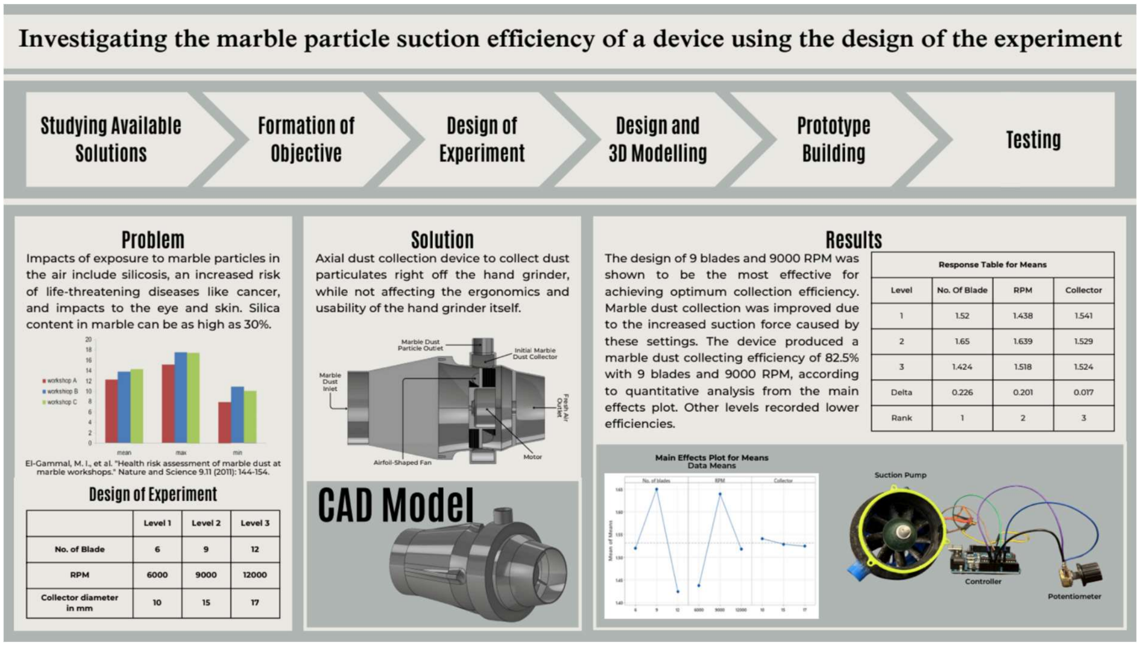
Cover Letter



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Investigating the marble particle suction efficiency of a device using the design of the experiment

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Abstract

Workers in stone-processing factories are exposed to high-levels of marble-dust, composed of up to 30% silica. This can cause diseases like silicosis, which kills almost 13,000 people annually, and cause eye-infections, such as conjunctival hyperaemia. Very few effective devices exist to purify air in the short distance between the worker and the machine (the hand-held grinders, in this case), and this study aimed to design one that was low-cost, portable, and easy-to-use. After initial brainstorming and literature review were performed to gather and shortlist ideas, a device was developed using 3D-printing techniques. The key elements of this device were the blade design, which had a NACA 24112 'airfoil' profile, the shape of the device, and the tangential collector holes. For optimization, a Design of Experiment procedure of an L-27 matrix was conducted to investigate the impact of the number of fan blades, the fan's angular velocity (in rotations per minute), and the diameter of the dust collection port on the effectiveness of the dust collector. Using an ANOVA Analysis, the optimal data for the variables investigated were found to be 9 blades rotating at 9000 rpm, and a port diameter of 10 mm. The results, in fact, showed that the marble dust collection efficiency is highly sensitive to the number of blades and to the angular velocity of the device's fan, but not to the diameter of the collection port. When the testing was conducted by measuring the difference in the mean mass of dust released and the mean mass of dust collected, the prototype was found to be 82.5% efficient in the lab and 60% efficient in the

field. Thus, the dust collection device may have the potential to reduce the health hazards that the community of workers face due to exposure to the marble dust.

Keywords: ANOVA, L-27 array, dust collection, marble collection device.

1. Introduction

The major health impacts of exposure to marble particles in the air include silicosis (a lung disease caused by inhaling crystalline silica dust, which can lead to permanent lung damage), an increased risk of life-threatening diseases like cancer and impact to the eye and skin. Thus, it poses a life threat to many workers. Silica content in marble is below 5% but can be as high as 30%, and silicosis is a very severe disease [1]. The 2019 Global Burden of Disease Study estimates that more than 12,900 people worldwide die from silicosis each year [2]. If it isn't life-threatening, then it can also pose other health issues to workers. For example, it could have a damaging effect to the eyes.

According to research published in 2022, 59.6% of a study of 250 marble workers were diagnosed with conjunctival hyperaemia, with dry eye being diagnosed using Schirmer's test for 60.4% of the workers [3]. The International Agency for Research on Cancer also classified marble dust as a Group 1 carcinogen in 1997 [4], so without right precautions, it can cause severe health issues to workers (who generally tend to be low-income, without access to the best healthcare to solve major problems). This marble dust could also cause skin abrasion.

A few solutions exist currently, but none come without their flaws. One such solution is the portable extraction units by AES Solutions [5], but they are relatively bigger in size. Hence, they may be impractical in a work shed, and may not be useful. Also, they are extremely expensive, costing between 7000-9000 pounds.

Then, there is the Camfil particulate air cleaner [6], but its size would make it difficult to operate effectively in the close range to the workers. Their main applications are 'dusty environments and large indoor premises' [7]. The same problem remains with the AirBravo cleaners [8]. Although these cleaners are more concentrated in one area of a workshop due to their 'arm-like' structure, they can be fixed in one place and rotated around and are flexible but, the size is very huge and inconvenient to use.

Below is the literature review of the sources that were researched and analyzed.

Siheng Sun et al. [9] aimed to assess the risk of dust explosions in dry dust collectors (spaces where dust and gas exist together) by creating an index system for assessing the risk. This was based on factors like dust characteristics and actual operation. To do this, the researchers created 3 main indexes and 7 sub-indexes, evaluating factors like dust explosion sensitivity, severity, environmental parameters, and control device usage. Then, they assigned weights to each index depending on their importance using the analytic hierarchy process, and developed a dust explosion risk assessment model for dry dust collectors using the fuzzy comprehensive evaluation method. The research was able to develop a reliable method for assessing the risk of dust explosions, then allowing specifically at level II using paper powder with a particle size of 75 μm, identifying and preventing dust explosion risks in these environments. However, the specific applicability and adaptability of the assessment model to various types of dust and operating conditions may need further research and validation, as this was a relatively specific case. Implementing this in the real world in an industrial setting will require further research as well.

Sang-Hee Woo et al. [10] aimed to develop and analyze two dust collectors (an inertial separator and an Electrostatic Precipitator (ESP), where the ESP relied on naturally induced charging, due to the friction between the brake disc and pad, to reduce brake wear particularly matter emissions, and focused on the collection efficiencies of these dust collectors based on different brake pad types (low-metallic (LM) and non-asbestos organic

(NAO) pads). The collection efficiencies for LM and NAO pads were compared for the inertial separator, and the cut-off size was determined to be 2.2 μm at 50% collection efficiency (D50). For the ESP, the BWP collection efficiency was greater for NAO pads than LM pads because of variation in frictional electricity generation and iron content. The maximum BWP collection efficiency, using the ESP, for LM pads was 60% and for NAO pads was 75%. The uncollected particles, in this case, were presumed to be those not frictionally charged. However, this study has a few limitations. Firstly, it only looks at two types of dust collectors and two types of brake pads. This limits potential generalization to other dust collection systems and other types of brake pads. The ESP it uses is based on naturally-induced electrostatic charging, potentially limiting its efficiency and effectiveness. Furthermore, the uncollected particles in the ESP collection efficiency analysis were presumed to be those not frictionally charged, without direct investigation supporting this claim (the answer to which may improve overall efficiency). The study also didn't look at the long-term durability of the dust collectors.

Du Lixing et al. [11] aimed to improve the dust collection of a dust collector by increasing the suction effect. To do this, they developed a suction generation device which consists of a housing with an accommodating cavity, an air inlet, and an air outlet. One impeller is placed next to the air inlet and another one adjacent to the air outlet, with a driving member connecting and rotating the two impellers. This method uses the impeller's rotation to create a stronger suction force, and thus, it could capture a greater volume of particulate matter. This can have a few potential limitations, although the research doesn't mention any. For one, the efficiency of the device would vary with the type and size of dust particles. Maintenance requirements of the impellers and driving member, and the noise levels generated by them, may also be another concern.

Liu Hebing et al [12] aimed to improve the suction capacity of a sand suction pump. They did this by designing an auxiliary device with a conical fixing cylinder, supporting plates, rotating shaft, fixing plates, and a fixing ring plate to boost the suction capacity and the stability of the pump. The device worked successfully: the conical fixing cylinder, with a smaller diameter at the upper end, the 4 annularly arranged supporting plates and the stainless-steel fixing ring plate improved the suction capacity by increasing the stability, durability, strength and the effectiveness of the pump. Although the research paper doesn't mention any limitations of the device, one limitation could be required for future research - to understand the long-term effectiveness of the device in real-world applications.

Goehring Daniel and Dietel Juergen [13] aimed to address dust accumulation and its environmental and health impacts during drilling activities. For this, they developed a dust suction device integrated into a hand-held tool, which includes a blower unit to generate an air volume flow, suction openings for removing drill cuttings and, suction intake openings to create negative pressure for dust extraction. The device was successful in reducing dust from boreholes during drilling, by generating negative pressure in the adhesive region between the device and the workpiece, ensuring cleanliness in the workplace. A potential limitation of this device could be the capturing of fine dust particles, but this can be significantly addressed by improving its suction power or filter system.

Yang Jiazhi [14] aimed to reduce inefficiencies in slag extraction during nonferrous metal smelting processes. To do this, a suction pump-type slagging-off device was designed, with an L-shaped slagging-off holding frame, a telescopic slag-sucking cylinder, a slag filtering tank device, and an air suction pump. The device used the gravity of the liquid and the suction effect of the air suction pump, the tank device, and the floating ball control frame to discharge the slag and the liquid efficiently and conveniently. Although the limitations aren't mentioned in the paper, more investigation into the device may be necessary to test its long-term effectiveness and durability on an industrial scale.

Krzysztof Nowak and Maria Bukowska [15] aimed to investigate how the efficiency of dust removal was affected by different construction parameters of cyclones with tangential inlets by analysing 5 types of cyclones with varying design parameters. They used this to understand the impact of the cyclones on the size of particle limit diameter, pressure drop, and overall cyclone efficiency. This involved analysing the performance of the different cyclones with tangential inlets, including high-efficiency, general-use, and high-performance cyclones. To draw conclusions on the efficiency of dust removal, data on the physicochemical properties of aerosol particles and their sizes, as well as the geometric shape and structural dimensions of the cyclones were used. The results indicated that the dust removal efficiency was directly influenced by the size of cyclone construction parameters. Smaller particle sizes led to reduced efficiency, emphasizing the importance of considering the physicochemical properties of aerosol particles in cyclone design. One major limitation of this study was that its results are specific to cyclones with tangential inlets only, limiting its generalizability to other types of dust collectors. The study also did not detail the specific numerical values of the efficiency improvements based on different design parameters, leaving room for further quantitative analysis.

Jeong-Min Jin et al. [16] aimed to boost the performance of a double suction pump by optimizing the shape of the impeller to reduce cavitation. That is because this cavitation can lead to noise, vibration, pump erosion, and performance degradation. To do this, the researchers established 25 design points by utilizing Central Composite Design (CCD) for 4 design variables related to the impeller's inlet and outlet angles. Then, by using the Response Surface Method (RSM), they determined the optimal design points based on the CCD results. The results were compared to existing experimental data with numerical analysis, conducted using ANSYS CFX ver. 18.1. The impeller angles' optimization led to an improvement of 2.34% in pump impeller efficiency and a 0.72% increase in head compared to the initial reference model. However, the influence of the impeller angle on the Net Positive Suction Head (NPSH), a measure of safe pump operation without cavitation, was noted to be insignificant. So, further research may be necessary to overcome this limitation and improve the NPSH as well.

Hüseyin Pehlivan and Zekeriya Parlak [17] investigated the parameters affecting the axial load in an end suction centrifugal pump with a single suction and closed impeller. To analyse the flow rate and physical properties like the back gap of the impeller, wear ring, and balancing holes, they used the Computational Fluid Dynamics (CFD) method. This helped them understand the impact of the flow rate and physical properties on the axial load. The wear ring and balancing hole were found to significantly influence the axial load, but the back gap of the impeller had a smaller impact. Following design changes based on the parameters, the axial force was reduced by up to 60%. Yet, this led to a 5% decrease in efficiency (considered negligible in the study). Higher efficiency was observed at a different operational point where the axial load was lowest. One potential limitation to this is the inability to generalize the results, as it only focused on one specific type of centrifugal pump (single suction, closed impeller). Furthermore, it only considered specific parameters affecting axial load, although there may be other parameters that need to be investigated, to reduce axial load even more.

Hua Yi et al. [18] aimed to develop a dust separation device to tackle the need to be able to effectively separate dust particles from the air. That is because dust accumulation can lead to environmental and health hazards and worsen air quality. To do this, the researchers connected a fan, a dust processing and separating unit, an integrated dual-chamber dust collecting box, and a filter cylinder to form the machine body sequentially. The fan was used to facilitate the suction of the dusty air, after which the dust processing and separating unit was used to separate and collect the dust in the dust collecting box. The dust collecting box was detached, and it was connected below the dust processing and separating unit to enhance the device's functionality. The filter cylinder was used to further capture fine dust particles to improve the air quality. This device may have a few limitations, although the paper does not mention any. For one, the detachable unit may pose a risk to air leakage, reducing the effectiveness of the device. The maintenance required by, and the durability of, the components may also possibly be a drawback.

Sung Kim et al. [19] aimed to improve the hydraulic efficiency and suction performance of a mixed-flow pump impeller, two properties which typically have conflicting design objectives. The design was achieved using a commercial CFD code and a Design of Experiment (DOE) methodology. Design variables in the meridional plane and vane plane development were defined for impeller design, with main variables in the inlet part and the incidence angle selected for optimization. Using numerical analysis and experiments, the researchers compared the performance of the optimised impeller model. This comparison focused on NPSH, total efficiency, and total head as objective functions. Although the results were similar in tendency, the optimised impeller model showed differences in quantitative values. However, there were differences between the numerical and experimental results, questioning the accuracy of the results.

Lee Han Sik [20] aimed to fulfill the need for a cheaper and more compact dust separation apparatus by eliminating the need for a cyclone device for centrifugal force generation. The new design included a main body, a pressure tank, a dust storage tank, a venturi unit, two mesh filters, an air compressor, an air incoming pipe, and a vacuum pump. The purpose of the venturi unit was to boost the flow velocity of the air passing through it, generating negative pressure for dust separation. When the dusty air flew in through the dust-inlet pipe on the side of the main body, the two mesh filters captured the dust particles. These captured particles were stored in the dust storage tank. Overall, this design reduced costs by eliminating the need of a cyclone device. This may have a few limitations, although the paper does not mention any. These limitations include difficulty in maintenance due to relatively high complexity, scalability problems, and durability of the device, all of which may need to be further investigated through research.

Qunli Zhao [21] aimed to improve dust separation efficiency of a dust separating device with a new design for the air inlet component. The new design for the air inlet part consisted of a first opening for air inflow, a second opening connected to the dust separator, and a third opening for diverting smaller particles away from the separator. The mouth direction of the third opening formed a 30-150 degree included angle with the first opening, allowing for the air streams to separate based on particle size. This separation enhanced the efficiency of the dust separator. This may have a few limitations, although the paper doesn't mention any. For instance, it may need to be tested in real-world settings before being able to be applicable in industries. Maintenance-related difficulties may be another concern that should be further investigated.

Jing-Cheng Bai et al. [22] aimed to analyze different operating parameters like louver angle, solids mass flow rate, and particle size of the bed material to improve the dust collection efficiency in a circulating 2-D granular bed filter (CGBF). By varying these operating parameters, the researchers aimed to identify the optimal conditions for maximum collection efficiency. Higher dust collection efficiency was observed at different solids mass flow rates with different louver angles, with the optimum efficiency seen at a 30° louver angle. Particle size of the bed material affected the dust collection efficiency too, with smaller average particle sizes showing better efficiency compared to larger ones. A major limitation of this model was a rapid decrease in the efficiency due to the attrition phenomenon of the bed material, requiring further research to improve the long-term efficiency of the filtration system.

Gerigk Wolfgang [23] aimed to design a dust separation device by using a cyclone filter or separator plate with a fan casing and neck. The device contained a separator plate (fixed or mobile, using an adjusting screw) that was used to divide the airflow into two streams. It was designed with an injector-type constriction at the end, which connected it with the cyclone filter below. This design allowed for the separation of fine dust from the cyclone filter, and worked successfully when tested. This may have a few limitations, although the paper does not mention any. These limitations include maintenance requirements and challenges in assembly, installation, and repair due to the complexity of the design. Furthermore, the size, capacity, and scalability of the device may be limited and would require further testing and investigation.

2. Methodology

2.1 Methodology Summary

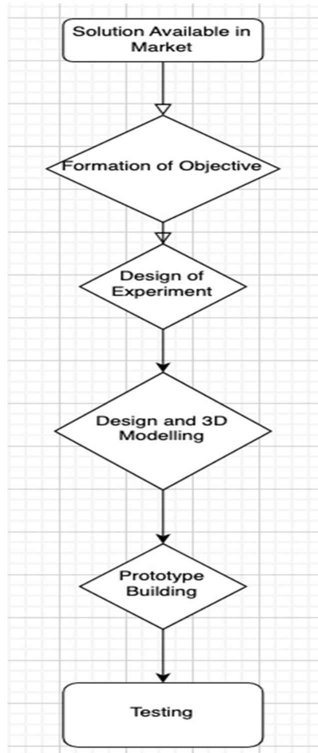

Fig. 1 Research Methodology

First, current solutions in the market were evaluated. The objective was to create a smaller device, with maximum collection efficiency and the aim of releasing the purified air out of the device. So, this research conducted a DOE analysis, using varying blade dimensions, device dimensions, and suction powers. Before building a physical prototype of the device, prototype design on Fusion 360 was created initially. After that, testing was conducted. Initial testing was done with powder found commonly, like salt, and then material mimicking the marble dust.

2.2 Solutions Available in the Market

As mentioned in the introduction, the solutions that exist currently have significant drawbacks. For one, their sizes are impractical for functioning in a work shed, where the aim is to have a close-range and personal device for the workers. Secondly, they are extremely expensive, deterring customers from using them in their workplaces. The objective is to minimize these flaws while maximizing the efficiency of the dust separator. So, the aim is to create a device that is smaller in size, cost-effective, can release purified air, and can work at an optimum efficiency in the conditions needed.

2.3 Design and 3D Modelling

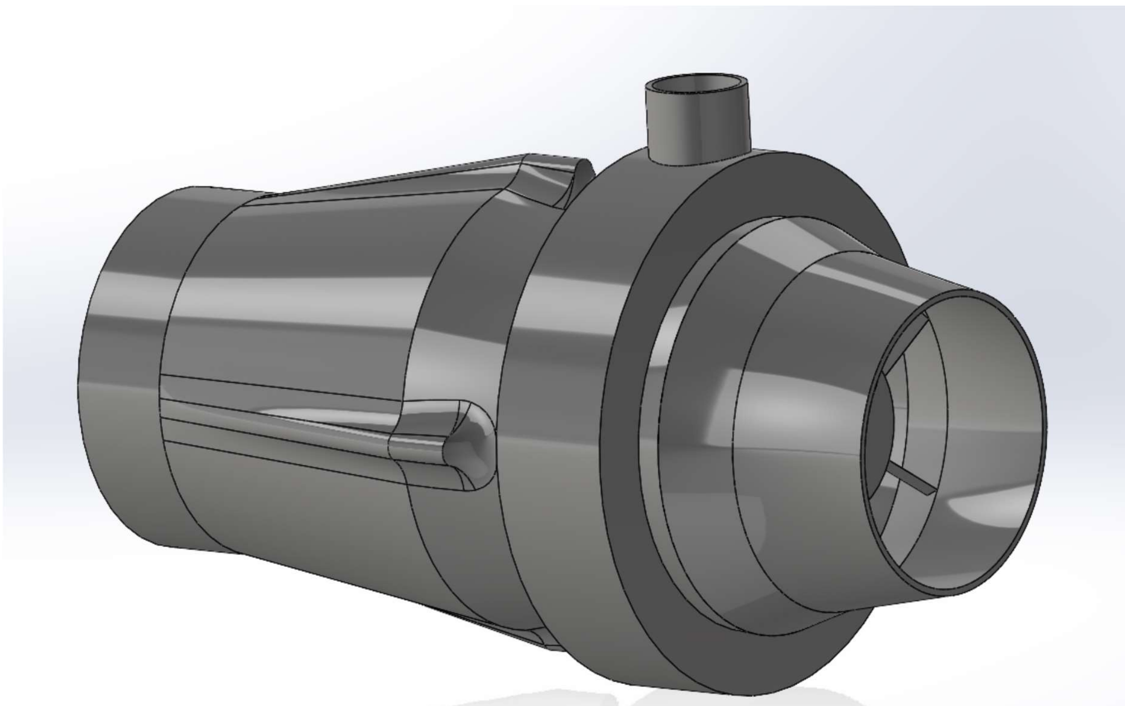

Fig. 2 3D Model of Dust Collector Device

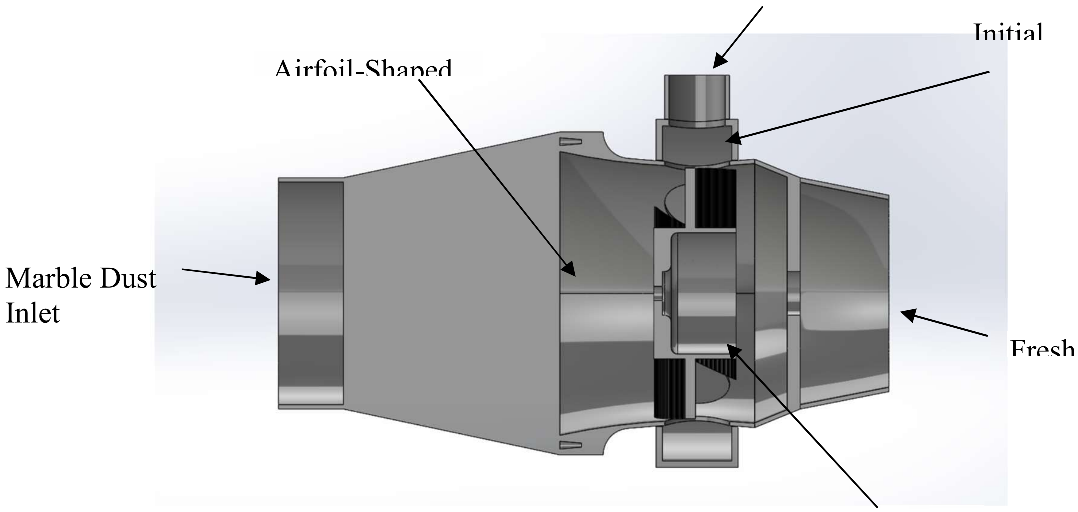

Fig. 3 Sectional Image of Prototype Device

Fig. 2 and Fig. 3 show a novel prototype design for collecting marble dust in real-time application. This device will be fitted just above the marble cutter, and an external power supply will be given. Once the marble-cutting operation starts, the device will also start. Once it starts, it will start sucking the marble dust mixture with air from the marble dust inlet, as shown in Fig. 3. As the density of marble dust and air is different, based on the centrifugal force created by the airfoil-shaped fan, the marble dust will collide at the wall of the device and will temporarily settle at the initial marble dust collector. The clean air, on the other hand, will be released directly from the fresh air outlet.

2.4 Prototype Building

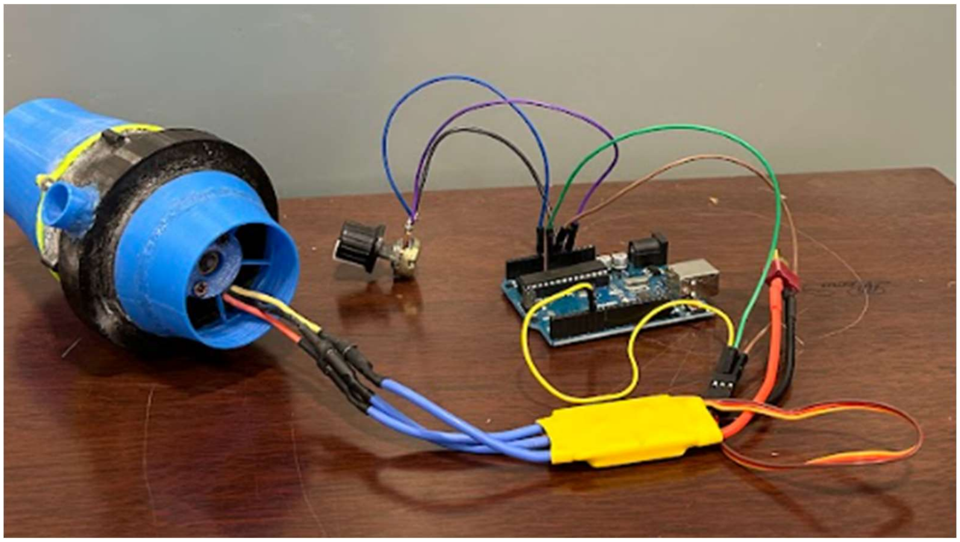

Fig. 4 Image of Prototype Device

Fig. 4 shows the actual device designed and developed to perform the experiment and achieve the objective of this research. The device is manufactured using 3D printing technology and a low-cost electronic system. The design principles followed to manufacture this device were easy to assemble, easy to use, and cheaper in maintenance.

2.5 Design of Experiment

To collect the systematic data and create a mathematical study, a DOE of L-27 matrix was used. The corresponding parameters are shown in Table 1:

	Level 1	**Level 2**	**Level 3**
No. of Blade	6	9	12
RPM	6000	9000	12000
Collector diameter in mm	10	15	17

Table 1 DOE parameter L-27

As shown in Table 1, three input parameters for ANOVA study were decided and three levels of variation were considered. The number of blades was one of the main components of the device, responsible for the overall suction pressure needed to be created inside the device.

Therefore, it was necessary to consider this as one of the parameters for the study. The RPM determined the power required to run the device; as the power increases, the suction would also get stronger, but the electricity costs would also rise. Henceforth, this parameter was important to compare the device with the available solutions in terms of operation costs.

Lastly, the tangential outlet through which dust could be collected was also taken as one of the parameters. Furthermore, to satisfy the condition of DOE L-27, three levels for each parameter were taken into consideration. The results from the ANOVA are presented in the next section of the paper.

3. Results and Discussion

The main objective of this research was to design and develop a portable, low-cost, easy-to-maintain marble dust collector device. To achieve the objective, a scientific study, mentioned in the methodology section, was formulated. To optimize the device efficiency, an ANOVA technique was used, and the results from the ANOVA are presented in Table 2.

Analysis of Variance for Means						
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
No. of blades	2	0.230719	0.230719	0.115359	12.02	0
RPM	2	0.184541	0.184541	0.09227	9.61	0.001
Collector	2	0.001341	0.001341	0.00067	0.07	0.933

Residual Error	20	0.191941	0.191941	0.009597		
Total	26	0.608541				

Table 2 Response Table of ANOVA

Table 2 shows the response from ANOVA. A low P value shows the highest influence of the parameter for achieving the output. This shows that marble dust collection efficiency was highly sensitive to changes in the number of blades. Considering the P value of the RPM gave a similar significance, but the collector diameter showed minimal significance to collection efficiency. By observing the ranking table of ANOVA (Table 3), it can be seen that the number of blades demonstrated the most significance, while collector diameter demonstrated the least.

Response Table for Means			
Level	**No. Of Blade**	**RPM**	**Collector**
1	1.52	1.438	1.541
2	1.65	1.639	1.529
3	1.424	1.518	1.524
Delta	0.226	0.201	0.017
Rank	1	2	3

Table 3 Ranking Table of ANOVA

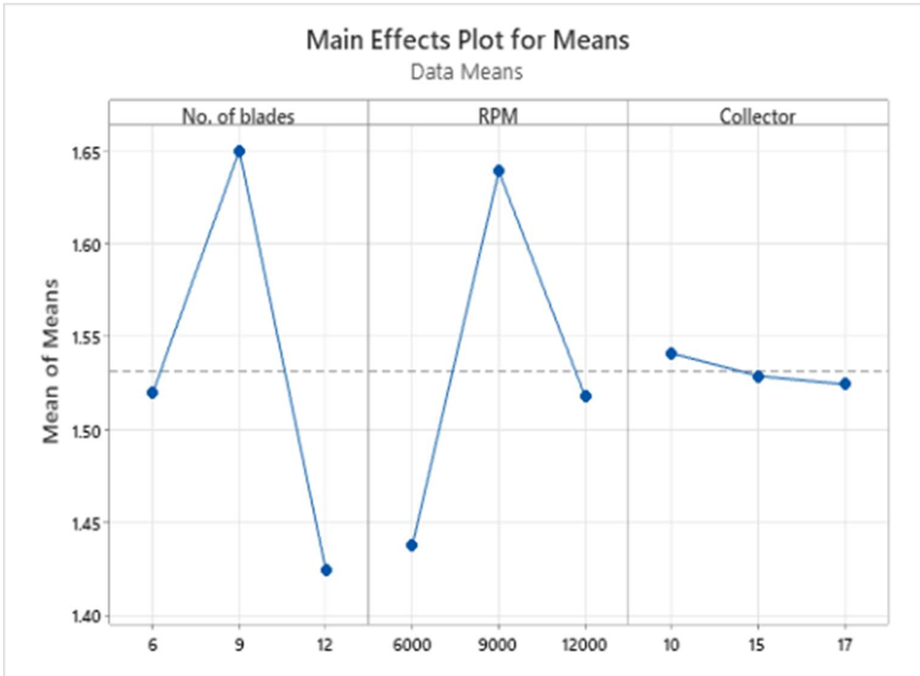

Fig. 5 Main Effects Plot

Fig. 5 shows the main effect plots of all parameters considered in the study. It was evident after looking at the graph that 9 blades can significantly affect the marble collection efficiency. Moreover, 9000 rpm was found to be the most significant value for RPM, and the smallest collection diameter of 10 mm was considered the most effective.

4. Conclusion

This study's main objective was to create a marble dust collector that was effective, small, portable, lightweight, inexpensive, and simple to maintain. To achieve this aim, DOE analysis and ANOVA technique were used. The main characteristics considered for this analysis were the number of blades, the RPM, and the collector diameter. The efficiency of the device was found to be highly influenced by the number of blades and the RPM, with the collector diameter having little effect. Specifically, the number of blades (which had a P-value of 0) and RPM (which had a P-value of 0.001) are crucial parameters as found by the ANOVA analysis, with F-values of 12.02 and 9.61 respectively. The design of 9 blades and 9000 RPM was shown to be the most effective for achieving optimum collection efficiency. Marble dust collection was improved due to the increased suction force caused by these settings.

The device produced a marble dust collecting efficiency of 82.5% with 9 blades and 9000 RPM, according to quantitative analysis from the main effects plot. Other levels recorded lower efficiencies. The ANOVA response table further complemented these results, because it ranked the number of blades as the most significant factor (with a Delta of 0.226) and RPM as the second most important parameter (with a Delta of 0.201). These findings emphasize the need to optimize both blade number and RPM to get the greatest performance. The created prototype effectively illustrated the efficacy and usefulness of the suggested design, offering a workable remedy for the health risks associated with marble dust in a stone-cutting work shed.

Further studies may examine the maintenance needs and long-term endurance of the developed device, to guarantee its dependability in industrial environments. They may also investigate the impact of different marble dust particle sizes, diverse forms of dust, or varying operational settings on the device's performance and suitability for other industries. The incorporation of filtration technology to collect fine dust particles and improve the general air quality could be another possible topic of attention.

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