Investigating natural fibers as pollutants filtration materials for exhaust gases

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Abstract

This research addresses the critical issue of air pollution caused by particulate matter emissions from automotive exhaust systems by exploring the use of natural fibers, specifically jute and coir, as filtration materials. Traditional synthetic filters are effective but expensive and environmentally unfriendly, prompting the search for sustainable alternatives. A novel device inspired by a silencer was designed to reduce exhaust gas temperatures, preventing the burning of natural fibers. CFD simulations optimized the design, achieving a temperature reduction from 420°C to 150°C with a venture ratio of 1/3. Experimental tests using a 3D-printed prototype demonstrated that jute fiber absorbed 1 gram of particulate matter per 2 grams of talcum powder at a velocity of 47.75 m/s with 4 layers of fiber, while coir absorbed 0.75 grams under the same conditions. The device's design allows for easy maintenance and replacement of fiber plates, proving practical for real-world use. Testing confirmed effective particulate matter trapping with even deposition across fiber plates, and optimal absorption was achieved with an appropriate number of layers to avoid back pressure issues. This study presents natural fibers as a viable, cost-effective solution for reducing automotive emissions, with potential for further research on durability and scalability.

Keywords—Natural fiber, CFD simulation, sustainable development, experimental testing.

I. INTRODUCTION

Cars, trucks, and buses powered by fossil fuels are the major contributors to air pollution. Transportation emits more than half of nitrogen oxides in our air and is a major source of heat-trapping emissions. Studies have linked pollutants from vehicle exhaust to adverse impacts on nearly every organ system in the body. The composition of the exhaust gases released from a typical petroleum or diesel-based engine contains nitrogen, oxygen, water vapor, carbon dioxide, carbon monoxide, oxides of nitrogen (NOx – NO and NO2), oxides of sulfur (SOx – SO2, and SO3), lead, hydrocarbons (HC) and particulate matter (PM). Generally, temperatures of 500–700°C (932–1293°F) are produced in the exhaust gases from diesel-cycle engines at 100% load to 200–300°C (392–572°F) with no load. Exhaust gases normally discharge at around 420°C (788°F)[1].

Catalytic converters use metallic catalysts to promote the desired reactions at lower temperatures than would otherwise be needed. The catalyst types could be base metals (e.g., copper, Cu, chromium, Cr) but are more usually noble metals (platinum, Pt, palladium, Pd, rhodium, Rh). The transition metal oxides of copper, cobalt, iron chromate, and vanadium are also useful as catalysts and have been considered., The disadvantages, however of using catalytic converters, are that they are very expensive to get/replace. In addition, because carbon dioxide is a product of the reaction that takes place inside catalytic converters, the widespread use of catalytic converters has also contributed to increased atmospheric levels of carbon dioxide. Catalytic converters also reduce the fuel efficiency of the vehicle [2].

It has been realized that the output temperature plays an important role in the preservation of the pollutant-absorbing natural fibre without which it will burn. Thus a device has been created in this research to reduce the output temperature to prevent burning of the fibre mesh based on the design of a silencer. A CFD simulation has been run on Ansys to test the efficiency of the device to reduce output temperature while also preventing backflow due to pressure differences. Further, several natural fibre meshes have been tested to choose the highest dust-absorbing fiber while also having high heat resistance. Several fiber plates of different natural fibres were made and tested with the device to obtain the best results. The next section of the paper presents the literature review that was essential for the selection of fiber and creating research methodology.

II. Literature Review

Phani Prasanthi et al.[3] conducted research to address the issue of air pollution caused by particulate matter and volatile organic substances, which may lead to adverse effects on human health. By utilizing natural fibres and plant-based materials, the researchers create an indoor air purifier. The researchers combined natural fibres like hemp jute silk cocoon and coir fibres with neem and aloe vera to act as filler materials and purify the indoor air by eliminating particulate matter and volatile organic materials. The air purifier effectively reduced PM10, PM2.5, PM1, and volatile matter levels by running for 1 hour in an indoor environment. For example, the PM10 levels decreased from 1200 ppm to 140 ppm demonstrating the efficiency of the purifier. Limitations of the prototype may include maintenance and scalability issues.

Jidan Sun et al.[4] researched to counter the challenges of porosity as well as flexibility in the preparation of aerogel from naturally occurring fibers. The team prepared an aerogel that has a void three-dimensional structure as well as high compressive resilience. This aerogel was produced by mixing cellulose fibre suspension with polyvinyl alcohol. The methodology involves the investigation of three-dimensional void structure as well as the surface morphology of cell aerogels by using a scanning electron microscope. It also involves evaluating the porosity, and pore size distribution with a mercury intrusion meter, and analyzing the crystal structure of cellulose by using X-ray diffraction and UV-Vis_nis spectroscopy to study its infrared reflectance. As a result of this research, the rate of removal of PM 2.5 reached 92.4%, and the thermal conductivity of the aerogel reached 0.028W/mK. The radiation cooling temperature of the aerogel was also 10 degrees lower.

Patricio J Espinoza-Montero et al.[5] conducted research to combat the challenge of controlling particulate matter in the air for the prevention of cardiovascular diseases caused by this pollutant emission. The researchers use electrospinning and air filtration applications for the synthesis of polymers and membranes. Modification in experimental parameters including the use of various polymers are explored to enhance filtration efficiency and reduce pressure drop. The methodology involves radical polymerization and melt electrospinning to produce membranes with desired characteristics. The result portrays that electrospun membranes are excellent alternatives to air filters. They have versatile applications, the ability to control fiber diameter and porosity, high filtration efficiency, as well as low-pressure drop.

Marichelvam Mariappan Kadarkarainadar et al.[6] conducted research to combat the impact emissions of dust, gas, and particulate matter from industries have on the environment, particularly from cement industries. The researchers developed an eco-friendly air filter using natural sisal fiber coated with zinc oxide and iron oxide nanoparticles to enhance dust absorption. A new bag filter was designed using Sisal fibre as a filtering media coated with metal oxide. The dust adsorption rate of the zinc oxide-coated sisal fibre was 34.4, which was higher than the other samples tested. The sisal fibre-based filter showed impressive results and potential use in cement industries.

Khandsuren Badgar et al.[7] conducted research that aims to explore sustainable applications of nanofibres in various industries including agriculture and Water treatment. The research focuses on areas such as filtration, biomedicine, energy storage as well as food packaging. The methodology of the researchers involves the production of natural nanofibres from plants and agricultural waste. It also involves reinforcing them with nanomaterials and utilizing them in agriculture for plant protection and growth enhancement. The results of the research were astonishing, showing that nanofibres deliver promising results for encapsulating bio-active molecules, in tissue engineering for implantation, and in the food industry for active-intelligent food packaging. This process can be used to enhance food safety and quality.

Lei Hou et al.[8] researched to investigate the quantitative effects of Coulomb forces on the filtration efficiency of aerosol particles. The quantitative effects were investigated by using a three-dimensional random fibre model. The researchers established computational flow models, particles as well as electric fields to investigate filtration efficiency. Variation tendencies of filtration efficiency and pressure drop were studied. These studies were based on factors like fiber potential, and particle charge-to-mass ratio. These studies provided insights into high-efficiency air filter design.

Paxton Juuti et al,[9] conducted research to address the issue of filters that become breeding grounds for Bacteria which can then be dispersed in the air, by incorporating antibacterial materials into filter media. The methodology of the researchers included adding silver nanofibres directly to the fibre fabrication process and also coating pre-existing filters with silver nanoparticles by using a liquid flame spray. The methods which were used by the researchers were found to be suitable for producing antibacterial filters. These were also tailorable and scalable for specific needs.

Chih-Te Wang et al,[10] researched to enhance filtration efficiency for airborne particles, a critical aspect in air quality control. The researchers utilize electrospinning to fabricate smooth and porous PMMA polymer fibres. The researchers also explore the impact of fibre characteristics on filtration performance. The researchers concluded that high surface voltage was detected on small-diameter PMMA fibres indicating better charge retention as well as filtration efficiency. The researchers concluded that the porous fibres exhibited superior performance in single fibre efficiency and filtration quality compared to smooth fibres.

Jozef Macala et al,[11] conducted research to address the issue of increasing nitrogen oxide emissions into the atmosphere primarily from human activities like burning fossil fuels in furnaces and automobile engines. The methodology of the researchers involved experimental measurement of natural Zeolite clinoptilolite's ability to adsorb nitrogen oxide. It also involves the measurement of the catalytic effectiveness of modified clinoptilolite. Zeolite samples were cleaned with a solution of ammonium chloride and then dried at 270 degrees Celsius for 24 hours and then used as a packing filter. Untreated natural Zeolite causes a 19.7% decrease in investigated compounds in exhaust gases. Thermally activated zeolite causes a mean effectiveness of 31, with the highest effectiveness observed between fifteen and thirty seconds of action.

Sakthivel.S et al,[12] conducted research to develop needle-punched nonwoven fabrics for filtering air by using reclaimed fibres , focusing on improving air filtration as well as other properties. The methodology of the researchers included manipulating machine variables to alter fabric physical parameters like air permeability and pore size distribution. The nonwoven fabrics included reclaimed cotton (60%) and polyester (40%) blend. The effects of calendering on pore size and filtration properties were assessed to enhance filter performance. The study showed improved filtration characteristics due to the calendering process.

Xiaochao Gao et al,[13] conducted research on efficient air filtration systems using sustainable methods. The researchers utilized silk fibroin which is a protein-based material to create a nano-filter for air filtration. The green nano-fibre constructed from silk fibroin demonstrated high filtration efficiency for various particle sizes which showcases its potential for air filtration.

Sarah J Dunnett et al.[14] researched to develop a numerical method to model the effect of particle deposits collected by fibrous filters on the flow fields within the filter and its impact on further deposition. The researchers created a single fibre model where the deposit was represented as a porous layer on a fibrous surface. Mathematical methods were used to determine the flow field inside as well as outside the porous layer. Once the flow field for a specific deposit is obtained, the equations of motion of the particles are solved to investigate the feedback effects of the deposit on further deposition.

From these research papers, it has been observed that the researchers worked on various fibers like hemp, jute, silk cocoon, coir fibers, cellulose fiber suspension, electrospun membranes, sisal fibers, nanofibres, PMMA polymer fibers, zeolite, unwoven cotton with polyester blend as well as silk fibroins for collection of dust particles and other air pollutants for purification of air. However, it has been realized that no such device has been created for the collection of dust and other air pollutants from automobiles which are a major contributor to air pollution. Due to this, the objective of this research has been decided to use low-cost natural fiber to create a device for the extraction of dust from automobile exhausts.

III. METHODOLOGY

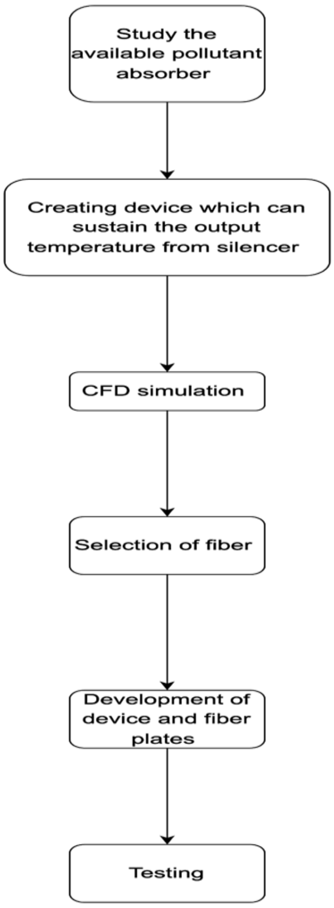

Figure 1: Research Procedure

The methodology shown in Figure 1 aims to develop a sustainable and efficient filtration device utilizing natural fibers to absorb pollutants from automotive exhaust gases. The device is designed to integrate with existing exhaust systems. Various natural fibers have been evaluated for their pollutant absorption properties, including particulate matter, nitrogen oxides, carbon monoxide, and hydrocarbons. The most promising fiber (s) have been selected to create a prototype filter, which has undergone controlled testing to assess filtration efficiency and impact on engine performance. A prototype has been designed including an expander to increase the surface area for absorption of pollutants.

Selected pollutants that can be filtered using the device:-

This project aims to absorb particulate matter from exhaust gases using a device that can externally be attached to the exhaust pipe efficiently and cost-effectively keeping sustainability in mind.

Creating the device:-

a.Analytical calculator:-

The temperature of the gases released from the exhausts of automobiles is very high which cannot be sustained by most natural fibers without reducing its temperature. Thus an expander device has been created which has been inspired by the design of a silencer. The expander device also creates a larger surface area for larger absorption of dust particles by the natural fibres The area of cross section has been calculated by using venture conversion to diversion relationship.

Two ratios have been taken under consideration which are ½ and ⅓

If ratio= 1/2

then diameter (d) is = 0.08 meters

X is the difference between the radius of the inlet and the outlet

x= (D-d)/2
x= (0.08-0.04)/2
x=0.02m
Length(l) is the distance between the inlet and the outlet
tanθ=x/l
l=x/tanθ
If θ=30
l=0.02/tan30
l=0.0346m
l=34.6mm

If ratio= 1/3
then diameter (d) is = 0.12 meters
X is the difference between the radius of the inlet and the outlet
x= (D-d)/2
x= (0.12-0.04)/2
x=0.04m
Length(l) is the distance between the inlet and the outlet
tanθ=x/l
l=x/tanθ
If θ=30
l=0.04/tan30
l=0.0692m
l=69.2mm

Based on the above ratio the Expander 2D device has been made and analyzed using the CFD simulation.

b.CFD calculation:-

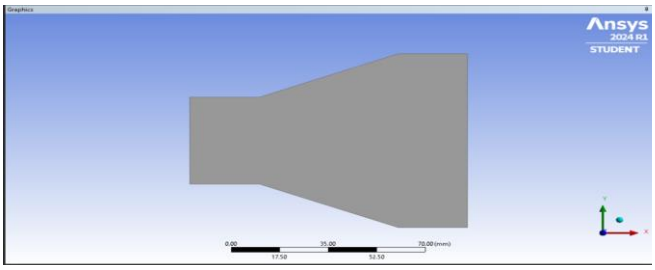

Figure 2: Expander geometry in FLUENT geometric section.

Based on the analytical calculation a 2D design of the expander has been made in ANSYS FLUENT geometric section. Figure 2 shows the same. The conversion cone will act as input from the exhaust pipe of the vehicle, whereas the diversion section will be output to the environment. The main purpose of the simulation is to identify the optimum length at the end of the diversion section, where the temperature should be adequate to place the natural fibre plates.

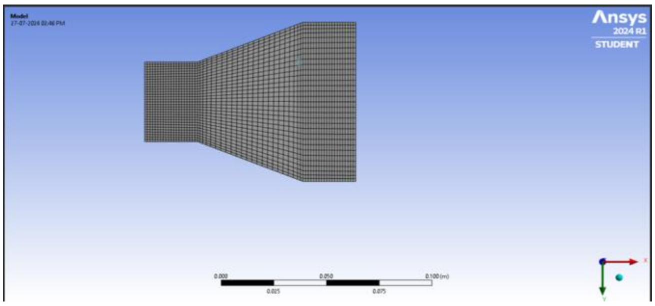

Figure 3: Mesh section of expander in ANSYS-FLUENT

Figure 3 shows the mesh setup for the expander in ANSYS_FLUENT, the mesh was selected based on the orthogonal quality check and aspect ratio. It was found that varying mesh between 0.7 to 1 mm doesn't have much impact on the results. Hence to save the computational power 1 mm mesh was adopted.

In the next phase, the mesh file was imported to the solver section of the FLUENT. Where the pressure-based solver where selected and the gravity effect was kept off. However, the energy equation kept on checking the temperature at input and output. The k-epsilon model was selected to capture the flow effect, whereas at the input of the expander, the mass flow rate from the exhaust is given as input value, and in the result temperature and velocity contour were observed. The flow contour is presented in the next section of the paper.

Selection of Fibre:-

Further natural fibres have been selected based on their thermal limit of degradation as well as their dust absorption capacity including the pore size as well as the cost of the raw fiber. Initially, 4 fibres: Hemp, jute, abaca, and coir had been considered because of the high heat resistance while maintaining absorption capacity. After careful analysis Jute and Coir fibers have been chosen as the most efficient while also being cheaper than other commercial fibres as abaca and hemp fibers were not easily available and were more expensive than jute and coir. Table 1 shows the various fibers and their properties explored for this research.

Table 1: Natural Fibre explored for this research

fibre	thermal resistance (in Celsius)	Diameter size (in microns)	cost per kg (in INR)
hemp	250 C	15-20	400 Rs
abaca	340 C	100-300	230 Rs
coir	400 C	10-20.	25 Rs
jute	550 C	17-20.	54 Rs

Development of the device and the fibre plates:-

Expander dimensions are finalized based on the CFD simulation and the fiber selection. Figure 4 shows the expander exploded CAD model. The device's inlet pipe section will be attached to the vehicle's exhaust system. The device works on the principle of a venture system the exhaust gas from the exhaust system still enters the device inlet at high velocity, and at the expander section, the velocity will drop, which result in a drop in the temperature. This will also make the flow speed slower, now this slow-speed gas will collapse with the fibre plates, which are attached at the end of the device. However, when these gases collapse with the fibre the pollutant particle will stick to the fibre and clean air will go into the atmosphere.

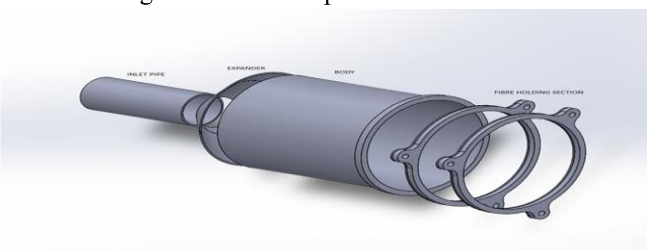

Figure 4: Expander 3D model

Fibre plates from jute have been created by cutting out unprocessed bags of jute into circles and fitting them into 3-D printed stencils. As woven coir fibres are not easily available, sheets from coir have been manually made by using medical acetone as a binding agent and binding the coir fibres by spraying them with acetone and then fusing them by pressing down the fibres with a hot iron.Figure 5 shows the actual prototype device made of 3D printing technology, using PLA as the base material. The device is made in such a way that it should be easy in use as well as maintenance to be simpler. It can be observed from Figure 5 that, to fit the fiber plate with the expander a simple fastening mechanism has been used, due to this when every fiber ends its life it will be easy to add a new fiber plate and fit it again to the exhaust system for further operation.

Figure 5: Prototype 3D printed device for testing purposes with fiber plate.

Testing procedure:-

To test the fibre absorption capacity and efficiency of the device experiment was performed by using talcum powder and an air pump at 50 watts at a speed of 47.75m/s . 2 grams of powder were weighed using a chemical scale and passed through a funnel into the inlet of the device. Air has been passed for 25 seconds per test section leading to deposition in the various layers. This layer was weighed before and after to measure the amount of absorption. This has been given in the results section of the research paper. Different layers of jute and coir have been attached to the outlet to check the efficiency of the layers and the resultant back pressure.

Figure 6 represents how the deposition looked in the various layers after testing with 4 layers of jute. The concentric pattern shows an even deposition

Figure 6: Particle deposition on fiber plates.

IV. Result and Discussion

As mentioned in the methodology section, to investigate the fiber pollutant absorption rate the device has been created. which can help the natural fiber to withstand the exhaust temperature. Figure 7 shows the temperature contour of the same. From the figure, it can be seen that a venture ratio of ⅓ works better when a substantial temperature drop is required. These simulation results also help in deciding the length of the expander which is directly proportional to the manufacturing cost of the device.

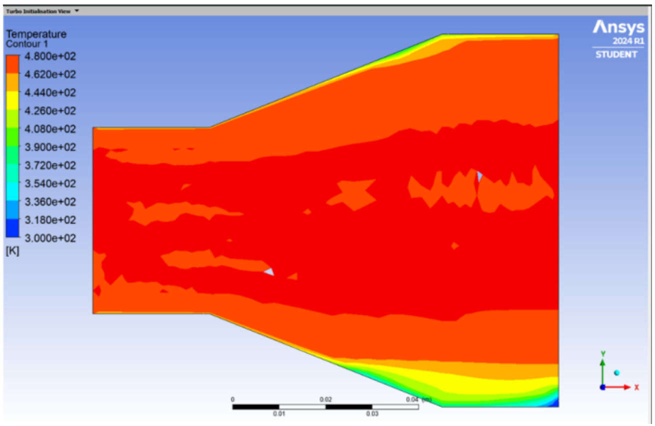

Figure 7: temperature contour of expander from FLUENT

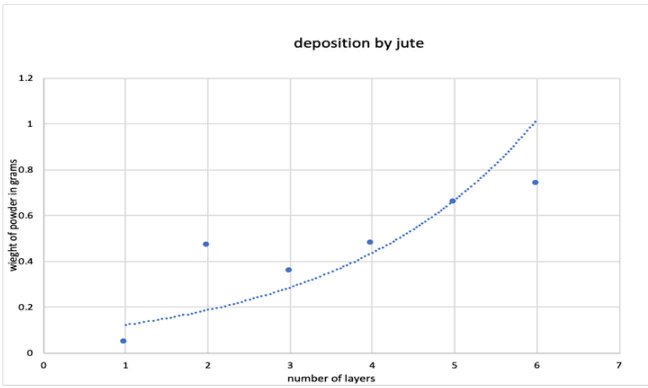

Figure 8: residue stored in an expander with many jute layers attached to the device.

Figure 8 shows the quantity of the residue collected in the device while performing the test using the jute fiber. From the figure, it can be observed that the number of layers has increased the quantity of the particles in the device. This suggests that the number of layers added to the device was responsible for creating the turbulent flow inside the device that results in back pressure. This phenomenon doesn't allow the fiber plate to absorb the maximum amount of particulate matter. Hence a new test has been conducted to check how much particulate matter fiber plates were absorbing. Figure 9 shows the absorption capacity of just fiber by adding the number of layers. It was found that 4 number of layers are optimum for the absorption of particulate matter while jute is potential fiber. However, after 4 number of layers, the absorption has reduced due to the backpressure created by direct obstruction to the exhaust gas because of the fiber layers.

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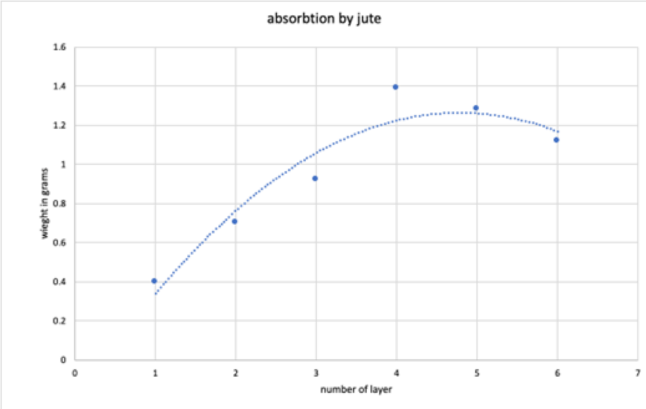

Figure 9: Test result of jute fiber absorption

When the test was conducted for the coir fiber, the deposition of particulate matter observed in the device was less compared to the jute fiber at the same number of fiber layers. The reason was may higher GSM fiber was used or the chemical composition. Figure 10 represents the same testing result, where it can be observed that particulate matter deposition in coir fiber is around 0.75 gm whereas in jute fiber it was 1 gm. So here the coir performs better than jute fiber.

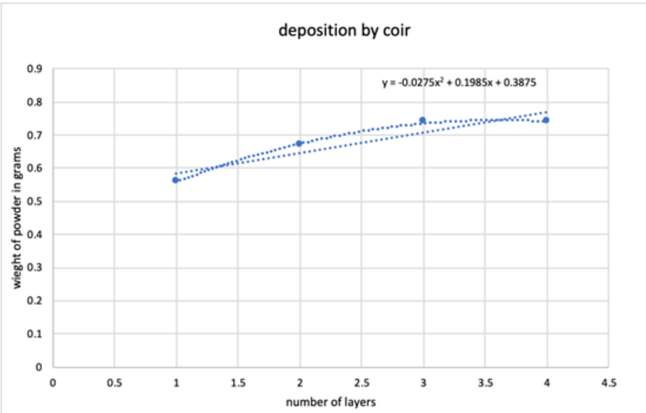

Figure 10: Coir fiber particulates matter deposition in the device.

When the particulate matter absorption was absorbed in the coir fiber by adding the number of layers while testing, the absorption capacity of the coir was lesser than that of the jute fiber at the same velocity and same number of layers. Figure 11 shows the testing graph of coir fiber absorption with many layers tested in the device.

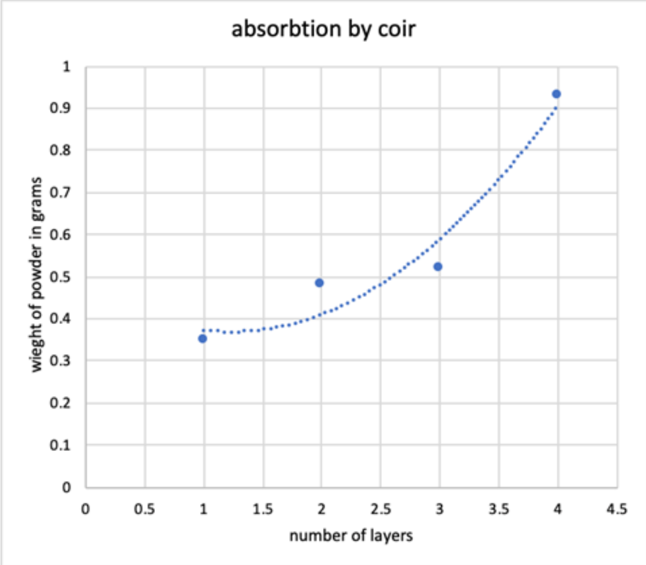

Fig 11. This graph shows the absorption of powder on the coir layers

The fibres are successfully able to absorb the particulate matter proving that the system functions as it intended. The particulate matter was entrapped as the design intended, making for a successful result showing that the exhaust material could be deposited and captured using natural fibre. Finally based on the simulation and the experimental testing the conclusion is carried out, which is written in next section

V. CONCLUSION

This research successfully demonstrates the feasibility of using natural fibers as filtration materials for automotive exhaust gases. The key innovation of this study is the development of a device inspired by the design of a silencer, which reduces the temperature of exhaust gases to prevent the burning of natural fibers, thereby enabling their use in filtration.

The CFD simulation provided critical insights into the design of the expander device, indicating that a venture ratio of 1/3 was optimal for a substantial temperature drop, which is essential for preserving the integrity of the natural fibers. The simulation results showed a temperature drop from 420°C to approximately 150°C, making it feasible for fibers like jute and coir to withstand the exhaust gases without degradation.

In the experimental phase, both jute and coir fibers were evaluated for their particulate matter absorption capacity. The jute fiber demonstrated superior performance, with a particulate matter absorption rate of 1 gram per 2 grams of talcum powder at a velocity of 47.75 m/s using 4 layers of fiber. Coir fiber, on the other hand, absorbed around 0.75 grams under the same conditions. These results suggest that while both fibers are effective, jute fibers offer a higher absorption efficiency. The prototype device, constructed using 3D printing technology and PLA material, proved to be user-friendly and easy to maintain. The design allows for the simple replacement of fiber plates, ensuring the device's practicality for real-world applications. Furthermore, a real-world device needs to be made to test in the real world of experimental tests by directly attaching the device to the end of the exhaust system.

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