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Post-disaster Air Purification System Based on Bionic Lung Design

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ABSTRACT

Disasters can have a significant impact on air quality and thus pose a threat to the health of people in the affected areas. There are no post-disaster air purification systems or specialized technologies currently. In this paper, a post-disaster air purification system is designed based on the mechanism of lung purification of mammals. It uses two-stage purification, which mainly purifies particulate matter in the air, such as PM2.5 and PM10. The first stage is coarse purification, which simulates the villi fibers in the nasal cavity to block particulate matter. The second stage simulates macrophages in the alveoli to achieve efficient purification of particulate matter. The post-disaster air purification system adopts intelligent control and introduces an innovative mechanical structure design with a special adsorption structure and guiding structure, which can effectively increase the adsorption area of particulate matter in the air and its adsorption capacity. Also, it has a simple structure and can be disassembled and assembled with less effort, which meets the special emergency needs after the disaster.

Keywords: air purification, bionic lung, post-disaster, particulate matter

1. INTRODUCTION

Disasters can have an impact on air quality in both the long and short term. Exposure of people in disaster areas to air pollution caused by disasters can have unpredictable health consequences [1]. Disasters have led to more severe air pollution, which exceeded the levels recommended by the World Health Organization air quality guidelines [2]. Taking the Wenchuan earthquake as an example, according to the Aba State Environmental Research and Monitoring Data and the number of respiratory disease clinics at the hospital in the county, the air pollution from the Wenchuan earthquake was extremely serious and caused many people to suffer from respiratory diseases [3]. Therefore, air purification is one way to reduce air pollution caused by disasters, which is an important part of safeguarding the health of people in disaster areas.

There is no technology specifically designed for post-disaster air purification, nor is there an air purification system produced for this purpose. At present, the main technologies for air purification are fiber filtration, activated carbon adsorption, electrostatic dust removal, low-temperature plasma, photocatalysis, ultraviolet lamps, and ozone.

The two-film theory proposed by Cooper and Alley in 1998 laid the foundation for air washing, which uses water droplets or fiber filtration materials as the adsorbent matrix for air washing, and impurities in the air come in contact with the adsorbent matrix and thus settle [4,5]. The treatment process using water droplets as a substrate is that gaseous substances are adsorbed onto the water droplet substrate by physical adsorption, and gaseous chemicals in the liquid substrate are captured separated, and removed from the air [5]. In 2017, De Vries compared the effectiveness of air purification systems with three different liquid matrices for the treatment of exhaust gases emitted from animal husbandry, where different chemicals were added separately to the water matrix and the liquid-air contact area was enhanced using liquid atomization [6]. In 2020, Heyden developed a mechanistic model for ammonia removal using an air purification system, which considered the effects of ventilation rate and air temperature on the adsorption effect of water droplets [7]. Kimre China INC. LTD designed an air purification system that uses a spraying device to generate micron-sized aerosol to produce a water droplet matrix for adsorption, and another three-dimensional mesh structure of fiber filter material to intercept particulate impurities as filter material [8].

Miaomiao Zhu et al. [9] reported that air purification using electrostatic spinning fibers is a promising new technology for intercepting fine particulate matter, volatile organic gases, and bacteria. However, it has poor mechanical properties and production efficiency with high manufacturing costs and the risk of organic solvent residues. Fariborz Haghighat et al. [10]

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suggested that Photocatalytic oxidation (PCO) is superior in the removal of low concentrations of pollutants. However, the reaction pathway and the main intermediates or by-products may be toxic. Photocatalytic deactivation leads to a significant decrease in removal efficiency and an increase in the number of byproducts due to partial oxidation of volatile organic compounds (VOCs). In addition, from an economic point of view, the short lifetime of the catalyst leads to frequent regeneration or replacement of the catalyst, which in turn increases the costs associated with the system. Haomin Huang et al. [11] proposed that activated carbon has the advantages of large specific surface area, abundant functional groups, and high adsorption capacity, and is widely used to treat different types of carbon-based gases, but its suitability and sustainability need to be improved. A.E. De Oliveira et al. [12] proposed electrostatic precipitation (ESP) technology in a review. ESP has advantages over other typical separators in this size range, such as high-efficiency particulate arrestance (HEPA) filters and air ionizers. However, it faces the limitation of being difficult to apply to large systems, as well as generating ozone during the precipitation process. Moreover, the UV lamp irradiation method propagates in a straight line, with weak penetration and limited irradiation locations. Also, the ozone disinfection method has high requirements for the disinfection environment, requiring ambient humidity greater than 70%, requiring personnel avoidance during disinfection, and having a corrosive effect on metals.

The post-disaster air purification system uses adsorption technology to achieve the purification of particulate matter, like other air purification systems. Also, based on the two-film theory, it uses water as the purification medium to greatly reduce the output of intermediate products and effectively reduce the possible toxic side effects. However, in comparison with previous studies, the post-disaster air purification system introduces an innovative design. Firstly, it adds the bionic mechanical design concept to the air purification process. Secondly, the post-disaster air purification system uses a connector and a water level sensor. It not only allows the water flow to be replenished and recycled to save costs but also reduces the waste of resources as much as possible. Thirdly, it can be flexibly adjusted to the size according to the application environment, and the mechanical performance and manufacturing cost can be controlled as well.

In this paper, we propose and design a post-disaster air purification system based on the mechanism of lung purification of mammals. The post-disaster air purification system uses a two-stage purification of particulate matter in the air such as PM2.5 and PM10 in a manner similar to that of lung purification. We have made innovative mechanical structure design and intelligent control for its adsorption capacity and adsorption area of air impurities so that it can efficiently adsorb and settle the particulate matter in the air. In view of the special situation after the disaster, we simplified the structure of the system as much as possible, so that it has a simple fixing method and labor-saving disassembly, to meet the emergency needs.

2. METHODOLOGY

2.1 Mechanism of lung purification

Mammals use lungs to breathe and perform two-stage purification of inhaled air, which is an inspiration for designing a post-disaster air purification system. The two-stage purification of mammals has the function of self-defense and selective filtration of particulate matter of different particle sizes in the inhaled air.

The first-stage purification is carried out by coarse filtration through the nasal cavity, tracheal folds, and villi fibers. However, most of the inhaled air is still entrained with the particulate matter after primary purification. The second-stage purification is alveolar filtration, where particulate matter is recognized and filtered by macrophages in the alveoli when they come into contact with the alveolar surface. For these particulate matter, organic particulate matter is absorbed, broken down, engulfed, and excreted through the kidneys, while the inorganic particulate matter is collected into the sputum and excreted through tracheal shock [13].

2.2 Mechanical structure based on bionic lung

The post-disaster air purification system is inspired by the mechanism of lung purification and developed by the software SolidWorks. The drawings and specifications are shown in Figure 1 and three views are represented in Figure 2.

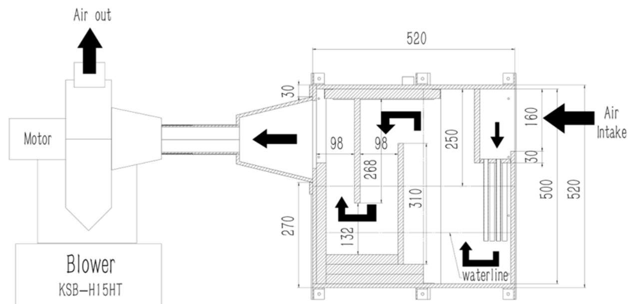

Figure 1. Drawing and specifications of the post-disaster air purification system.

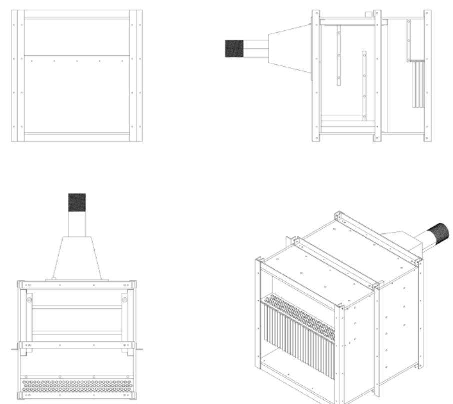
Figure 2. Three views of the post-disaster air purification system.

The post-disaster air purification system can be divided into different modules according to their structural characteristics, and then the designed modules are assembled and combined. Figure 3 offers perspective views of the post-disaster air purification system.

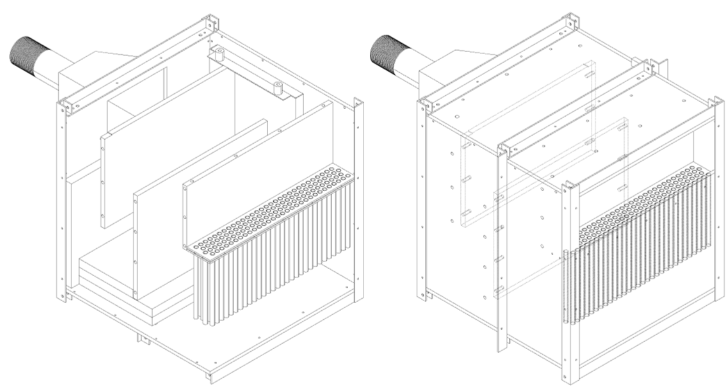
Figure 3. Perspective views of the post-disaster air purification system.

The post-disaster air purification system consists of two-stage purification for particulate matter like PM2.5 and PM10 based on the bionic lung. The first-stage purification mimics the villi fibers in the nasal cavity that block particulate matter. At first, water is added to the inside of the system until it reaches the mouth of the tube. Air is passed through the air inlet and along the tube below the water surface to produce dense bubbles. The denser the bubbles, the better the treatment effect. This stage of purification achieves coarse filtration by settling the large particulate matter in the air such as sand and dust.

For the second-stage purification, the coarsely filtered air enters the cavity of the post-disaster air purification system. An absorbent sponge is set up at the air turning part, which can absorb PM2.5, PM10, and other particle matter due to its loose and porous nature. This process mimics the recognition and filtration of particulate matter by macrophages in the alveoli. The absorbent sponge can be replaced and is located in a position that facilitates timely replacement. The replacement process is similar to the elimination of organic particulate matter through the kidneys. At the same time, a water turbidity sensor is installed in the transparent housing to monitor the use of the replacement cartridge.

The air travels inside the post-disaster air purification system following a guide defined by the baffle, which is like the inhalation path of the gas entering the lungs. It contributes to improving the efficiency of purifying the particulate matter in the air. First, the path through which the airflow increases, the contact area between the air and the absorbent sponge during filtration becomes larger, and the number of times the air contacts the absorbent sponge can be increased to two, thus increasing the efficiency. Also, the particulate matter in the air detaches from the air at the turn due to inertia, making the efficiency improve again.

2.3 Calculation on air purification volume based on ASHRAE standard

ASHRAE Standard 62 is a representative international standard for air volume. It takes into account both occupant and building pollution and sets different design methods for air volume in buildings with different occupant densities. Based on ASHRAE Standard 62, the air volume can be calculated by the following Equation (1):

$$\mathrm{V}_{bz} = R_p P_z + R_a A_z \tag{1}$$

where V_{bz} is air volume of the breathing zone design (unit: L/s), R_p is the air volume required by per person (unit: $L/(person*s)$), P_z is the number of people in the room (unit: $person$), R_a is the amount of fresh air required per unit of floor area, A_z is the floor area (unit: m^2).

With the calculated air volume, the airflow design and size of the post-disaster air purification system can be determined. Table 1 represents some parameters of the motor, blower, and post-disaster air purification system, which can help engineers quickly process one that meets the standard air volume.

Table 1. Parameters of the post-disaster air purification system.

Motor	Blower			Post-disaster air purification system	
rpm (Hz)	Air speed (m/s)	Air volume (m^3/h)	Pressure (Pa)	Temperature ($^\circ C$)	Pressure (Pa)
0	0	0	0	27	0
20	6.83	220.9	-300	27	-200
30	15.75	509.5	-800	27	-500
40	18.86	610.1	-1700	27	-800
50	24.74	800.4	-2600	27	-1150
60	26.36	852.8	-3750	27	-1500

3. DESIGN OF INTELLIGENT CONTROL HARDWARE

3.1 Overall design

In the post-disaster air purification system, the overall design of the hardware of the intelligent control system is shown in Figure 4. The intelligent control uses ATMEL89C51 MCU as the main control unit, non-contact liquid level sensors, environment sensor, PM2.5 laser sensor as data acquisition module, Bluetooth, button, and OLED LCD screen display as external thermal interaction. According to the sensor monitoring data and human-computer interaction control, the adapted power supply module is driven to realize the efficient control of fan wind speed, water level control and pump rate of the post-disaster air purification system. Intelligent control is helpful to save human and material resources, and the automatic monitoring function is crucial in the post-disaster situation when resources are scarce.

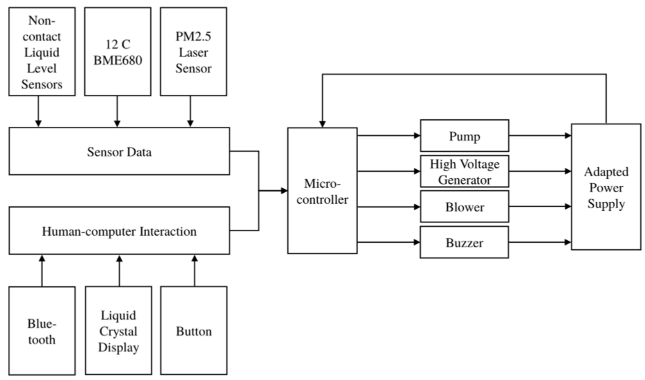

Figure 4. Structure of the post-disaster air purification system.

3.2 Sensor data acquisition

3.2.1 Non-contact liquid level sensors

The post-disaster air purification system uses the non-contact liquid level sensor of the model XKC-Y26-NPN as a solution for controlling the water level. The sensor uses the inductive capacitance of water to detect the presence of liquid and has the function of outputting data through the serial port. It can monitor the water level information of the system in real-time to ensure that the water level is not over the pipe mouth to produce dense bubbles.

3.2.2 Environment sensor

The post-disaster air purification system uses an environmental sensor of model BEM680 to measure four parameters—VOC (Volatile Organic Compounds), temperature, humidity, and air pressure, which are used to monitor the adequacy of various indicators of the system. It has the function of outputting data through the serial port. Also, it can provide real-time feedback on the processing of the device. Therefore, it is able to adjust the system to stop the motor when the temperature or humidity is low and moderate the air pressure to meet the needs of different areas.

3.2.3 PM2.5 laser sensor

The PM2.5 laser sensor is a digital general-purpose particulate matter concentration sensor that can be used to obtain the particulate matter concentration—the number of suspended particulate matter per unit volume of air from 0.3 to 10 microns. It can output it as a digital interface, as well as the mass data of each particle. The monitoring sensitivity is high, and it can communicate directly with the microcontroller through the IIC signal. Also, it can monitor the environmental quality and realize the automatic opening of the system to the feedback information from the microcontroller.

4. CONCLUSION

In response to the air pollution caused by disasters, this paper introduces a design of a post-disaster air purification system based on the bionic lung to provide air quality assurance for people in disaster areas. It has a simple structure and is easy to put together. It can efficiently remove airborne respirable particulate matter, such as PM2.5 and PM10, and has the advantages of monitoring filtration quality. The air in the natural environment is weak in autonomous purification, and the post-disaster air purification system in this paper innovatively applies the bionic lung structure to its structure, increasing the adsorption structure and guiding structure with a unique mechanical structure design. Also, it adopts the hardware design of a high-performance microcontroller and peripheral multi-sensor combination and is driven by an intelligent software control program, which makes up the core control unit to make the post-disaster air purification system smoothly.

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