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Design and Implementation of a Multistage Smart Air Purifier

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Abstract*: This project focuses on the design and implementation of a multistage household air purifier that integrates advanced filtration, real-time air quality monitoring, and humidity control to enhance indoor air quality efficiently and cost-effectively. The system incorporates a three-stage filtration process using an activated carbon filter for volatile organic compounds (VOCs) and odor removal, a HEPA filter for particulate matter filtration, and a silica gel filter for humidity regulation. Additionally, an ultrasonic humidifier ensures optimal indoor humidity levels, while high-sensitivity sensors continuously monitor air quality and display real-time data. The design process includes problem analysis, component selection, system modeling using CAD, prototype development, testing, and data analysis to optimize efficiency. Key design calculations consider airflow requirements, fan selection, filter efficiency, humidifier sizing, and overall power consumption to ensure an effective and sustainable solution. Expected outcomes demonstrate the air purifier's ability to remove 99.97% of airborne particles, significantly reduce VOC levels, and maintain relative humidity within the recommended range of 40-60%. By addressing air pollution concerns and maintaining a healthy indoor environment, this project presents a practical and innovative solution for modern households at an affordable cost*

Keywords: HEPA filters , Activated carbon filters , Silica gel, Cost-effectiveness

I. INTRODUCTION

1.1 Overview

Indoor air pollution is a growing concern worldwide, significantly affecting human health and overall well-being. With rapid urbanization, increased industrial activities, and the rising use of household chemicals, indoor air quality has deteriorated, leading to various respiratory diseases, allergies, and other health issues. Pollutants such as dust, pollen, volatile organic compounds (VOCs), smoke, and microbial contaminants can accumulate in enclosed spaces, making air purification an essential aspect of modern living. Conventional air purifiers often lack a comprehensive approach to address multiple pollutants simultaneously, making it necessary to develop an advanced, multistage household air purification system that ensures a healthier indoor environment.

This project aims to design and implement a cost-effective, multistage household air purifier that integrates high-efficiency air filtration, real-time air quality monitoring, and humidity control to deliver superior indoor air quality. Traditional air purifiers primarily focus on particulate removal using HEPA filters but often neglect humidity regulation and gaseous pollutant adsorption, which are equally critical for maintaining a balanced and comfortable indoor atmosphere. By incorporating a three-stage filtration process—activated carbon for odor and gas adsorption, HEPA for fine particulate matter removal, and silica gel for humidity control—this system enhances air purification efficiency beyond conventional solutions.

The integration of an ultrasonic humidifier further optimizes indoor humidity levels, preventing excessive dryness or excessive moisture that could lead to mold growth. Additionally, an AQI (Air Quality Index) monitoring system with high-sensitivity sensors provides real-time data, allowing users to track indoor air conditions and make informed decisions. The combination of these features ensures a comprehensive solution for improving air quality, making it suitable for households, offices, and other enclosed spaces prone to poor ventilation.

One of the key aspects of this project is ensuring an energy-efficient and user-friendly design. The purifier is engineered to consume minimal power while maintaining high performance, making it an affordable and sustainable solution for long-term use. The system's CAD-based design allows for optimal airflow, ensuring effective pollutant removal while maintaining compactness and aesthetic appeal. Moreover, the use of easily replaceable filters and minimal maintenance requirements enhances user convenience and system longevity.

To validate the effectiveness of the proposed air purifier, rigorous testing is conducted to measure its filtration efficiency, air quality improvement, and humidity regulation capabilities. These tests involve assessing particulate removal, VOC reduction, and AQI monitoring accuracy against industry benchmarks. By analyzing real-time data and comparing results with conventional purifiers, this project aims to demonstrate the superior performance and feasibility of the developed system.

This multistage air purifier presents a novel approach to tackling indoor air pollution by integrating advanced filtration, real-time monitoring, and humidity control in a single unit. With increasing concerns over air quality and its impact on health, the development of efficient and affordable air purification solutions is crucial. This project not only addresses existing challenges in air purification technology but also paves the way for further innovations in sustainable indoor air management.

1.2 Motivation

The motivation behind this project stems from the increasing concerns over indoor air pollution and its adverse effects on human health. With rising levels of airborne contaminants such as dust, VOCs, allergens, and humidity imbalances, conventional air purifiers often fail to provide a comprehensive solution. This project aims to develop an affordable, energy-efficient, and multistage air purification system that effectively removes pollutants, regulates humidity, and monitors air quality in real time. By integrating advanced filtration and smart monitoring, the purifier enhances indoor air quality, ensuring a healthier and more comfortable living environment.

1.3 Problem Definition and Objectives Problem Definition

Indoor air pollution is a significant concern due to increasing urbanization, industrial emissions, and household pollutants, leading to respiratory issues and poor air quality. Existing air purifiers lack an integrated approach to address multiple pollutants, humidity control, and real-time air quality monitoring. This project aims to develop a cost-effective, multistage air purifier that efficiently removes pollutants, maintains optimal humidity levels, and provides real-time AQI feedback to enhance indoor air quality.

Objectives

- To study the effectiveness of HEPA, activated carbon, and silica gel filters in air purification.
- To study the integration of an AQI monitoring system for real-time air quality assessment.
- To study the role of humidity control in improving indoor air quality.
- To study the energy efficiency of the proposed multistage air purifier system.
- To study the feasibility of developing a cost-effective and user-friendly air purification solution.

1.4 Project Scope and Limitations

This project focuses on designing and developing a multistage household air purifier that integrates HEPA, activated carbon, and silica gel filtration with real-time AQI monitoring and humidity control. The system aims to enhance indoor air quality by efficiently removing pollutants, odors, and excess moisture while maintaining an energy-efficient and cost-effective operation. The air purifier will be optimized for compactness, ease of maintenance, and affordability, making it suitable for residential and small office environments.

Limitations

- Limited effectiveness in extremely high-pollution environments.
- Requires periodic maintenance and filter replacement.

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- Humidifier effectiveness depends on room conditions.
- Power consumption may increase with extended usage.
- Not suitable for industrial-scale air purification.

II. LITERATURE REVIEW

1. Multi-Stage Air Filtration System for Indoor Air Quality Improvement

Authors: Zhang et al. (2021)

Summary: This study focuses on the performance of a multi-stage air filtration system using HEPA, activated carbon, and ionization technology. The research evaluates the system's effectiveness in removing particulate matter (PM2.5 and PM10), volatile organic compounds (VOCs), and microbial contaminants. The study found that the combination of HEPA and activated carbon filters effectively reduced airborne pollutants by 95%, with activated carbon significantly adsorbing VOCs. However, the study also highlighted that regular maintenance is required to maintain efficiency.

Relevance to Project: This paper supports the implementation of multi-stage filtration in the proposed air purifier to maximize pollutant removal.

2. Performance Evaluation of HEPA Filters in Air Purification

Authors: Kim et al. (2020)

Summary: This research examines HEPA filter efficiency in trapping fine airborne particles, including dust, pollen, bacteria, and viruses. The study conducted experimental tests in controlled environments and found that HEPA filters removed 99.97% of particles larger than 0.3 microns. Additionally, the research highlighted airflow resistance and the need for proper fan selection to optimize filtration efficiency.

Relevance to Project: This study provides valuable insights into the HEPA filter's role in the air purifier, confirming its importance in achieving high air quality standards.

3. Adsorption Capacity of Activated Carbon in Indoor Air Pollution Control

Authors: Liu et al. (2019)

Summary: The study investigates the adsorption properties of activated carbon in removing VOCs and gaseous pollutants. The research highlights that activated carbon filters effectively reduce indoor concentrations of formaldehyde, benzene, and ammonia by 65-80%. The paper also discusses filter saturation and the necessity of timely replacements to maintain performance.

Relevance to Project: This paper validates the use of activated carbon in the proposed system to remove harmful gases and odors from indoor air.

4. The Role of Humidifiers in Enhancing Indoor Air Quality

Authors: Patel & Singh (2022)

Summary: This study evaluates the impact of humidity control on indoor air quality and human health. The research shows that maintaining relative humidity between 40-60% helps reduce respiratory illnesses and minimizes the spread of airborne pathogens. It also highlights the effectiveness of ultrasonic humidifiers in achieving optimal moisture levels without excessive energy consumption.

Relevance to Project: This study supports the integration of a humidifier in the proposed air purifier to maintain balanced humidity levels, improving comfort and health.

5. Smart Air Purifiers with IoT-Based AQI Monitoring

Authors: Choudhary et al. (2021)

Summary: The paper presents an IoT-based air purification system that continuously monitors air quality using real-time sensors. The study describes how integrating sensors with a digital display allows users to track AQI levels and adjust filtration settings accordingly. The research highlights improved user experience and the ability to optimize energy usage based on pollutant levels.

Relevance to Project: This paper supports the use of AQI monitoring in the proposed air purifier, enabling real-time assessment of indoor air quality and data-driven optimization.

III. METHODOLOGY

The proposed multistage household air purifier is designed to enhance indoor air quality through advanced filtration, real-time AQI monitoring, and humidity control. The system follows a structured approach to ensure efficient functioning, cost-effectiveness, and ease of use. Below is a detailed explanation of the working methodology.

3.1 System Overview

The air purifier consists of multiple stages of air filtration and monitoring to remove dust, allergens, volatile organic compounds (VOCs), and regulate humidity. The system's main components include:
Filtration Unit: Comprising HEPA, Activated Carbon, and Silica Gel Filters
AQI Monitoring System: Sensors for real-time PM2.5, PM10, and VOC detection
Humidification Unit:Ultrasonic humidifier to maintain balanced air moisture
Fan & Air Circulation Mechanism: Optimized for steady airflow and low noise
Power Supply & Control Circuit: Microcontroller-based smart operation

3.2 Step-by-Step Working of the Proposed System

Step 1: Air Intake & Pre-Filtration
Ambient air is drawn into the purifier through an intake vent using a high-speed axial fan.
Pre-filter (mesh filter) removes large dust particles, pet hair, and pollen, preventing clogging of subsequent filters.
Step 2: Multistage Filtration Process
The system employs three advanced filtration stages:
HEPA Filter (High-Efficiency Particulate Air Filter)
Captures 99.97% of particles ≥0.3 microns, including fine dust, mold spores, bacteria, and allergens.
Ensures cleaner air by removing microscopic pollutants.
Activated Carbon Filter
Adsorbs volatile organic compounds (VOCs), harmful gases, smoke, and odors.
Essential for reducing chemical pollutants from household items like paints, cleaning agents, and cooking fumes.
Silica Gel Filter
Absorbs excess moisture from air, preventing mold growth and humidity-related issues.
Helps in maintaining a balanced relative humidity level indoors.
Step 3: Real-Time AQI Monitoring
Integrated Air Quality Index (AQI) sensors measure PM2.5, PM10, and VOC concentrations in real time.
Data is displayed on an LED digital screen, showing air quality levels in numerical and color-coded formats.
The system triggers an alert mechanism (e.g., indicator light or sound) when air quality deteriorates.
Step 4: Humidity Control Mechanism
If air humidity falls below 40%, an ultrasonic humidifier is activated to release fine mist, restoring optimal levels.
If humidity exceeds 60%, the silica gel filter absorbs excess moisture, preventing condensation.
Step 5: Smart Air Circulation & Auto Mode
The microcontroller automatically adjusts fan speed based on AQI sensor data.
Auto Mode: If pollution levels are high, the fan operates at maximum speed to increase filtration.
When air quality improves, the system reduces speed to save energy and minimize noise.
Step 6: Power Management & Efficiency Optimization
The purifier operates on a low-power circuit (~70W total) for energy efficiency.
Standby mode is activated when air quality remains stable, reducing unnecessary power consumption.

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3.3 Prototype Development & Testing

Component Selection & Assembly

- Selected components (HEPA filter, carbon filter, AQI sensor, humidifier) are integrated into a compact casing.
- CAD modeling ensures optimal airflow design and efficient component placement.

Performance Testing

- The purifier undergoes testing in controlled indoor environments with varying pollution levels.
- Filtration efficiency is measured using standard AQI meters before and after purification.
- Humidifier performance is evaluated by monitoring relative humidity changes over time.

Data Analysis & Optimization

- Collected air quality data is compared against industry benchmarks.
- Design improvements are made based on test results to enhance filtration efficiency, airflow, and power consumption.

3.4 Summary of the Working Process

The proposed multistage household air purifier is a smart and energy-efficient solution for improving indoor air quality. The system effectively removes pollutants, monitors air quality in real-time, and maintains optimal humidity levels using advanced filtration and automation. The methodology ensures that the purifier operates with high efficiency, low maintenance, and user-friendly controls, making it an ideal choice for household applications.

IV. DESIGN CALCULATIONS

The performance of the smart air purifier is based on critical design calculations to ensure effective air purification, proper airflow, and energy efficiency. The key parameters considered include airflow requirement, fan selection, filter efficiency, humidifier sizing, and power consumption.

A. Airflow Requirement

For an average room size of 5m × 4m × 3m, the total air volume is 60 cubic meters. To maintain clean air, at least five air changes per hour (ACH) are required. This results in an airflow requirement of approximately 300 cubic meters per hour (or 5 cubic meters per minute).

B. Fan Selection

Based on the airflow requirement, a fan with a capacity of 300 cubic meters per hour is selected. The fan must also provide sufficient static pressure to compensate for resistance from filters.

C. Filter Efficiency

The system incorporates a HEPA filter and activated carbon filter for high air purification efficiency:

HEPA Filter: Captures 99.97% of airborne particles down to 0.3 microns, with an airflow resistance of approximately 0.15 inches of the water column.

Activated Carbon Filter: Effectively adsorbs volatile organic compounds (VOCs) with an efficiency range of 50–70%, adding a resistance of 0.05 inches of the water column.

D. Humidifier Sizing

To maintain an indoor relative humidity (RH) of 40–60%, a water output of around 6 liters per day is required. A 2-liter ultrasonic humidifier operating for 12 hours daily meets this requirement.

E. Power Requirements

The total power consumption of the system is optimized for energy efficiency:

Fan: 30–40W

Humidifier: 25W

Air Quality Sensor & Display: 5W

Total Power Consumption: Approximately 70W

This design ensures a balance between effective air purification, humidity control, and energy efficiency, making the system suitable for smart indoor environments.

V. CONCLUSION

5.1 Conclusion

The design and implementation of the multistage smart air purifier successfully integrate advanced air filtration, real-time AQI monitoring, and humidity control to enhance indoor air quality. By utilizing a combination of HEPA, activated carbon, and silica gel filters, the system effectively removes particulate matter, VOCs, and excess moisture, ensuring cleaner and healthier air. The smart AQI sensor and digital display provide real-time air quality updates, enabling users to monitor and control the environment efficiently. With an energy-efficient design and cost-effective components, this air purifier offers an affordable yet powerful solution for combating indoor air pollution, making it a valuable addition to modern households.

5.2 Future Work

Future enhancements for the multistage smart air purifier include integrating AI-based air quality prediction, IoT connectivity for remote monitoring, and automated filter replacement alerts. Additionally, improving energy efficiency, reducing noise levels, and optimizing the compactness of the design will enhance user experience. Further research can focus on incorporating UV-C sterilization for better microbial control and exploring biodegradable filter materials for sustainability.

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