Developing an Energy Efficient and Sustainable IoT-Enabled Indoor-Air Cooling System Using Earthen Materials

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ABSTRACT

This research focuses on the development of an energy-efficient and sustainable Internet of Things (IoT)-enabled system for indoor air cooling in residential buildings. The system incorporates an earthen air-cooling unit designed from locally sourced clay, leveraging the natural evaporative cooling properties of earthen materials. To identify the best-suited clay for the cooling process, soil samples are collected and tested from three locations in Bhubaneswar, Odisha. The components of the system are crafted by local potters and kiln-fired at 900 °C for durability and functionality. The air-cooling unit design is optimized through Computational Fluid Dynamics (CFD) simulations for maximum temperature reduction by combining evaporative cooling and the Venturi effect. Integrated IoT sensors and controllers enable real-time monitoring and remote control, ensuring energy-efficient operation and consistent indoor cooling. Testing the system in a residential setting in Bhubaneswar suggests a maximum indoor temperature reduction to 24 °C, while consuming 72% less energy than the traditional desert air coolers. This research highlights the potential of combining traditional earthen materials with the modern IoT technology to create a sustainable and energy-efficient solution for indoor air cooling.

Keywords-earthen cooling system; energy efficiency; indoor air cooling; internet of things; smart environmental control; sustainability

I. INTRODUCTION

Earthen air-cooling systems, which operate on the principle of evaporative cooling have gained attention due to their sustainable design and effective passive cooling performance. For instance, multilayer hollow clay walls have been explored for their ability to reduce the indoor air temperature [1]. In addition, porous earthen air pipes buried in moist soil indicated a reduction in the indoor air temperatures by 13.2 °C [2]. In [3], a cooling pad system combining clay plates with jute fiber and water circulation was developed to enhance the evaporative cooling performance. A composite air-cooler with wet clay tubes and an exhaust fan achieved a temperature drop of 19 °C [4]. Authors in [5] addressed the indoor air cooling through the use of mud pot and clay tube air coolers. In [6], terracotta tubes cooled the air from 50 °C to 35 °C via evaporative cooling. Underground earthen tubes, leveraging the earth's stable temperatures, facilitated an effective natural temperature exchange [7]. An evaporative air-cooler incorporating interconnected earthen cylinders and porous materials was utilized for efficient indoor cooling [8]. Staggered and aligned clay pipe arrangements led to temperature reductions between 7 °C and 11 °C, depending on the pitch and air velocity [9]. Pot-in-pot cooling combined with materials with dehumidifying attributes, such as silica gel, outperformed conventional coolers by 5 °C in warm and humid climatic conditions [10]. Furthermore, Maziara jars integrated into windows were employed for natural evaporative cooling [11]. In [12], Sintered Nigerian clay pads exhibited a 6 °C temperature drop. Porous earthen tubes integrated into walls facilitated the indoor temperature reduction through water circulation [13]. Hydrothermal transfer in terracotta tubes achieved a cooling effect down to 15 °C [14]. Porous evaporative plates reduced temperatures by 5 to 8 °C [15]. Earthen chambers presented reductions in relative humidity, enhancing the cooling performance by up to 8.3 °C [16].

The integration of earthen air-cooling systems in modern technology, specifically the convergence of IoT technology, enhances the performance and adaptability under various conditions. IoT-enabled sensors allow real-time monitoring and adjustment of the cooling parameters, maximizing the efficiency and comfort while reducing the energy consumption [17]. Although research on IoT integration with earthen coolers is limited, adding digital thermometers, relative humidity sensors, and controllers can regulate the energy use and improve the system effectiveness [18, 19].

This study proposes an IoT-enabled earthen indoor-air cooling system based on indirect evaporative cooling. This system is effective in warm and humid climates by cooling the air without increasing the moisture.

II. MATERIALS AND METHODS

The objectives of this research include: (a) the design and development of a prototype relative to earthen indoor air-cooling, (b) the simulation and analysis of the airflow and cooling efficiency of the earthen Venturi module using CFD software, (c) the onsite implementation and performance evaluation of the system in real-world indoor settings, and (d) the integration of an IoT-based data flow architecture for real-time monitoring of the air temperature changes over time.

1) Prototype Design

The prototype of the earthen indoor air-cooling system, as shown in Figure 1, is designed to reduce the temperature of the air that flows through it.

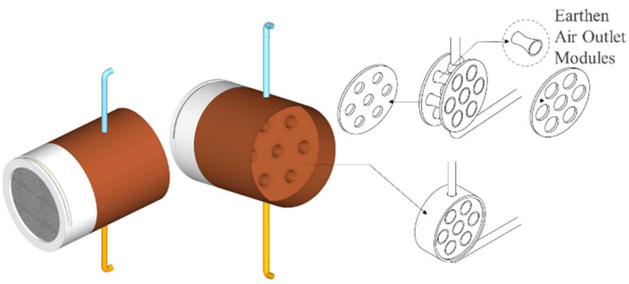

Fig. 1. Prototype design of the earthen indoor-air cooling system.

Soil samples were collected from three different locations in Bhubaneswar, Odisha, for their superior evaporative cooling performance. The reduction in the water temperature was measured in the earthen containers that were made up of three distinct soils and were kiln fired at a maximum temperature of 900 °C. The results indicated that the water temperature in the earthen pot samples was similar to each other. In a single container, the temperature reached 42 °C and then was decreased to 21 °C in 26 min due to their high porosity of 47.82% and high-water holding capacity of 49.35%. The earthen indoor air-cooling unit was designed utilizing this specific soil.

Figure 2 illustrates the earthen Venturi pipe modules before kiln firing and at the final assembly of the indoor air-cooling unit. The choice of the soil, mixing proportions, and molding techniques was carefully optimized to ensure structural integrity, porosity, and cooling efficiency.

Fig. 2. Soil samples and manufacturing process of earthen Venturi pipe modules and of the earthen indoor air-cooling unit.

The under study system, parts of which are depicted in Figure 3, consists of earthen clay and features an outer hollow cylinder, containing small hollow clay modules arranged in a circular pattern inside the outer hollow cylinder. These modules are held at place by two base plates with voids, on either side of the outer cylinder.

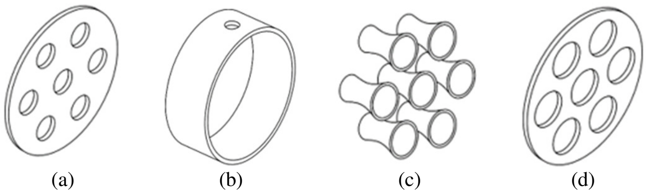

Fig. 3. Parts of the earthen indoor air-cooling unit.

The system's pipe modules, as portrayed in Figure 4, increase the air velocity and reduce the temperature according to the Venturi effect. These compact pipes become wet as water circulates through the outer hollow cylinder, which features an inlet that fills the inner chamber with water and an outlet for overflow, helping to cool the indoor air, as shown in Figure 5.

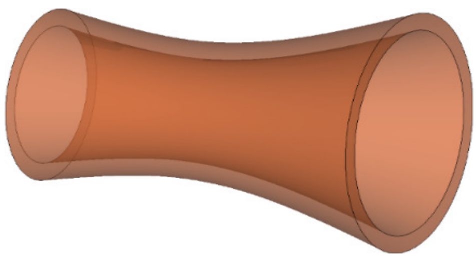

Fig. 4. Isometric view of a small earthen module within the earthen indoor air-cooling unit to leverage the Venturi effect.

Insulated pipes supply water of an average room temperature of 27 °C through the inlet of average room temperature of water of 27 °C to the earthen indoor air-cooling unit and is considered constant during this experiment. As the water is introduced, the small earthen modules absorb and then cool the water through evaporative cooling.

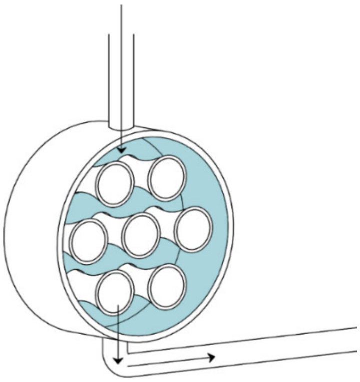

Fig. 5. Isometric vew of the earthen indoor air-cooling when filled with water.

2) Simulation Analysis

The earthen cooling modules function according to the Venturi effect, where an increase in the air velocity through a constricted section leads to a decrease in pressure. The expansion of air leads generates a suction effect. In turn, this effect results in warmer air drawn through the wet clay, enhancing the airflow and cooling efficiency.

A virtual simulation using CFD is conducted, as presented in Figure 6, with a sample surface temperature of 22 °C, and using incoming air between 28 °C and 40 °C with a wind velocity of 2.5 m/s. For an initial air temperature of 40 °C, the air's temperature was decreased to 33 °C after passing through the sample in 9 min. Beyond this point, the surface temperature was equivalent to the air temperature and the process was repeated utilizing water for the surface to return to 22 °C. Similarly, with an initial air temperature of 28 °C the air was decreased to 23.5 °C in 11 min. These temperature reductions were achieved by recirculating the 40 °C and 28 °C air through the sample.

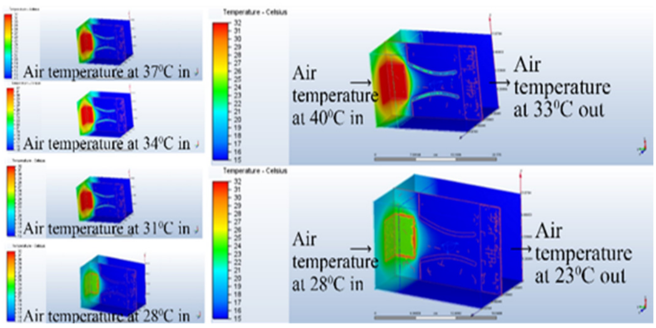

Fig. 6. CFD software simulation of the earthen Venturi module.

3) Onsite Implementation and Testing

An onsite installation of the earthen indoor air-cooling and quality control system was performed, along with IoT for the thermal performance monitoring of the system, utilizing the conditions and parameters of the simulation. The earthen indoor air-cooling system's performance was tested in a real world indoor environment, as shown in **Error! Reference source not found.**Figure 7.

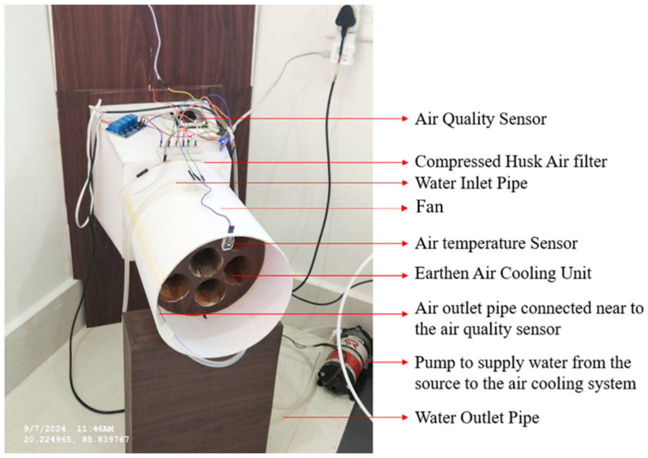

Fig. 7. Onsite installation of the earthen indoor air cooling and quality control system.

The outdoor air temperature is 40 °C, while the water's is 27 °C and is circulated through earthen Venturi modules. A fan draws the outdoor air through the cooled unit into the indoor space. The system incorporates IoT to monitor and manage the cooling process. Additionally, a compressed husk board is installed at the air inlet to filter the incoming air, improving the air quality. To further ensure a healthy indoor environment, the Particulate Matter (PM) levels are continuously monitored using the air quality sensor SDS011. PM with a diameter of 2.5 (PM2.5) and 10 (PM10) µm or less is employed. This integrated system effectively cools the indoor air while maintaining optimal air quality.

4) IOT Based Monitoring System

A DHT22 sensor near the air outlet measures the air temperature difference between the outdoor and indoor air. Figure 9 presents the IoT data flow architecture for smart air quality and temperature monitoring. The integrated IoT system employs a microcontroller unit (ESP32) that connects all sensors (DHT22, SDS011) to a Wi-Fi network, enabling real-time data transmission to a cloud platform. The collected environmental parameters, such as the temperature, PM2.5, and PM10 concentration levels, are continuously logged and visualized on an online dashboard.

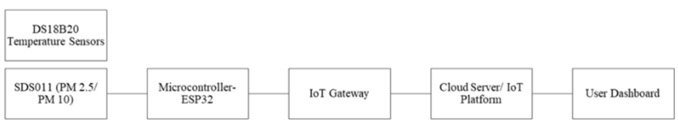

Fig. 8. IoT data flow architecture for smart air quality and temperature monitoring.

Moreover, threshold-based notifications are configured to inform users when the air quality deteriorates or the temperature deviations exceed the predefined limits. This enables proactive control actions, such as activating auxiliary ventilation or adjusting the evaporative cooling process. Data analytics algorithms are applied to identify the usage patterns, optimize the cooling performance, and reduce the energy consumption.

By leveraging IoT, the system ensures intelligent environmental monitoring and adaptive control, offering a sustainable and user-friendly solution for indoor air cooling and purification.

III. RESULTS

The earthen Venturi pipe modules showcase a promising solution for cooling the indoor air while enhancing the air quality through innovative design and technology integration. According to Figure 9 and Table I, an indoor air temperature reduction is observed. The system efficiently reduces the air temperature from 40.2 °C to 24.4 °C in 12 min. The cooling is enhanced by the evaporative cooling mechanism.

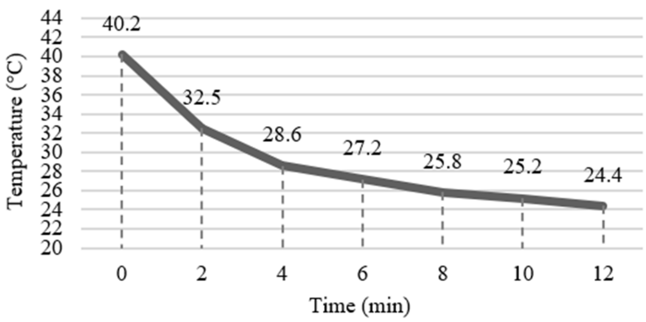

Fig. 9. Indoor air temperature against time.

TABLE I. RESULT SUMMARY

Parameter	Initial value	Final value	Duration
Outdoor temperature	40 °C	-	-
Inlet water temperature	27 °C	-	-
Air temperature	40.2 °C	24.4 °C	12 min
PM2.5 concentration	>35 µg/m³	< 25 µg/m³	Continuous
PM10 concentration	>50 µg/m³	< 35 µg/m³	Continuous

The inclusion of a compressed husk board at the air inlet serves filters larger particles and improves the overall air quality. The system is recorded at 0.025 kWh/h, compared to the 0.1 - 0.5 kWh/h of the desert coolers. Employing these natural cooling methods leads to significant savings on energy bills by 72% compared to the conventional desert coolers and a reduced carbon footprint, aligning with sustainable practices. Conventional desert coolers consume on average 0.3 kWh/h in contrast to the proposed system, which requires 0.025 kWh/h. Considering a daily runtime of 8 h and an emission factor of an average grid in India of approximately 0.82 kg CO_2/kWh, a comparison of the annual CO_2 emissions is performed. Utilizing a conventional desert cooler leads to a carbon footprint of 718.32 kg CO_2/year. On the other hand, the proposed system leads to a carbon footprint of 59.86 kg CO_2/year, resulting in a 658.46 kg CO_2/year or 91.7% reduction in the CO_2 emissions annually per unit.

The integration of the IoT technology allows for a continuous monitoring and adjustment of the system based on real-time environmental conditions. This enhances the overall performance and responsiveness of the cooling system. By maintaining a comfortable indoor temperature and good air quality, the system improves the overall occupant comfort and well-being. A comparative analysis of similar indoor air-cooling systems is presented in Table II.

TABLE II. COMPARATIVE ANALYSIS OF INDOOR AIR-COOLING SYSTEMS

System	Cooling reduction (°C)	Energy use	IoT integration	Sustainability
Clay pipe cooling [9]	7–11	Moderate	No	Moderate
Terracotta tube cooling [6]	15	Low	No	High
Clay and Jute Pad cooler [3]	~19	Moderate	No	Medium
Local earthen clay (proposed system)	16	Very low	Yes	High

IV. CONCLUSIONS

The natural earthen Venturi pipe modules manufactured with clay offer an innovative and sustainable solution for indoor air cooling and quality improvement. By utilizing the Venturi effect and evaporative cooling process, the system effectively reduces the indoor air temperatures, achieving significant cooling from 40.2 °C to 24.4 °C within 12 min. Integrating a filtration system and real-time air quality monitoring, ensures that Particulate Matter (PM) remains at safe levels, promoting a healthier indoor environment. This approach not only enhances user comfort, but also reduces the reliance on conventional air conditioning, leading to lower energy consumption and a reduced carbon footprint. The integration of the Internet of Things (IoT) technology further optimizes the system performance allowing for an adaptive response to the changing conditions. In addition, the use of local materials and local artisans reduces the cost and supports the local economy, empowering the rural pottery communities in Odisha.

The novelty of the system, which led to 72% energy savings compared to the conventional desert coolers, lies in:

- The integration of IoT for real-time monitoring of the temperature and air quality in a traditionally passive earthen system.
- The application of the Venturi effect in earthen modules to accelerate the airflow and enhance the cooling efficiency
- The use of locally sourced and high-porosity earthen material.

Overall, this system demonstrates the potential for eco-friendly cooling solutions that prioritize both the thermal comfort and air quality, making it a valuable addition to sustainable building practices. The future scope of the research includes a study on the scalability and potential use of cloud-based big data analytics for predictive maintenance and integration into smart home ecosystems. Future versions could integrate solar PV and AI-based adaptive control for a fully autonomous climate control.

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