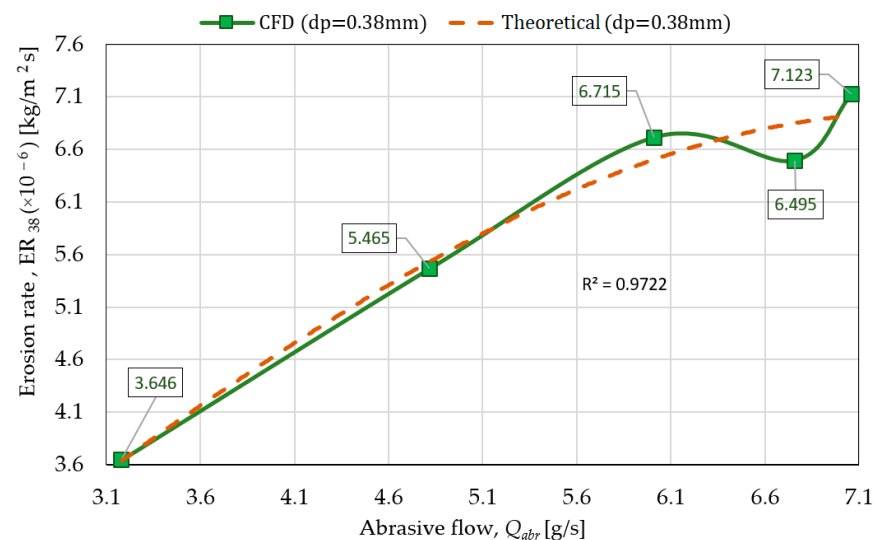


Figure 22. The graph of ER produced by particles with a diameter of 0.38 mm.

This shape of the diagram is given by the value of the erosion rate at a flow rate of 6.758 g/s (machine division 15), where, after several simulations of the program for the same abrasive flow rate, the erosion rate varies around $6.5 \cdot 10^{-6}$ kg/m²·s. From this, it can be concluded that the erosion rate produced by particles with an average diameter of 0.38 mm can be represented by a parabola of the third order.

4. Conclusions

This study presents a comprehensive computational fluid dynamics (CFD) analysis of the erosive effects of abrasive fluid flow on the active components of the WUXI YCWJ-380-1520 water jet cutting machine. The innovative aspects of this research are reflected in its detailed examination of the relationships between abrasive particle size, flow rate, and the resulting erosion rates on critical machine components. By integrating a granulometric analysis, experimental determination of abrasive flow rates, and three-dimensional CFD simulations, this study provides valuable insights that extend beyond the scope of previous research.

The study's main innovative aspects are:

- ✓ **Granulometric Analysis:** The study provides a precise characterization of the abrasive material used, identifying the particle sizes and distributions that are critical in understanding the erosion process. The use of M50 granulation (average particle size of 0.285 mm) as the basis for the erosion analysis is particularly innovative, as it reflects the most common particle size in practical applications, ensuring the relevance of the findings.
- ✓ **Shape Factor Determination:** By applying the Wadell method, the research introduces a thorough analysis of the shape factor ($\Psi_i = 0.622$) of abrasive particles, which significantly influences the erosion process. This approach allows for more accurate modeling of the particle interactions within the AWJ system.

- ✓ **Experimental Determination of Abrasive Flow:** The study establishes a direct relationship between the abrasive flow rate and control settings of the AWJ machine, providing a second-order parabolic model that accurately predicts flow variations. This experimental insight is important for optimizing machine operation and reducing unnecessary wear on components.
- ✓ **Three-Dimensional CFD Modeling:** This research advances our understanding of the erosion patterns within AWJ systems by simulating the impacts of different particle sizes (0.19 mm, 0.285 mm, and 0.38 mm) on the erosion of the mixing tube. The study identifies that the maximum erosion occurs at the entry surface of the truncated zone of the mixing tube, with erosion rates following distinct mathematical distributions (parabolic and polynomial) depending on particle size.
- ✓ **Correlation Between Particle Size and Erosion Rate:** The study demonstrates a clear, size-dependent increase in erosion rates, confirming that larger particles result in greater erosion due to their higher mass and kinetic energy. This correlation is supported by our findings, which align with existing research [48], further validating the study's conclusions.

The present work has some limitations, such as:

- ✓ **Assumptions in CFD Modeling:** The CFD simulations, while comprehensive, rely on certain assumptions regarding the abrasive flow, particle behavior, and material properties. These assumptions, necessary for the feasibility of the study, may not fully capture the complex, real-world interactions within the AWJ system.
- ✓ **Scope of Particle Sizes:** While the study examines a range of particle sizes, the focus on three specific sizes may limit the generalizability of the findings to other particle sizes or types of abrasive materials not considered in this analysis.
- ✓ **Experimental Validation:** Although the study incorporates experimental data for abrasive flow rates, the CFD model's predictions of erosion patterns would benefit from further experimental validation under varying operating conditions to ensure broader applicability.

In conclusion, this study contributes significantly to the optimization of AWJ machine components by providing a detailed analysis of how different factors influence erosion rates. The insights gained from this research can guide the design of more durable and efficient water jet cutting machines, ultimately enhancing their industrial application and lifespan. However, further research and experimental validation are recommended to address the limitations and extend the findings to a wider range of conditions and materials.

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