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THEORETICAL OPTIMIZATION OF AN INDUSTRIAL VACUUM CLEANER TANK FOR THE SEPARATION OF LIGHT AND HEAVY PARTICLES

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Abstract: *This research paper aims to establish a theoretical foundation for manufacturing a tank for an industrial vacuum cleaner designed to collect both light and heavy particles. Through the examination of existing approaches, we have concluded that a prefiltration step in the form of a cyclonic separator is essential. The authors have developed multiple tank variants designed to maximize cyclone separation efficiency for heavy particles while simultaneously ensuring efficient aspiration for light particles. The proposed designs also aim to identify variables that impact cyclonic separation and are not currently included in widely used models. Through rigorous finite element analysis and evaluation, we have selected the most promising model. By applying Lapple's equation, the chosen design was optimized for both types of particles. The results indicate exceptional collection efficiency of 99.99% for heavy particles. For light particles, the removal efficiency ranges from 32.68% to 97.21%, depending on the particle size.*
The findings of this study provide valuable insights into the development of a multipurpose industrial vacuum cleaner tank capable of effectively collecting light and heavy particles. Future research can explore strategies to improve the evacuation efficiency for light particles and the development of the current mathematical model of cyclonic separation.
Key words: *industrial vacuum cleaner, metal chips, solder fumes, cyclone separator, collection efficiency*

1. INTRODUCTION

Industrial vacuum cleaners are specialized equipment dedicated to the collection and removal of waste. They are widely used in commercial and productive settings to ensure optimal processes and environments.

The public interest in environmental preservation and occupational safety has increased significantly in the past decades. As a result, more stringent legislation has been passed in these fields at an international level. Consequently, various industries have adopted dedicated vacuuming solutions not only to adhere to these regulations but also to increase the quality of their products.

Currently there are many industrial vacuuming solutions available on the market for a variety of applications. Unfortunately, these solutions are highly customized for specific applications and have a substantial cost. Those aspects make the implementation of such equipment infeasible for small-scale production companies, workshops, and research laboratories due to the diversity of applications that are being carried out in those facilities and their limited financial capabilities.

The core focus of this study revolves around the development and optimization of the design of a multipurpose industrial vacuum cleaner tank. This optimization process will draw upon existing equipment, current needs, prevailing mathematical models, and outcomes from finite element analysis. Our aim is to address the challenges faced by small-scale enterprises and research facilities by offering the theoretical base for an efficient vacuuming solution.

2. METHODS

As mentioned in the introduction of this article, the aim of the tank is to collect a large variety of particles. In this study, two distinctive categories of particles will be considered: light and heavy. A widely common type of light particle is solder. This material is broadly used in the electronics industry, where it is found as fumes consisting of particles with a size of 0.5 to 20 μm [1]. These particulates pose a significant health risk, given the presence of lead within most solder alloys, coupled with their relatively high density spanning the range of 7.26 to 11.34 g/cm^3 [2]. The heavy particles that were studied are aluminum and steel chips that are derived from machining operations. Typical densities for aluminum alloys and steel alloys amount to 2.7 g/cm^3 and 7.83 g/cm^3, respectively [3]. Given the dependency of particulate size to the machining parameters, 50 aluminum chips and 50 steel chips were randomly selected from the workshop of the Technical University of Cluj-Napoca to assess their size. The analysis of the samples resulted in the determination of 2.557 mm as the average diameter for an equivalently sized, spherical aluminum particle and a diameter of 1.505 mm for the steel particles.

Considering the significant differences between the two particle groups, it was concluded that in order to obtain high collection rates for both light and heavy particles, the latter ones would need to be separated from the airflow containing the light particles headed for the filtration media. An efficient preliminary filtration technique is cyclonic separation. This methodology finds extensive application across diverse industrial sectors to accomplish the segregation of solid particulates from a gas. Conventional cyclone design contains a central body with cylindrical upper part and conical lower part. An inlet that is tangential to the cylindrical body induces helical airflow. Two outlets, one in the upper part and one in the lower part enable the evacuation of clean air and separated particles respectively. The underlying operational principle is strongly tied to centrifugal and gravitational forces. One of the most popular mathematical models that describe this principle is that of C. E. Lapple. His work was further developed in the following decades, resulting in the following equation of cyclonic separation efficiency [4].

$$\eta_j = \frac{1}{1+\left(\frac{\sqrt{\frac{9\cdot\mu\cdot B_c}{2\cdot\pi\cdot\frac{1}{a}\left(h+\frac{H-h}{2}\right)\cdot\frac{Q}{A}\cdot(\rho_p-\rho)}}}{D_{pj}}\right)^2} \quad (1)$$

where: η_j – separation efficiency, μ – gas viscosity, B_c – diameter/width of inlet, a – diameter/height of inlet, h – height of cylindrical section, H – height of cyclonic separator, Q – volume flow rate, A – inlet's area, ρ_p – particle's density, ρ – gas density, D_{pj} – particle's diameter.

The Coynco BF 3 vacuum motor was chosen from the market as suitable for the considered application [5].

Multiple design variants for the tank will be realized with the objective of identifying the most suitable for both considered particles. To additionally identify potential other parameters that might affect the separation efficiency, variables embodied within equation (1) will be kept constant. The selection of the following design and analysis parameters was based on a constructive approach and the technical characteristics of the vacuum motor.

Table 1

Constant parameters for the design variants

Parameter	Symbol	Value	Unit
Air density	ρ	1.225	kg/m^3
Air viscosity	μ	$1.789 \cdot 10^{-5}$	N·s/m^2
Light particle density	ρ_{p_1}	11340	kg/m^3
Light particle diameter	D_{pj_1}	$2 \cdot 10^{-2}$	mm
Heavy particle density	ρ_{p_2}	2700	kg/m^3
Heavy particle diameter	D_{pj_2}	1.505	mm
Height of cyclonic separator	H	500	mm
Height of cylindrical section	h	300	mm
Width of inlet	B_c	38	mm
Height of inlet	a	38	mm
Area of inlet	A	1444	mm^2
Diameter of upper inlet	D	50	mm
Diameter of lower inlet	D_c	38	mm
Volume flow rate	Q	0.089	m^3/s

3. CONCEPTION OF DESIGN VARIANTS

In order to successfully accomplish the considered application, the ideal tank needs to obtain a high separation efficiency for heavy particles and a low efficiency for light particles. After computing equation (1) for light and heavy particles using the parameters presented in table 1, a separation efficiency of 99.96% is obtained for light particles and 99.99% for heavy particles. Given these results and the theoretical aspects presented earlier, the tank variants will be designed while taking into consideration the following criteria: minimum airflow velocity, minimum static pressure, cyclone homogeneity, fit in vacuum motor's limits.

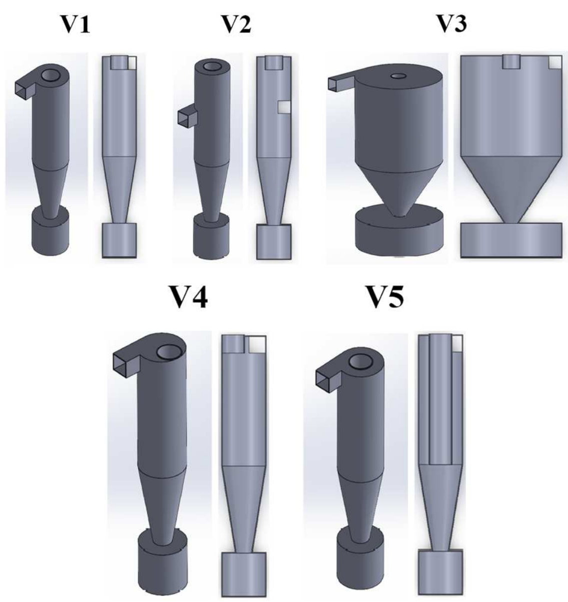

Fig. 1. Tank design variants

The first design variant, hereafter referred to as V1, is a standard cyclone separator model with a square inlet that serves as a reference for further models.

The second design variant, named V2, has the inlet placed below the vortex finder with the goal of imposing light particles a tendency to follow the trajectory of the air that exits the separator.

The third design, called V3 is identical to V1 with the exception of the separator's diameter which in case of V3 is three times that of V1. Behind this design is the assumption that the larger diameter will reduce the airflow velocity and subsequently the separation of particles.

The fourth variant, named V4, has its upper outlet off-centered. The purpose is to better capture the airflow that accumulates in the wall region of the separator due to the centrifugal force.

The last variant, referred to as V5, includes a prolonged vortex finder that extends all the way to the end of the cylindrical section. Behind this feature is the assumption that a sufficiently strong central suction column will reduce the particle rotation speed without affecting cyclone formation.

4. RESULTS

For each individual variant, the static pressure and tangential velocity profiles were analyzed in the vertical section illustrated in figure 1. The results were obtained using the Ansys Fluent 2023 R1 finite element analysis software.

4.1 Analysis of V1

Figure 2 illustrates the formation of the vortex through the slightly low-pressure column joining the two outlets. However, in the case of an effective cyclone, as shown in other studies [6], the static pressure in the central column tends to reach zero. Furthermore, the light differences in static pressure in the central air column indicate a weaker tendency of particles to exit the separator through the upper outlet. The maximum static pressure is significantly higher than the limit value of 32000 Pa indicated by the manufacturer of the Coynco BF 3 vacuum motor [5].

Next figure presents the distribution of tangential velocities in the analyzed section. The cyclone is better highlighted in this figure, compared to the previous one. Although the inlet velocity is just over 61 m/s, the cyclone separator achieves a remarkable performance in accelerating this flow almost twofold. This indicates increased performance in cyclonic separation, unlike shown in the previous figure. Another aspect that supports this conclusion is the presence of portions of minimum tangential velocity, in the peripheral zones, in close proximity to the tank walls. Minimum tangential velocity zones indicate particle deceleration and gravity-driven collection.

4.2 Analysis of V2

In the static pressure figure, the cyclone formation is even less pronounced. Another aspect that is noticeable in figure 2 is the substantially lower static pressure compared to the V1 separator.

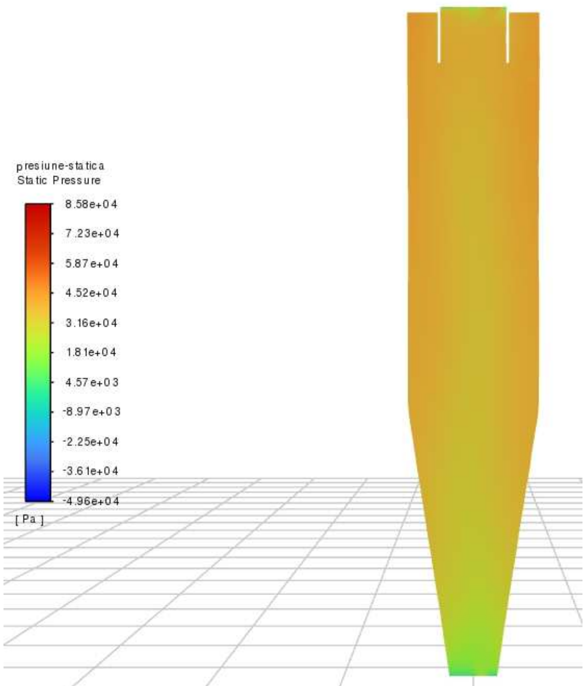

Fig. 2. Static pressure profile for V1

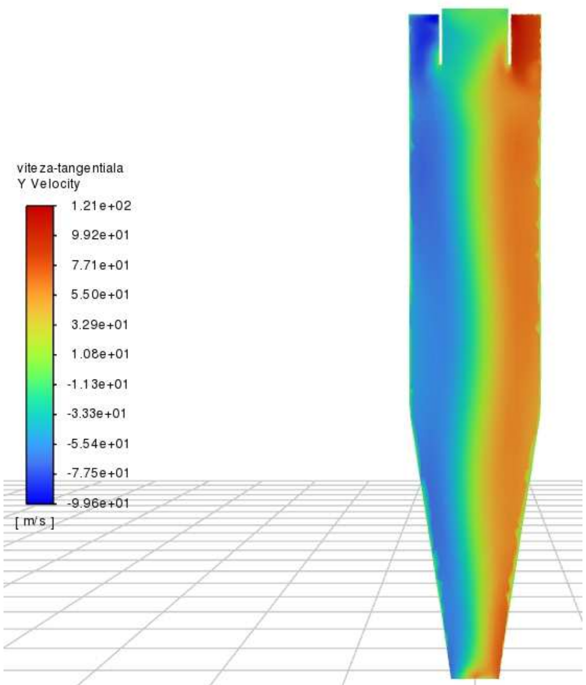

Fig. 3. Tangential velocity profile for V1

This finding carries an ambivalent connotation: on one hand, it is positive due to the fact that the recorded pressure falls below the nominal value presented in the motor specifications; on the other hand, it assumes a negative aspect as reduced pressure implies more difficult aspiration of heavier particles.

As predicted by the static pressure distribution, the maximum tangential velocity recorded within the section of this variant is over 20% lower than that of the V1 separator, given that the inlet flow velocity remains constant. This outcome partially corroborates the hypothesis underpinning the realization of this design variant, wherein the placement of the inlet orifice beneath the vortex finder negatively influences cyclonic separation performance. Furthermore, conspicuous perturbations in the flow pattern are evident, accentuated by the sinuosities at the cyclone center. Analogous to the prior variant, regions of minimal velocity near the cyclone walls are present, indicating the air flow's contact with the separator surface.

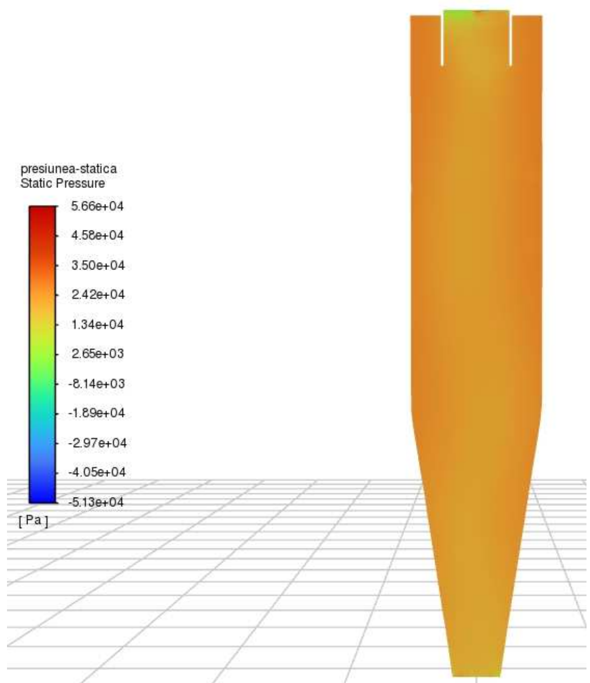

Fig. 4. Static pressure profile for V2

4.3 Analysis of V3

The central isobaric column, depicted in green, signifies the cyclone center, which is particularly well-defined in the case of the V3 variant. While this static pressure map is still divergent from the presentation norms in specialized literature, a robust tendency toward aspirating the flow through the upper exhaust orifice is noticeable in this case. Based on this depiction, it can be stated that the enlargement of the section enables the creation of multiple levels of static pressure. Furthermore, this variant does not exceed the vacuum motor's operational limits. The localized zones where the value of 32000 Pa is exceeded are positioned within the exhaust regions and exhibit turbulent characteristics, hence they do not disqualify this design variant.

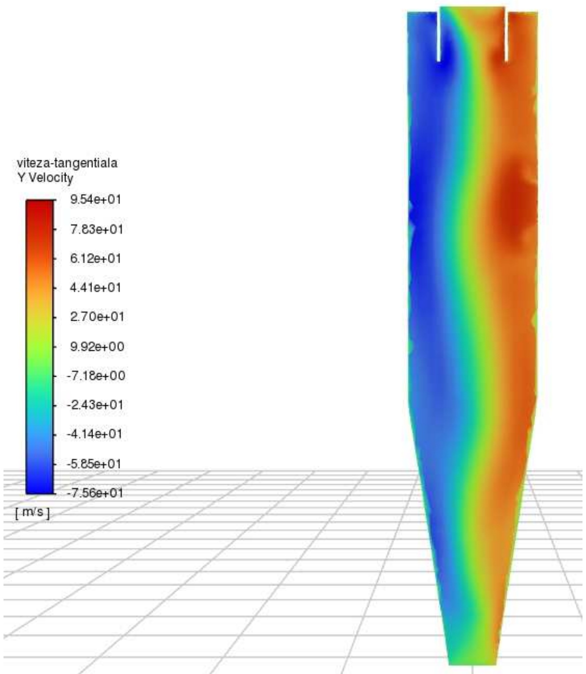

Fig. 5. Tangential velocity profile for V2

The tangential velocity profile confirms the hypothesis that underpins the development of the V3 variant. The maximum tangential velocity recorded in the analysis is approximately 78.7 m/s, being the lowest among all design variants examined so far. While the initial reasoning was based on the idea that a larger rotational radius will generate a decrease in the airflow's tangential velocity, the concept of flow section seems to be the primary cause for this outcome based on the obtained results. Specifically, it is observable that the blue and red areas are significantly larger for the V3 configuration compared to the other two design variants. These regions denote the flow sections of the aspirated airflow. With the area of these sections being greater, according to the Bernoulli principle, a reduction in flow velocity occurs, inversely proportional to the increase in the flow section.

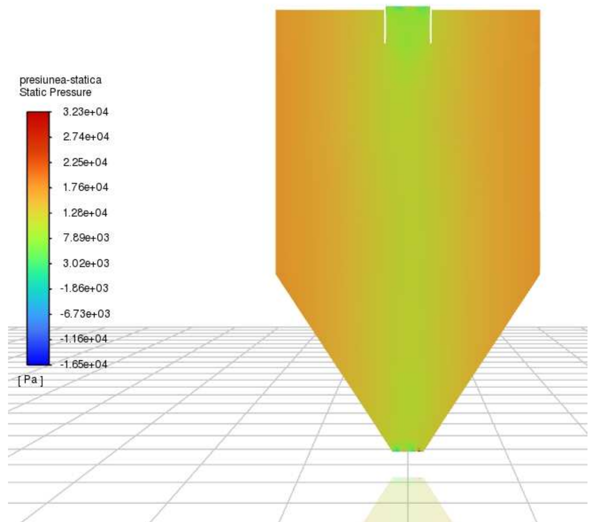

Fig. 6. Static pressure profile for V3

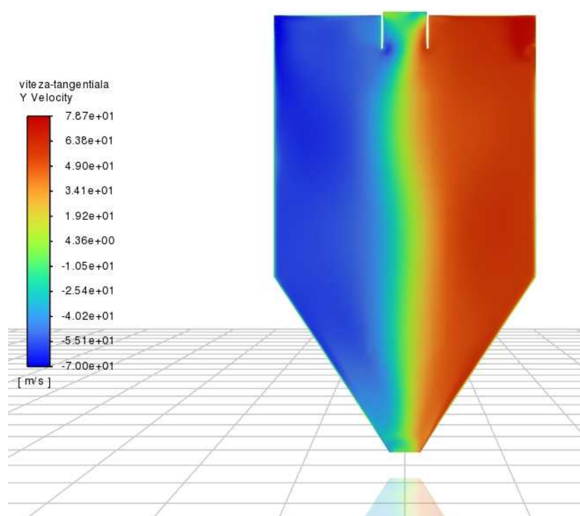

Fig. 7. Tangential velocity profile for V3

4.4 Analysis of V4

Figure 8 depicts the cyclone formation most clearly among all design variants proposed so far. Nonetheless, this phenomenon is primarily attributed to a drastic reduction in the maximum static pressure recorded. Consequently, the absolute pressure differential between the central section and its extremities is not as substantial as in prior cases, leading to a significantly smaller scale and thereby emphasizing small pressure differences more prominently. On the other hand, the static pressure diagram validates the hypothesis underlying the conception of V4, which suggested that the off-center placement of the upper exhaust orifice destabilizes vortex formation. Furthermore, this outcome highlights the strong tie between the formation of a cyclone and the recorded pressure drop.

The maximum tangential velocity recorded during is also notably diminished in comparison to the preceding variants. This result confirms another part of the hypothesis behind the conception of V4, namely, that the off-center positioning of the upper exhaust orifice significantly decreases the airflow velocity. Another depicted aspect is the subtle contrast between the central region characterized by low tangential velocity and the peripheral region, where velocities were much more disparate in comparison to the other analyzed design variants.

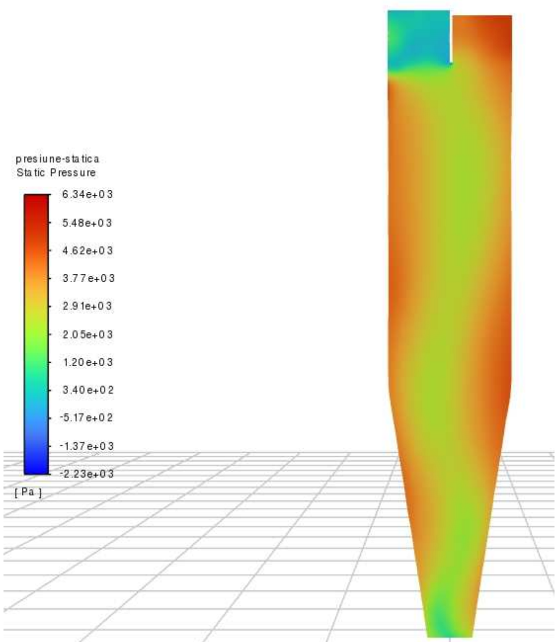

Fig. 8. Static pressure profile for V4

4.5 Analysis of V5

In the static pressure figure, the formation of the cyclone is clearly evident, represented through the ordered and contrasting arrangement of static pressure zones. This cyclone's formation aligns with patterns presented in other studies [6]. The maximal pressure zone stretches along the vast majority of the peripheral region. Towards the center of the cyclone, static pressure declines until it reaches its minimal value at the cyclone's core.

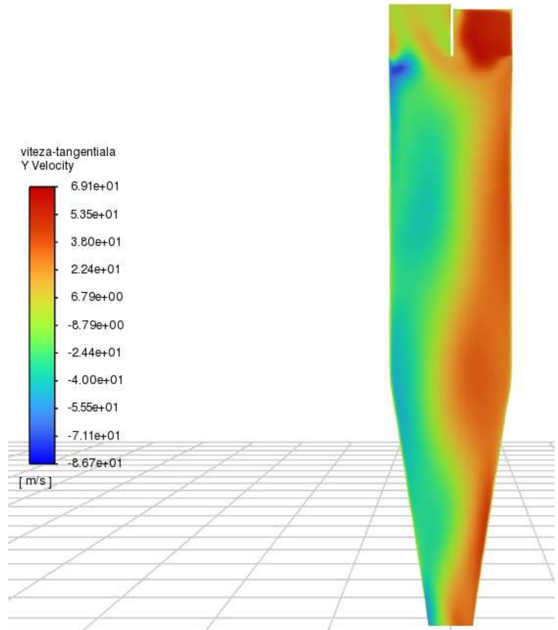

Fig. 9. Tangential velocity profile for V4

This substantial reduction is indicated not only by the color spectrum employed in Figure 10, but also by the values indicated on the scale. Another essential aspect pictured in this diagram is the exceedingly low static pressure, nearly approaching zero, recorded within the vortex concentrator—a highly advantageous feature for the application of vacuuming light particles.

Figure 11 depicts a highly symmetrical arrangement of tangential velocities. The diagram complements the preceding figure in supporting the conclusion drawn in the preceding paragraph, asserting that the cyclone formed in V5 is the most homogeneous among all examined configurations. This aspect holds significant importance in obtaining enhanced collection and aspiration efficiency.

4.6 Comparison of the design variants

Based on the results of the finite element analysis described above, the five proposed design variants received a score from 1 to 5, where 5 is the highest, for each of the four criteria presented in the previous chapter. The results were centralized in table 2.

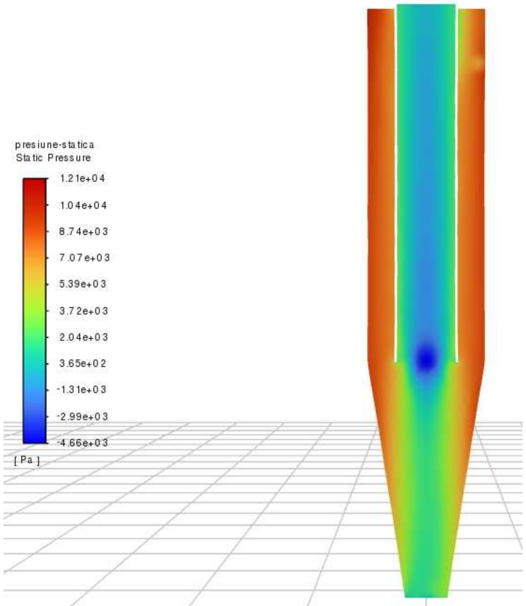

Fig. 10. Static pressure profile for V5

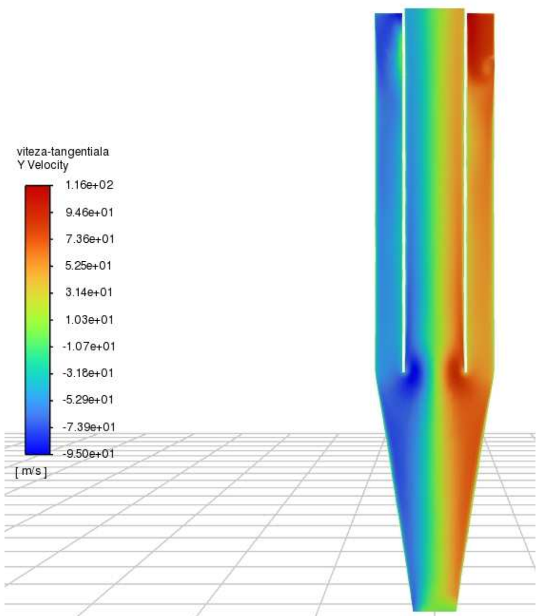

Fig. 11. Tangential velocity profile for V5

Table 2

Comparison of the presented design variants

Criteria \ Design variant	V1	V2	V3	V4	V5
Minimum air velocity	1	3	4	5	2
Minimum static pressure	1	2	3	5	4
Cyclone homogeneity	3	2	4	1	5
Fit in motor's limits	1	2	3	4	5
TOTAL	6	9	14	15	16

In conclusion, based on the scores obtained from the analysis, the V5 design is the most suitable for the extraction of both heavy and light particles. Based on the close scores for V3, V4 and V5, it is recommended to adopt elements from V3 and V4 in the optimization of V5.

4.7 Optimization of the selected variant

The first proposed variant based on V5 and V3 is presented in the figures below.

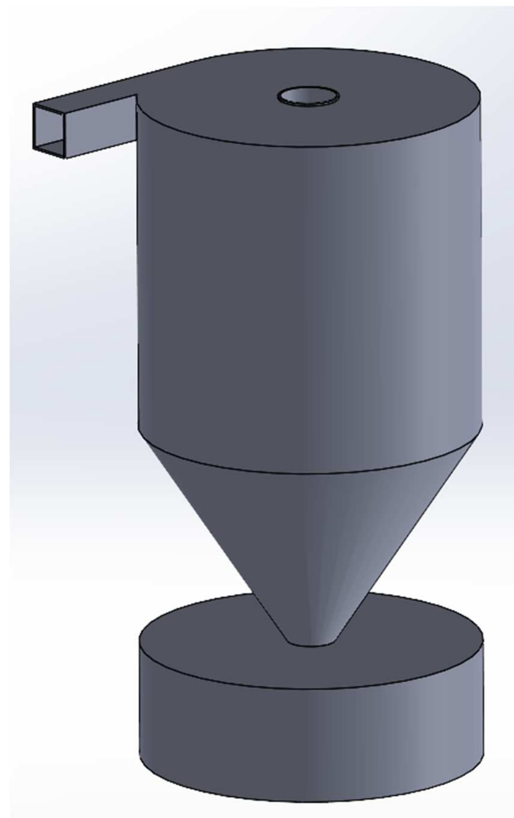

Fig. 12. Isometric view of the first proposed variant

As mentioned in the previous chapter, high separation efficiencies were obtained for both cases. Given these results, the goal is to identify the ideal parameters from equation (1) that result in the minimum value of η_{j_1} while maximizing the value of η_{j_2}.

According to the standards for industrial vacuum hoses, the only sizes that are suitable for vacuuming both metal chips and fumes are Ø50, Ø120 and Ø150 mm. After subsequently plugging the three values in relation (1) for both light and heavy particles, it was concluded that the optimum value for the inlet is Ø150 mm.

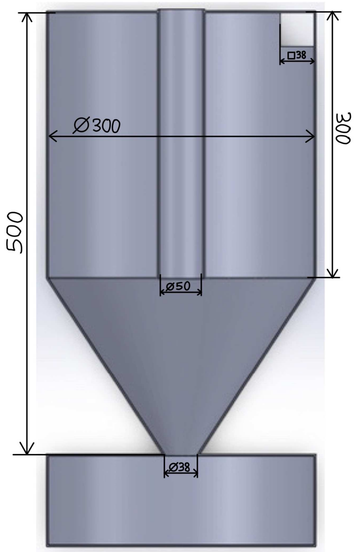

Fig. 13. Section view of the first proposed variant

By graphing equation (1) in relation to the height parameters h and H it was determined that decreasing the heights decreases the separation efficiency. As presented in the introduction of this paper, the height of the cylindric section cannot be lower than the size of the inlet. Therefore, we adopt the ideal h as 150 mm. In order to keep the already proven proportions and to maintain the collection capacity to a satisfactory level, parameter H was constructively adopted as 250 mm.

Given these two optimizations, the second proposed variant was obtained. This variant is depicted in the figures below.

As all potential geometrical optimizations have been exhausted, this particular configuration stands as the ultimate iteration in tank design.

By reducing equation (1) to a simplified form it can be stated that a reduction in volume flow rate results in a reduction of separation efficiency. Given the fact that the considered vacuum motor has a variable speed, a reduced speed, below the nominal value can be employed in the case of vacuuming light particles.

Because the volume flow rate cannot be zero, a volume flow rate value that is similar to that of other solutions on the market was selected. The value that obtains the best efficiency for vacuuming light particles without compromising vacuuming power is $Q = 0.02314\ [m^3/s]$. Considering all the operated optimizations and presented information, the relevant operating parameters of the final tank variation were centralized in table 3.

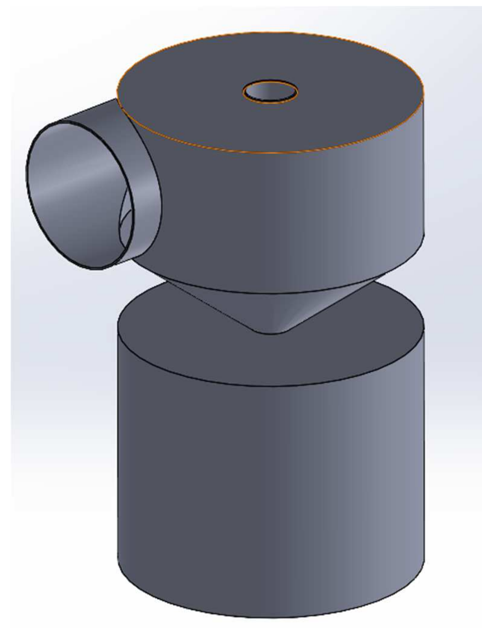

Fig. 14. Isometric view of the final variant

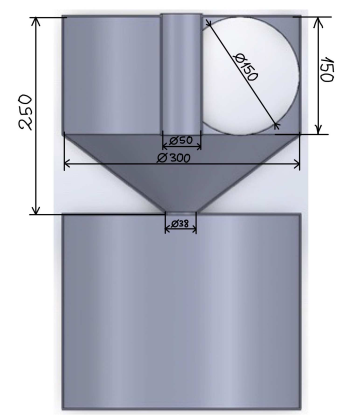

Fig. 15. Section view of the final variant

Table 3

Operating parameters of the final tank variant

Parameter	**Symbol**	**Unit**	**Light particles**	**Heavy particles**
			Value	**Value**
Max. pressure drop	ΔP_{max}	Pa	8320	32000
Nominal pressure drop	ΔP	Pa	6500	25000

Volume airflow	Q	m^3/s	0.02314	0.089
Heavy particle separation efficiency	η_{j_2}	%	-	99.99
Light particle aspiration efficiency	1-η_{j_1}	%	32.68 – 97.21	-

5. CONCLUSION

This scientific endeavor was directed towards creating a theoretical foundation for the design of an industrial vacuum tank capable of capturing both heavy and light particles, intended for use within workshops and research facilities.

Through an extensive review of literature, a precise definition of the aspiration application was obtained. By examining steel and aluminum chips as well as solder fume particles, it was determined that these particles vary in size from 0.5 microns to approximately 2.5 mm in diameter. In the pursuit of collecting fine solder particles in a specialized filter without impairing its integrity through the aspiration of chips, cyclonic separation emerged as the optimal prefiltration solution. The objective of cyclonic separation is to maximize the removal of chips from the aspirated airflow.

To mitigate the excessive cyclonic separation of lightweight particles without compromising the efficiency of heavy particle separation, five distinct design variants were conceived. These variants aimed to identify additional design parameters, beyond those discerned from the literature review, that influence cyclonic separation efficiency. Consequently, a cyclonic separator variant featuring an elongated vortex finder and increased cylindrical section diameter was chosen, as it yielded the highest potential for low separation of light particles, without compromising cyclonic separation of heavy particles. The selected design variant was subsequently optimized concerning the aspirated flow rate, height, and inlet orifice dimensions, while respecting standards and limitations. The final tank variant attained an excellent separation efficiency of 99.99% for heavy particles, whereas for the range of lightweight particles, evacuation efficiency ranged from 32.68% to 97.21%.

Considering the unsatisfactory results obtained for lightweight particle efficiency, the recommendation is to introduce an additional detachable filter within the tank, dedicated to capturing lightweight particles. For future endeavors, the conduction of a particle trajectory analysis and the fabrication of a prototype for the proposed tank variant is suggested. This would benefit the development of a more accurate mathematical model for determining the cyclonic separation efficiency.

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CERCETĂRI PRIVIND OPTIMIZAREA A UNUI ASPIRATOR INDUSTRIAL PENTRU SEPARAREA PARTICULELOR UȘOARE ȘI GRELE

Rezumat: Această lucrare își propune să stabilească o bază teoretică pentru fabricarea unui rezervor pentru un aspirator industrial, conceput pentru colectarea particulelor ușoare și grele. Investigația s-a concentrat pe așchiile de aluminiu şi oţel ca particule grele și vapori de la adezivi ca particule ușoare, predominante în diferite medii industriale. După examinarea soluțiilor existente, s-a ajuns la concluzia că o etapă de prefiltrare sub forma unui separator ciclonic este esențială. Separatorul ciclonic permite separarea particulelor grele de particulele ușoare, prevenind astfel deteriorarea altor medii de filtrare. Autorii au dezvoltat mai multe variante de rezervor al ciclonului, concepute pentru a maximiza eficiența de separare a particulelor grele, asigurând în același timp o aspirare eficientă pentru particulele ușoare. Variantele propuse au urmărit, de asemenea, să identifice variabilele care influențează separarea ciclonică și nu sunt incluse în prezent în modelele utilizate pe scară largă. Prin analiză și evaluare riguroasă cu elemente finite, am selectat cel mai eficient model. Prin aplicarea ecuației lui Lapple, designul ales a fost optimizat pentru ambele tipuri de particule.Rezultatele indică o eficiență excepțională de colectare de 99,99% pentru particulele grele. Pentru particulele ușoare, eficiența de îndepărtare variază de la 32,68% la 97,21%, în funcție de dimensiunea particulelor. În concluzie acest studiu oferă informații valoroase asupra dezvoltării unui rezervor de aspirator industrial multifuncțional, capabil să colecteze eficient particulele ușoare și grele. De asemenea, studiile demonstrează limitările modelului lui Lapple.

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