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Design, Modeling, and Evaluation of a Cost Effective Particulate Control System

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ABSTRACT

A cost effective, portable particulate control system was developed, built, and evaluated at the University of Louisiana at Lafayette. Prototype of the presented system was developed for experimental assessment and its computational model was also created for CFD simulation. The experimental and computer simulation results showed that the developed system could efficiently and safely remove and dispose accumulated particulate matter (in the size range of 5 ~ 1000 μm), and be tolerant to the abrasive properties that the particulate matter may have. The developed particulate control system as well as the applied technology can be further optimized and extended to be applied in aerospace and space engineering to remove suspended particles out from the closed cabinet of aircrafts or spacecrafts. The outcome of this project will also impact other commercial sectors and industries.

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INTRODUCTION

Particulate control system is broadly used in many industries and commercial sectors for removal and disposal of particles and controlling contamination. Such industries and sectors include aerospace industry, automotive industry, chemical and pharmaceutical production, fossil fuel power plant operations, ore processing, HVAC industry, and environmental protection. Due to its significance and wide applicability in industry, many advanced particulate control systems and technologies have been developed and put into use. Meng et al. [1] developed a household filtration process to use phosphate and silicate to remove arsenic from Bangladesh groundwater by hydroxides. The household filtration process included co-precipitation of arsenic by adding a packet of ferric and hypochlorite salts to well water and subsequent filtration of the water through a bucket sand filter. Experimental results proved that the household treatment process removed arsenic from approximately 300μg/L in the well water to less than 50μg/L. Bedrikovetsky et al. [2] designed a deep bed filtration system and formulated a mathematical model for it. This system can effectively remove solid and liquid particles dispersed in injected water through porous medium. Fritsky et al. [3] developed a catalytic filter system to replace the woven fiberglass filter bags and used the new system to control the medical waste. It was found that with the using of the catalytic filter system, the particulate emission was 12-17 times less than the regulatory limit. Blanchard et al. [4] equipped a diesel particulate filter system which uses a ceria-based fuel-borne catalyst in PSA Peugeout Citroen. The engine test results clearly demonstrated the attractiveness of fuel-borne catalyst technology for the particulate filter system in series applications. Akoum et al. [5] investigated a permeate flux and chemical oxygen demand reduction in dairy process waters using a vibratory shear-enhanced filtration system (VSEP) and various nanofiltration and reverse osmosis membranes. A definite advantage for the VSEP operated at the same pressure and temperature were showed by comparing its performance to existing filtration systems. The better performance of the VSEP was attributed to its higher membrane shear rate which reduces lactose concentration at membrane and its transmission. Shi et al. [6] focused on the development and application of predictive-based strategies for control of particle size distribution in continuous and batch particulate processes described by population balance models. The presented control algorithms were designed on the basis of reduced-order models, utilized measurements of principle moments of the PSD, and were tailored to address different control objectives for the continuous and batch process. The strategy was shown to be able to reduce the total volume of the fines by 13.4% compared to a linear cooling strategy and was shown to be robust with respect to modeling errors.

Based on the previously developed systems, a cost effective, portable particulate control system is designed and prototyped for experimental validation. Capacity and efficiency of the developed particular system are evaluated through experiments, from which the advantages of the presented design are demonstrated.

DESIGN PROCESS

Design Objective

The main objective of this system is to trap, absorb, and remove particulate and fibrous matter (ranging in size from 5 - 1000 μm) from the circulating air without losing material or dispersing content into the air. It is expected that the designed system can collect and dispose all particulate matter generated and suspended within a confined space.

Theoretical Background

A fundamental hydrodynamic equation, Bernoulli's principle, will be used in designing the system. In fluid dynamics, Bernoulli's principle states that for an inviscid flow, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy. According to that principle, when a pipe is partially immersed such that one end is above the liquid level and the opposite end is near the bottom of a plastic container partially filled with liquid and a suction is applied to that bag at a point significantly above the liquid level, the particles entering the liquid through the pipe will be trapped there. After absorbing the particles, the liquid level will rise to a certain level while air/gas is bubbling through it, but will never reach the suction point. Such a rise in the liquid level will be carefully calculated using Bernoulli's equation, which will ensure that the liquid will stay in the container to trap the particulate matter without being discharged through the suction point and outside the container.

Fig. 1 illustrates the Bernoulli principle, where the mixture of air and particles of various sizes will enter the suction head at certain velocity and under suction (negative) pressure. The suction pressure and the air velocity will be regulated via a simple valve, which only allows the viscous liquid in the container to rise within certain, pre-determined levels in the container. Once the particles travel through the suction tube and enter the viscous liquid or foam section, they will meet with the viscous resistance of liquid phase or foam under a regulated pressure and at entrance velocity. In this way, the particles will be trapped and settled at the bottom wall of the container. In this work, a particle control system is designed and prototyped based on the Bernoulli principle as explained in Fig. 1.

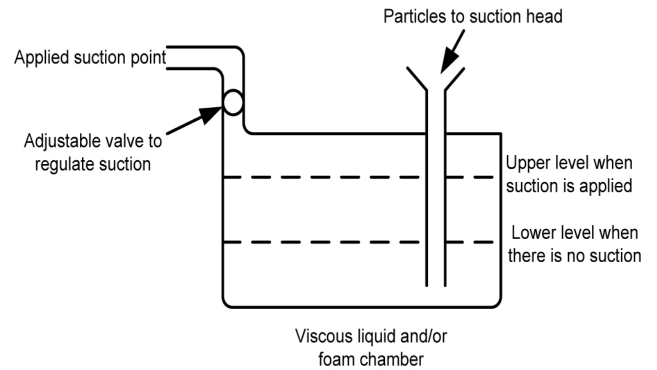

Figure 1. Illustration of the Bernoulli principle

Initial Design

Based on evaluation and comparison of all design alternatives, the initial design scheme was selected for further prototyping and experimental validation (Fig. 2). In this design, filter papers are used as indicators to measure the absorbing capability of this system. Viscous liquid is used as the main filter medium, through which the air passes and is cleaned. As shown in Fig. 1, after passing through the filter medium (liquid), the air enters a triple valve outlet where only one is open for flow at a time. Afterwards, the cleaned air will pass through the filter paper. In the selected design, three valves are installed for air to pass but at one time, only one of them is open and the other two are closed. Such mechanism allows us to measure the particles captured by a filter paper and/or replace the filter paper during the experiment without affecting the circulation. For example, after a while if we want to inspect the filter paper from the first tube, we can turn off the first valve and turn on the second valve, while removing the filter paper from the first tube, the air will flow through the second valve and we can continue running the experiment.

This design scheme was selected because compare to the aforementioned design options, the present design offers unique advantages. At first, this apparatus is designed based on a simple but innovative idea. The usage of filter papers to measure the capacity and efficiency of the system decreases design and manufacturing costs and allows users to easily observe the progressive absorption of the particles by the filter medium. Secondly, the overall size of this system can be scaled within its size limits to be employed for a wide variety of applications with different requirements. Another attractive advantage of this design is its low cost and high flexibility, which will be illustrated through experimental validation.

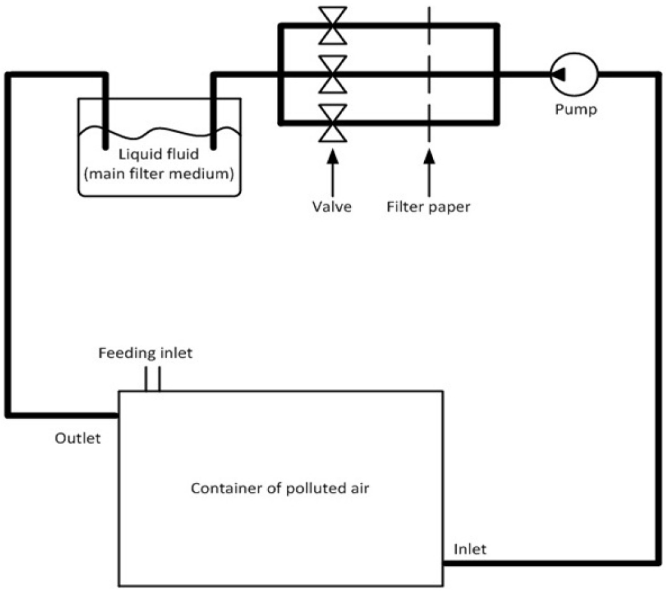

Figure 2. Schematic of the initial design

PROTOTYPING

As shown in Fig. 2, the particulate control system includes a container, three valves, filter papers and tubes that connecting them together. In the prototype, a plastic container with 1.8ft × 1.25ft × 1.25ft is used to store the filter medium (we use water for our validation), which was well sealed with silicone to avoid any leakage. The plastic container, instead of a glass container, was chosen for experiments because the glass material is very fragile and extremely hard to be drilled. With the plastic container, holes can be easily drilled onto it for adding tubes and fittings. Also, the plastic container significantly reduces the overall weight of this system and makes it very portable and cost efficient. Three cylinders are connected to the container in parallel, each of which has a valve and filter paper inside. The valve is to control the air flow and the filter paper, as mentioned before, is used as an indicator to show the particles being caught by this system. Besides major components in this system, several auxiliary apparatus are installed in order to run experiments. A flask with ashes and other particles is prepared for "polluting" the air, which will be caught and trapped by the system. A 12V rechargeable air compressor is employed to compress air and pump the ashes and other particles from the flask into the air. The compressed and "polluted" air then goes into the container and will be trapped there. The flask, compressor, as well as other components are connected in series through tubes and fittings, which are sealed with epoxy and silicone to avoid potential leakage due to the pressurized water. Fig. 3 shows the container with the compressor and Fig. 4 displays the flask and three cylinders.

Figure 3. Partially water-filled container attached to air outlets

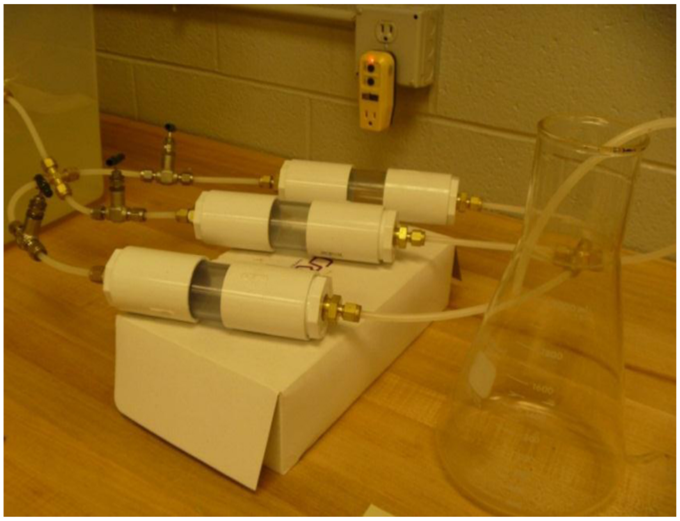

Figure 4. Flask and three cylinders with valves and filter papers inside

EXPERIMENTAL ANALYSIS AND EVALUATION

Running Experiment

In running the experiment, the flask with certain amount of ashes and particles inside is connected to the air compressor through a tube. The air compressor is first turned on to compress air and drive it through the flask to absorb the ashes and particles. Afterwards the compressed and "polluted" air enters the container and is trapped by the filter medium (viscous water here) according to the Bernoulli principle. The cleaned air then passes through the tube and the remaining particles will be captured by the filter papers.

Finally, the filtered air is disposed into the environment through an outlet.

Analysis of Experimental Results

After the experiment, the efficiency and capability of the developed system in removing the particles suspending in the air can be evaluated through comparing the amount of particles and ashes (in the flask) before and after the experiment, the ashes and particles trapped by the filter medium (from the bottom of the container), and the particles filtered by the filter papers (measured from the filter papers). The difference of the amount (in terms of weight) of mixtures of particles and ashes before and after the experiment identifies the amount of particles mixing into the air. At the outlet, the remaining particles of the discharged air were also collected and measured. The difference between the particles included in the original "polluted" air and the remaining particles indicate the particulate matters captured and filtered by the filter medium and the filter papers, which is used to depict the efficiency and capability of the developed system. The experiment was kept running for six hours and about 1 pound of particles was trapped by the developed system. It was found that most particles were trapped by the filter medium and located on the bottom of the container, and only a few particles were captured by the filter paper, which was observed and measured in UL lafayette's Microscopy Center, as shown in Fig. 5. At the end of the experiment, the particles captured on the bottom of the container and on the filter papers were safely disposed. Fig. 5 shows the entire experiment system.

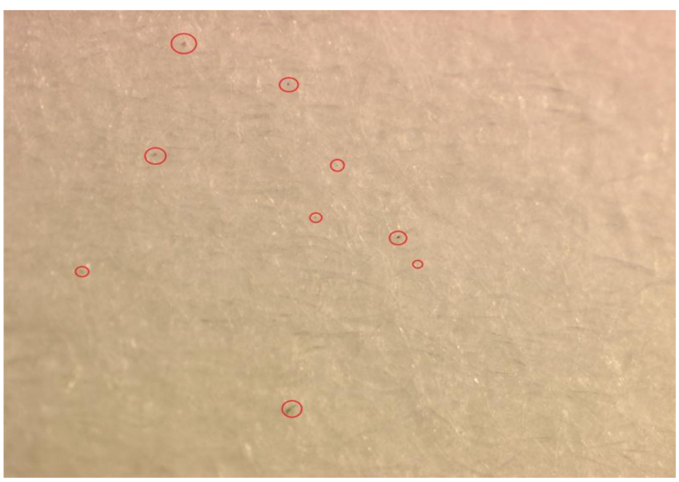

Figure 5. Particles captured by the filter paper

Figure 6. Particulate control system for experimental validation

SUGGESTIONS

The experimental results are satisfying; however, it was found from the experiment that the presented system can be improved in following facets:

1. First, it was found the 12V air compressor used for the experiment is not powerful enough. It is planned to use a high power pump to effectively and massively compress the air and drive it into the particulate control system. The using of the high power pump will significantly reduce the experimental time.

2. Water was used for this experiment to trap the particles, which does not have any viscosity. In next step, we plan to increase the viscosity of the filter medium (for example, to add polymers into the water or change a new filter medium with higher viscosity) and rerun the experiment. The obtained experimental results will reveal the effects of the viscosity of the filter medium on the efficiency of the developed system, based on which an ideal filter medium can be selected for further development.

3. In the future, abrasive particles will be used for the experiment to test tolerance of the developed system to the abrasive properties of particles. The capability of processing abrasive particles will be a unique merit of this system, with which the system can be applied in spacecraft, workstation, and other planetary structures to remove the abrasive particles such as lunar surface dust.

4. Further investigation will be conducted to study the efficiency of the system in removing and disposing particles of different size and optimize the design accordingly. Our ultimate goal is to develop a flexible particulate control system that can efficiently process particles of a wide range (from 5 to 1000 μm).

5. Containers with different shapes and dimensions will be evaluated through this experiment in order to find the optimal shape and size of the container so as to achieve the best particle removal capability, and to make the developed system applicable for different occasions.

6. After finishing the experimental design and study, all experiments will be modeled and reproduced in computational environment through computational fluid dynamics (CFD) simulation. The computer models then can be combined with the experimental techniques for further optimizations and developments, such as extend its lifetime, minimize the operation cost, and commercialization, etc.

ADVANTAGES OF THE DESIGN

Based on the experimental results, it was found that compare to existing particulate control systems the developed prototype offers following unique merits. (1) The developed system represents a simple and robust technology to cleanly remove particles suspended in air while avoiding dispersing them in the environment. (2) The system is very flexible: its size can be scaled up and down, and the filter medium inside can be easily switched so as to be applicable on different occasions. (3) The system can be easily built with a very low cost. The developed particulate system only includes a plastic container, three valves, filter papers, filter liquid, and tubes, whose overall cost does not exceed $10. (4) The performance of this system and its efficiency in air cleaning can be easily evaluated by measuring the weight of the trapped and filtered particles. (5) Because of its flexibility, the proposed system can be interfaced with or made compatible with many types of particles, for example, mitigating the amount of particles entrained in smoke or even mitigating the effect of an unpleasant odor.

Due to the aforementioned advantages, the designed prototype has a broad applicability in industry and therefore possesses strong prospects for commercialization. In aerospace and space engineering, particulate matter suspended in the habitable cabin atmosphere is a challenge for all phases of crewed lunar surface exploration missions. The particulate control system built in this project can be applied to efficiently and safely remove and dispose the particulate matter originating from sources internal to the habitable cabin and from lunar surface dust intrusion in the cabin environment. In automotive industry, the present particulate management technology can be used to develop filter systems to work in-line with the vehicle or habitat ventilation system. In that regard, the designed prototype can be modified into a portable device to decouple the filtration system from the vehicle's ventilation system. Meanwhile, the designed system and presented particle transfer technology can also be applied in any civil industries where materials, because of potential hazard, contamination, general cleanliness or other reasons, must be processed in a manner that exposure to the outside must be minimized or eliminated. Such industries include, but are not limited to, chemical and pharmaceutical production, fossil fuel power plant operations, ore processing, HVAC industry, and environmental protection.

The body of the paper should include detailed and structured description of the work performed, including (as appropriate) methodology, assumptions, hardware, observations, analysis, and a comparison of results with prior work. The information presented must be self-contained (in the sense that the reader is not assumed to have read prior papers) and provide an appropriate level of detail for the intended audience. Define all terms at first usage and apply them consistently.

The body section is not entitled *Body*. Rather it comprises multiple sections and subsections titled using topical headings in a four-level structure. Template styles [Head1] through [Head4] are used to tag and format titles of the different levels. No specific heading titles are mandated, but common examples include Methods, Results, and Discussion. Figures, tables, and equations fall under the body section. Here are examples of a figure, a table, and an equation (3.5″ wide to ensure effective flow of information throughout your paper).

CONCLUSIONS

In this project, a particulate control system is designed based on the Bernoulli principle and prototyped for experimental validation. The advantages and prospects of the developed system are illustrated through the experiment results. Meanwhile, the present system can be extensively optimized and developed to be able to efficiently and safely process a wide range of particles with different size and properties and be applicable for different occasions. For example, the system can implement an ideal filter medium with optimum permeability and porosity, which can be a walnut shell medium wet with a fluid or a polymer filter medium with micro size permeability. Moreover, the particulate control system can include a microfibrous support and a nanofibrous facial layer or use many-layer nanofibrous filters combined with a single microfibrous backing to make it more profitable from the quality factor standpoint in the improvement phase. In summary, due to its low cost, portable size, and high flexibility, the developed system has bright prospects for commercialization and has the potential to benefit many industries.

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