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Research Paper

A Ventilation and Cooling System with Dust-free Air for Residential Spaces of Asalouye City

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Abstract
High temperatures and air pollution are significant challenges in ensuring fresh air supply in the hot-humid climate of Asalouye City. These conditions compel residents to rely heavily on mechanical cooling, which subsequently escalates energy consumption and deteriorates indoor air quality. The primary air pollutants include Particulate Matter (PM), Volatile Organic Compounds (VOCs), and microorganisms. Fiber filters and electrostatic filters are the most common methods for purifying PMs from the air, with the electrostatic method offering advantages such as high efficiency, the ability to remove a wide range of particles, low-pressure drop, and no need for frequent replacement. This study proposed a ventilation system integrating a window, a precipitator using electrostatic technology, a cooling coil, and an exhaust fan. The system's performance was evaluated using CFD simulation in Ansys-Fluent software (2021) to assess its effectiveness in reducing PM concentrations, pre-cooling incoming air, and maintaining the standard ventilation rate. The findings revealed that at air velocities of 6 m/s and 1 m/s, the system could completely remove copper, nickel, and sulfur particles with diameters of 0.1 μ and 10 μ. Additionally, the distance between the system's air inlet (window opening) and its air outlet (where air enters the interior) significantly influences the particle reduction level. The proposed cooling coil, however, only managed to reduce the air temperature by 2°C. In the absence of wind, an exhaust fan with a pressure jump of at least 250 Pa or 500 Pa is necessary to achieve the standard airflow and ventilation rate.

Keywords: *Natural ventilation, Cooling, Particulate matters, Electro-filters, Residential buildings, Asalouye city.*

INTRODUCTION

Spending extended periods in indoor environments with limited fresh air, where cooling is primarily provided by mechanical systems like split air conditioners, can negatively impact indoor air quality and the health of residents. In Asalouye City, the provision of fresh air is further hindered by the high concentration of Particulate Matter (PM) in the atmosphere. The use of mechanical ventilation systems equipped with filters to supply fresh air is not ideal for residential areas. These systems not only consume non-renewable fossil fuels but also contribute to increased carbon emissions and higher levels of pollutants such as PM10, SO2, CO, and NO2 in the external environment (Martins, Barreto, Souza, & Souza, 2021). Additionally, these systems are often only equipped with filters that do not fully prevent the infiltration of particles indoors and have drawbacks such as the need for regular replacement. The high temperatures in the hot and humid climate of Asalouye City further complicate the use of natural ventilation to provide fresh air.

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Air pollutants can be categorized into three main groups: Particulate Matter, which includes dust, pollen, secondary pollutants, and soot with diameters ranging from 0.01 to 100 micrometers; Volatile Organic Compounds (VOCs), such as formaldehyde, benzene, and ammonia, with diameters between 0.0001 and 0.001 micrometers; and microorganisms, including bacteria with diameters of 0.2 to 10 micrometers and viruses with diameters of 0.01 to 0.3 micrometers (Y. Zhang et al., 2011).

The most prevalent and significant air pollutants emitted by refineries and fossil fuel industries include SO2, TSP, NO2, and CO, with Particulate Matter (PM) being the most critical and predominant among them (Dab et al., 1996). In the Asalouye region, the gas and petrochemical industries produce a variety of pollutants such as Volatile Organic Compounds (VOCs) including benzene and petroleum hydrocarbons, hydrogen sulfide, nitrous oxides, sulfur oxides, PM2.5 and PM10 particles, Polycyclic Aromatic Hydrocarbons (PAHs), and heavy metals like arsenic, cadmium, chromium, lead, mercury, and barium (Keshmiri et al., 2018). These heavy metals released into the atmosphere from gas and petrochemical industries often bind to airborne dust and subsequently deposit onto the soil and vegetation (Ugolini, Tognetti, Raschi, & Bacci, 2013).

The World Health Organization (WHO) and the Global Environment Monitoring System (GEMS) have identified Particulate Matter, whether of natural or anthropogenic origin, as the most significant air pollutant in major cities worldwide (WHO, 2022; WHO & GEMS, 1992). In many polluted regions across the globe, fine dust particles are among the most pressing air pollution issues (Wang, Wang, Zhou, & Shang, 2005). The health impacts of these pollutants on the residents of Asalouye City have been extensively studied, with research indicating serious effects such as cancer, leukemia, respiratory issues, headaches, dizziness, fatigue, digestive disorders, cardiovascular diseases, and skin problems (Chiang, Yuan, Shie, Chen, & Chan, 2016; D’Andrea & Reddy, 2016a, 2016b; Rehman, Fatima, Waheed, & Akash, 2018; Skrtic, 2006). Given these harmful effects, it is crucial to develop effective strategies to control the infiltration of air pollutants into the residential areas of Asalouye City.

Pollution purification technologies can be broadly classified into three main categories: dust removal technology, gas purification technology, and sterilization (G. Liu et al., 2017). The primary methods for purifying airborne particles include filtration, water washing, electrostatic precipitation, and anion technology (Y. Zhang et al., 2011). These methods are effective for particles ranging in size from 0.01 to 100 microns, such as dust (Chen, Gonze, Ondarts, Outin, & Gonthier, 2020; G. Liu et al., 2017; Y. Zhang et al., 2011). Filters serve as a barrier to prevent outdoor air pollution from entering buildings. The three principal filtration technologies are mechanical filters, corona dischargers, and electrostatic precipitators. Filters can be generally categorized into fiber filters, membrane filters, and electrofilters (Turner, O'Connell, Kowalski, & Bahnfleth, 2005), with fiber filters and electrofilters being the most commonly used.

While fiber filters are widely utilized, they have several drawbacks, including susceptibility to microbial contamination (G. Liu et al., 2017), air pressure drops that significantly impact annual energy consumption and costs (Matela, 2006), as well as the initial and lifetime costs, gradual reduction in filtration efficiency, and the need for regular replacement. In contrast, electrofilters offer several advantages, such as high efficiency, a low-pressure drop that is independent of particle size, the ability to remove a wide range of particle sizes, and the capacity to handle large volumes of gas under high temperature, pressure, or acidity. Additionally, they do not require replacement and are easy to clean. Extensive research has been conducted to reduce the electricity consumption and operational costs associated with electrofilter technology.

Based on this background, the aim of this research was to explore the feasibility of utilizing natural ventilation through windows to supply dust-free fresh air to residential spaces in the hot, humid, and polluted climate of Asalouye City. To achieve this primary objective, three sub-objectives were identified. The first sub-objective was to evaluate the performance of a proposed electrostatic precipitator integrated with windows in removing particles and maintaining standard ventilation rates. The second sub-objective was to assess the effectiveness of a proposed cooling coil integrated with windows in reducing air temperature before it enters the building and preventing energy loss, particularly considering that indoor air may already be cooled by mechanical systems before windows are opened. The third sub-objective was to examine the performance of a proposed exhaust fan in facilitating air circulation to compensate for potential pressure drops and to enable the system's use in the absence of sufficient air velocity.

Previous research on air pollution and particle control has predominantly focused on monitoring indoor particle concentrations, with solutions largely limited to optimizing the use of air conditioning systems. Industrial applications of precipitators have been extensively studied, but their use in residential settings remains underexplored.

THEORETICAL PRINCIPLES

Figure 1 illustrates a schematic of the particle removal process in a cross-section of a single-stage electrostatic precipitator. Electrostatic precipitators consist of several plates (in the case of plate precipitators) and a series of electrodes. When a high voltage is applied between the wires and plates using an external device, air particles passing through the resulting electric field become ionized. These ionized particles are then attracted to the oppositely charged collecting plates at a high velocity, which exceeds the speed of gravity and diffusion velocity, thereby separating them from the airflow. The accumulated particles on the plates can be removed through various methods, such as washing, or mechanical agitation—shaking or striking the plates in both horizontal and vertical directions—or by scraping. In the case of two-stage precipitators (Al-Shujairi, 2013), the collection efficiency tends to be lower. The efficiency of particle removal is influenced by factors such as air velocity, particle diameter, particle type, and system voltage. Generally, the removal efficiency decreases with increasing air velocity and decreasing particle diameter. In some systems, optional pre-filters and post-filters may be installed at the air inlet and outlet to enhance performance.

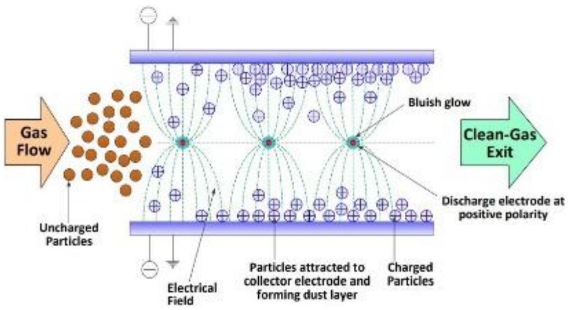


Fig 1. A schematic of the process of removing particles from the air in a single-stage electrostatic precipitator

(Afshari et al., 2020)

The United States Environmental Protection Agency has also presented a similar picture. Refer to (Parker & Plaks, 2004)

To pre-cool the air before it enters indoor spaces, cooling coils that use refrigerant gas or Thermoelectric Cooling (TEC) devices can be employed. Historically, R-22, commonly known as Freon, was the most widely used refrigerant. However, due to its environmental impact, including ozone depletion and global warming, its use has been banned since 2012. R-410 has since become the most prevalent refrigerant on the market due to its superior environmental characteristics compared to other refrigerants, though it is less efficient than R-410. TEC devices, on the other hand, produce cooling with very low energy consumption and offer advantages such as compact size, low cost, and environmental compatibility (Baru & Bhatia, 2020; Salah & Abuhelwa, 2020). TEC devices can achieve temperatures as low as -8.25 degrees Celsius (Xia et al., 2021).

A fan functions as an air movement device, capable of either blowing or suction. Exhaust fans, in particular, are employed to introduce fresh air into certain spaces by creating negative pressure, which enables air suction and circulation. When selecting a fan for a specific area, factors such as airflow capacity, required ventilation rate, and noise level are critical considerations. To maintain acoustic comfort, manufacturers typically recommend using a fan that produces a maximum noise level of 45 decibels at a distance of 1.5 meters from the listener. The pressure jump generated by the fan is another important parameter, as it directly impacts the fan's overall performance and effectiveness in moving air.

METHODS

The core of this research lies in the simulation and analysis of the performance of the proposed electrostatic precipitator integrated with a window, focusing on its ability to reduce air particle concentrations and provide fresh air at a standard ventilation rate in the hot and humid climate of Asalouye City. Additionally, the study explored the feasibility of pre-cooling incoming air using a proposed cooling coil integrated with the window, as well as selecting an appropriate fan to compensate for fluctuations in airflow. These evaluations were conducted using Three-dimensional Computational Fluid Dynamics (CFD) simulations in Ansys-Fluent software, version 2021.

Proposed Details

Electrostatic precipitator integrated with the window

The proposed specifications for the window integrated with the collecting and discharge electrodes of the electrostatic precipitator are illustrated in Figure 2. Using these models, the study examined how the dimensions of the air inlet (specifically, the width and height of the window) and the distance between the air inlet and the air outlet (where the air enters the interior space) affect the system's performance. In all models, only the air inlet—the open area of the windows—was simulated, while the non-opening glass portion of the window was excluded from the calculations.

The performance of the electrostatic precipitator, including particle removal efficiency and ventilation rate, was assessed across various particle types and diameters, air velocities, and different air inlet dimensions. Additionally, the air velocity at the precipitator outlet (the point where air enters the interior space) was measured. The ventilation rate was then calculated and compared against the limits recommended by the ASHRAE standard to evaluate compliance with standard ventilation requirements.

Cooling coil

To explore the feasibility of pre-cooling the air, a cooling system was simulated, featuring coils that were cooled using two different methods. The temperature reduction of the air as it passed through these coils was determined. The coils were modeled after the traditional window bars known as "Mashrabiya" or "Shenashil" (Figure 3). Mashrabiya is an indigenous architectural element commonly found along the Persian Gulf coast. In traditional Iranian architecture, Mashrabiya serves multiple functions, including providing privacy, shielding interiors from intense sunlight, and adding aesthetic value.

In this study, this native and traditional element was integrated with the window and the electrostatic precipitator, aiming to fulfill part of the consumer's cooling needs while also maintaining its decorative purpose. Figure 3 presents the interior view and a longitudinal section of the proposed model, which includes the window, precipitator, and cooling coils. The cooling methods simulated involved using R-410 refrigerant inside the coils as well as Thermoelectric Cooling (TEC) technology to achieve the desired cooling effect.

Exhaust fan

An axial suction fan was utilized for the study, chosen for its lack of need for ducting systems. A case study plan (Figure 4) was developed to examine the airflow dynamics within indoor spaces influenced by the fan. The suction fan was positioned at the location of the air supply vent in the sitting room. The dimensions of the window opening and precipitator were modeled according to model number 10 shown in Figure 2.

The pressure jump was identified as a critical parameter for fan simulation. Various pressure jump values were set in the Software Settings tab. The average air velocity entering the room through the window opening was determined based on the simulation results. The simulations were iteratively performed until satisfactory values were obtained for air velocity in the fan area, the standard ventilation rate, and effective airflow circulation within the indoor space.

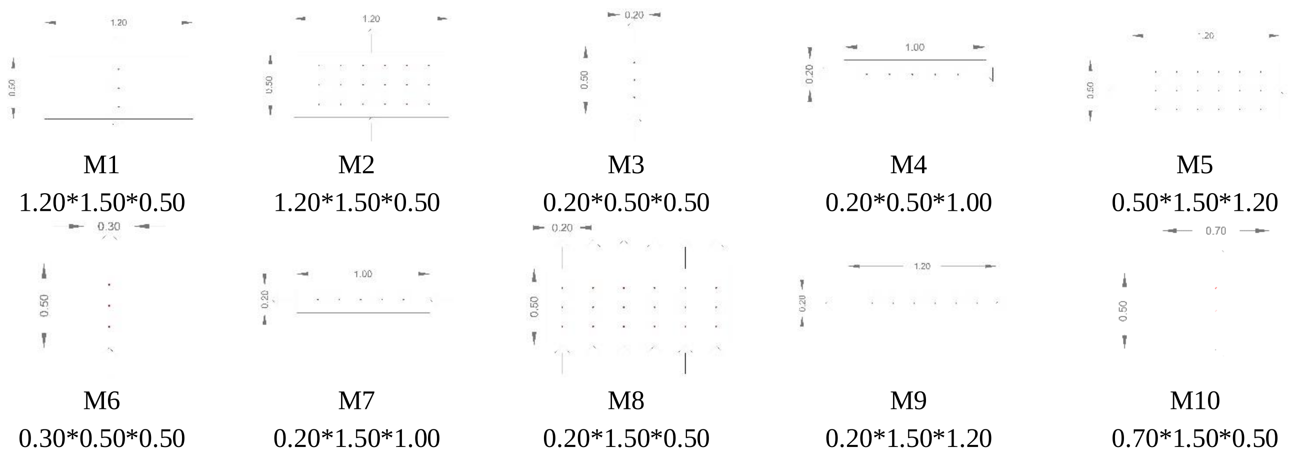


Fig 2. Schematic view from above of the window, the position of the collecting plates, electrodes, and air inlet and outlet in the precipitator, (The width, height, and depth of the window opening are written below each model from left to right. Dimensions are in meters).

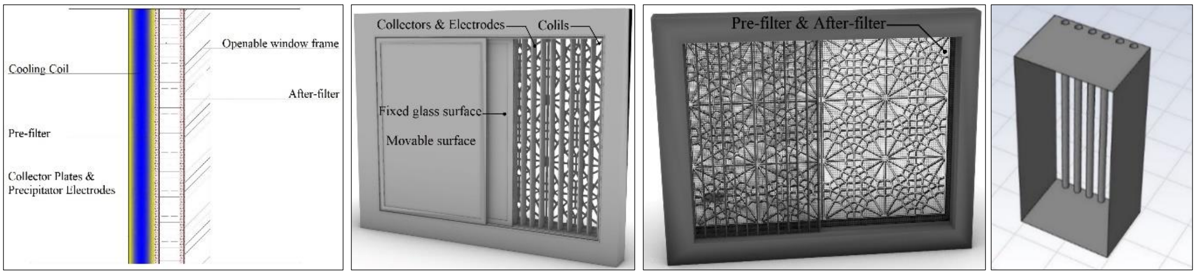


Fig 3. Cooling aluminum coils at the air inlet (right), and internal view and longitude section of the proposed model for the precipitator and Mashrabiya as the cooling coil (Pre-filter and After-filter are optional on both sides of the electrodes)

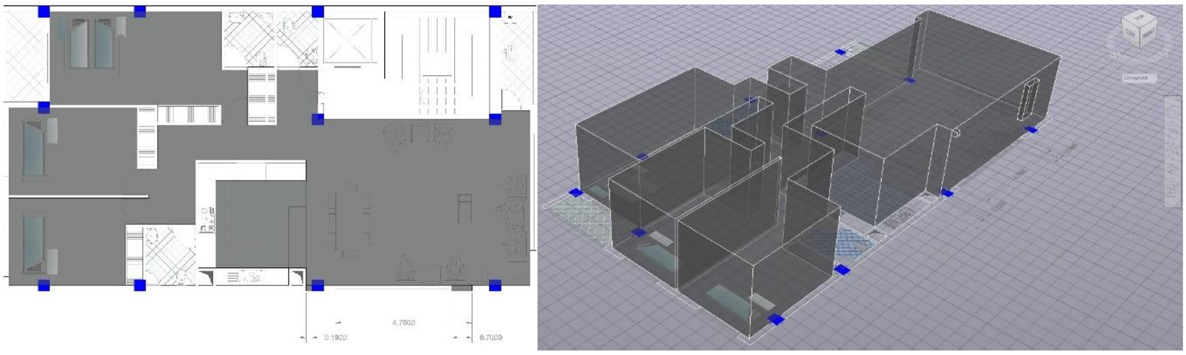


Fig 4. Simulated plan and volume to investigate the airflow behavior affected by the fan

(The width of the window opening and the fan zone in the sitting room are 0.7^m and 0.192^m, respectively. The windows of other spaces were closed in the simulation).

Simulation in the software

Boundary conditions

The boundary conditions for the simulation were defined as follows: "Velocity-inlet" for the air inlet, "Pressure outlet" for the air outlet, and "Exhaust fan" for the fan zone.

The study evaluated the performance of the electrostatic precipitator in removing particles of copper, nickel, and sulfur. Copper was chosen due to its high abundance in Asalouye City and its association with human activities. Nickel was selected as it originates from non-human sources (Khademi, Naderizadeh, & Ayoubi, 2016; Naderizadeh, Ayoubi, & Khademi, 2016). Sulfur was included based on official reports indicating it as a major air pollutant in Asalouye. Various studies have examined the concentration, emission sources, and health impacts of heavy metals in dust, including Lead (Pb), Cadmium (Cd), Zinc (Zn), Manganese (Mn), Copper (Cu), Nickel (Ni), Cobalt (Co), and Chromium (Cr) across different countries and cities (Ali et al., 2017; Sezgin, Ozcan, Demir, Nemlioglu, & Bayat, 2004; Tang et al., 2017; H. Zhang, Wang, Zhang, Ding, & Li, 2015). Notably, more than fifty percent of dust pollution has been attributed to copper (Vlasov, Kosheleva, & Kasimov, 2021). Additionally, studies have indicated that copper levels are linked to human activities, while nickel levels are associated with natural or non-human processes (E. Liu, Yan, Birch, & Zhu, 2014; Pan, Lu, & Lei, 2017).

The densities of copper, nickel, and sulfur particles were determined to be 8978 kg/m³, 8900 kg/m³, and 2046 kg/m³, respectively. Particulate Matter (PM) is categorized based on particle size into three main groups: coarse particles (2.5 to 10 microns in diameter), fine particles (0.1 to 2.5 microns in diameter), and ultrafine particles (less than 0.1 microns in diameter). Specifically, PM10 refers to inhalable coarse particles with diameters between 2.5 and 10 microns, while PM2.5 encompasses fine particles with diameters of 2.5 microns or less. PM2.5 and PM10 are among the five principal pollutants used to describe outdoor air quality. For this study, particle diameters of 0.1 and 10 microns were considered, corresponding to the ranges of PM2.5 and PM10.

In each model, the performance of the electrostatic precipitator was first assessed by evaluating its ability to remove copper particles with a diameter of 0.1 micron at an air velocity of 6 m/s, representing the most challenging conditions. Subsequently, the system's performance was tested at an air velocity of 1 m/s and a particle diameter of 10 microns, representing more favorable conditions.

Wind was modeled as a fluid with a density of 1.225 kg/m³ and a viscosity of 1.7894e-05 kg/ms. The observed wind velocities in Asalouye City ranged from 2 to 12 meters per second, based on observational meteorological data collected over 11 years (2011-2022). The maximum and minimum wind velocities at a height of 13.30 meters for buildings in urban centers were calculated as 6 and 1 m/s, respectively, using Equation 1.

$$V_H = V_m \times (\frac{\delta_m}{H_m})^{a_m} \times (\frac{H}{\delta})^a \qquad \text{(Ashrae, 2009)}$$

V_H: Wind speed at the desired height in the intended region (m/s). The height of 13.30 meters in this study.

V_m: Wind speed (m/s). 2 and 12 m/s in this study.

δ: Wind gradient height in the intended region. Urban areas in this study and equivalent to 460^m.

δ_m: Wind gradient height in the reference region. Weather stations in this study and equivalent to 270^m.

H: The desired height (m). The height of 13.30 meters in this study.

H_m :Reference height. 10^m is considered for the weather stations.

a: Texture coefficient for the intended region. Urban areas in this study and equivalent to 0.33.

a_m : Texture coefficient for the reference region. Weather stations in this study and equivalent to 0.14.

The average air temperature in the study area was found to be 45 degrees Celsius. Based on observational meteorological data collected over 11 years (2011-2022), temperatures of 50, 49, 48, 47, and 45 degrees Celsius were recorded most frequently.

The cooling coils were made of aluminum, characterized by a thermal conductivity of 202.4 W/m·K, a specific heat capacity of 871 J/(kg·K), and a density of 2719 kg/m³. The coil temperatures were set to -9°C for refrigerant cooling and -20°C for Thermoelectric Cooling (TEC). These temperatures represent the lowest achievable values for cooling using these methods, as specified in the manufacturer's catalog.

MODELS AND SOLUTION METHODS

Steady-state conditions were established for the simulation, using a pressure-based solver type. The "Coupled" scheme was employed for solution methods, with the Second Order Upwind method applied to Pressure and Momentum for spatial discretization. For Turbulence Kinetic Energy and Turbulence Dissipation Rate, the First Order Upwind method was used, which is the default setting of the software.

To explore the effect of an electric field on charged particles, a User Defined Function (UDF) was incorporated. This UDF defined a body force that charged the particles and directed them towards the collecting plates. The simulation primarily focused on parameters related to architectural design, with the assumption that the minimum required voltage was supplied by an external device. Key areas of interest included system dimensions, particle type and diameter, and air velocity.

Turbulent airflow was modeled using the "Realizable k-e" model, with "Standard Wall Function" applied for "Near-Wall Treatment." The "Curvature Correction" was not considered, as this model includes independent terms for rotational effects.

The "Discrete Phase Model" was used to simulate the two-phase flow. This model employs either the Euler-Lagrange or Euler-Euler approaches for multiphase flow simulations. The Euler-Lagrange approach treats the fluid phase as continuous and the particles as dispersed, with exchanges of mass, momentum, and energy between the phases. It allows for the specification of particle tracks and is appropriate when the fluid flow influences the particles through drag and turbulence, but the particles do not impact the fluid flow. This model can also be applied when particles affect the fluid's momentum and turbulence. For this study, inert particles were used to simulate particle trajectories. Additionally, the energy model was integrated into the simulation of the cooling coil.

Grid Quality

Tetrahedron grids were utilized for the simulation. To ensure the validity and accuracy of the results, grid independence was verified through a grid study, and the "mass flow rate" results were used for further validation. For the Tetrahedron grid, the average values of "Aspect Ratio" and "Skewness" were assessed to determine grid quality. A grid with an Aspect Ratio ranging from 1 to 5 and a Skewness between 0 and 0.5 was deemed to have appropriate quality.

Calculation of Ventilation rate

The ventilation rate was calculated using Equation 2:

Flow rate (m^3/s) = Air velocity (m/s) × Cross-sectional area (m^2)

The results were compared with the Ashrae standard. According to Ashrae standard 62.1 (Ashrae, 2019), 0.3 liters per second per square meter is enough.

RESULTS AND DISCUSSION

Electrostatic precipitator performance

The air velocities at the outlet of the precipitator system (where air enters the indoor space) for models 1 to 10 are detailed in Tables 1 and 2. Additionally, Tables 1 and 3 provide data on the system's performance in removing sulfur and nickel particles for models 9 and 10.

Overall, no significant differences were observed in the average air velocity or the particle removal efficiency at the precipitator outlet for copper, nickel, and sulfur particles across the various models.

The results presented in Tables 1 to 3 highlight the impact of changes in system components, including window opening dimensions, particle material and diameter, and inlet air velocity on system performance.

In Model 1, the application of the electric field caused particles to move towards the plates at a much higher velocity than the air entering the system. As illustrated in the figure of Table 2, the particles did not pass through the air outlet.

Model 2, which is similar to Model 1 but includes more electrodes with a reduced distance between the electrodes and the plates, showed no difference in particle behavior or removal percentage compared to Model 1.

Models 3 and 1 have the same number of electrodes and the same distance between the air inlet and outlet. However, the window opening dimensions were altered, with the width and height reduced from 1.20 to 0.20 meters and from 1.50 to 0.50 meters, respectively. No changes in particle behavior were observed.

In Models 3 and 4, the width and height of the window openings are the same, but the distance between the air inlet and outlet was increased from 0.50 meters in Model 3 to 1.00 meters in Model 4. This increase in distance led to an increase in the number of electrodes from 3 in Model 3 to 5 in Model 4, though the distance of the electrodes from the plates remained unchanged. No change in particle behavior was observed.

Models 5 and 2 are similar in terms of opening height, number of electrodes, and electrode-to-plate distance. However, the width of the opening in Model 5 was reduced from 1.20 meters to 0.50 meters, and the air inlet and outlet distance was increased from 0.50 meters to 1.20 meters. A significant change in particle behavior was noted in Model 5, with approximately 40% of the particles entering the indoor space.

Models 6 and 3 share identical characteristics in terms of the number of electrodes, the distance between the electrodes and the plates, the height of the window opening, and the air inlet and outlet distance. The only difference is that the width of the air inlet in Model 6 has been increased from 0.2 meters to 0.3 meters. Despite this change, no difference in particle behavior was observed.

Models 7 and 4 are identical in all respects except for the height of the air inlet. In Model 7, the opening height was increased from 0.5 meters in Model 4 to 1.5 meters. There were no observed changes in particle behavior due to this adjustment.

Model 8 closely resembles Model 3 in all aspects, except that the height of the air inlet was increased from 0.5 meters in Model 3 to 1.5 meters in Model 8. Additionally, Model 8 is similar to Model 2 except for the number of collecting plates. No changes in particle behavior were noted.

Models 9 and 7 are comparable in terms of the number of electrodes, the distance between the electrodes and the plates, and the dimensions of the window opening. The key difference lies in the air inlet and outlet distance, which increased from 1 meter in Model 7 to 1.20 meters in Model 9. To accommodate this increased distance, the number of electrodes was also increased. This modification led to a significant change in particle behavior.

In Models 9 and 5, the height of the air inlet, the air inlet and outlet distance, and the number of electrodes are consistent. However, the width of the air inlet was reduced from 0.5 meters to 0.2 meters in Model 5. Despite these changes, the distance between the electrode rows and the plates remained constant, and no significant difference in particle removal was observed.

For Model 10, the window dimensions were set to 1.50 meters in height and 4.7 meters in length, which are standard for such windows. The window opening was designed to be 5% of the total window surface area, resulting in dimensions of 1.50 meters (height) by 0.7 meters (width). Consequently, Model 10 simulated an opening of 1.50 meters in height, 0.7 meters in width, and 0.50 meters in depth.

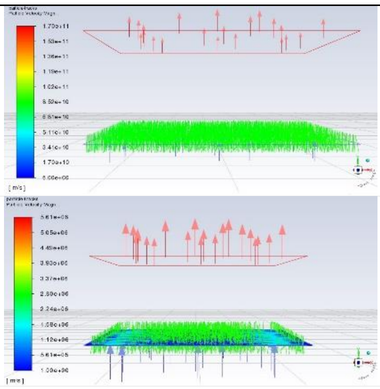
Cooling coil performance

Table 4 and Figure 5 present the average air velocity and temperature after the air has passed through the cooling coils. The results indicate that the air temperature decreases by approximately 2 degrees Celsius when passing through a 0.50-meter path with coils cooled by either refrigerant at -9°C or by Thermoelectric Cooling (TEC) at -20°C. There was no significant change in the air velocity; the initial air velocity and temperature were 1 m/s and 45°C, respectively.

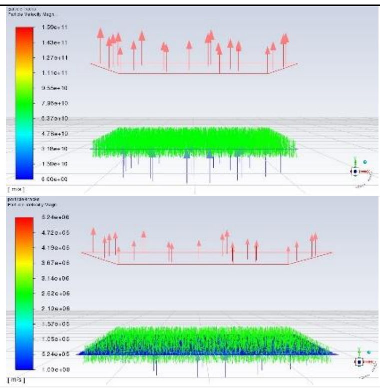
Table 1. The average air velocity and percentage of particle removal in the outlet of the electrostatic precipitator (models 1 to 10) for Copper, Nickel, and Sulfur particles with diameters of 0.1 and 10 microns and inlet air velocity of 6 and 1 m/s

Model Number	6m/s & 0.1µ			1m/s & 10µ			
	Copper	Nickel	Sulfur	Copper	Nickel	Sulfur	
1	6.0829612	-	-	1.0131567	-	-	100
2	6.5624686	-	-	1.0880535	-	-	100
3	6.9985722	-	-	1.1491977	-	-	100
4	6.2174808	-	-	1.038297	-	-	100
5	6.5681745	-	-	1.0931448	-	-	60
6	6.2240654	-	-	1.0328837	-	-	100
7	6.353298	-	-	1.0542822	-	-	100
8	6.4418533	-	-	1.0672118	-	-	100
9	6.5785964	6.5742949	6.5742949	1.0997886	1.0998484	1.0997886	48
10	5.9933242	5.9933242	5.9933172	0.99877654	0.99877654	0.99877853	100

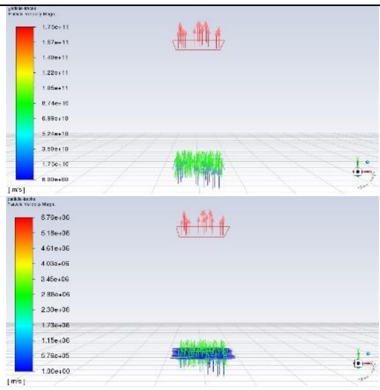
Table 2. The air velocity and the behavior of Copper particles with a diameter of 0.1 and 10 microns at an inlet air velocity of 6 and 1 m/s, from the top view of the window in models 1-10



M1



M2



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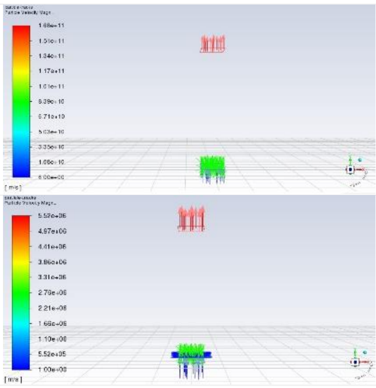
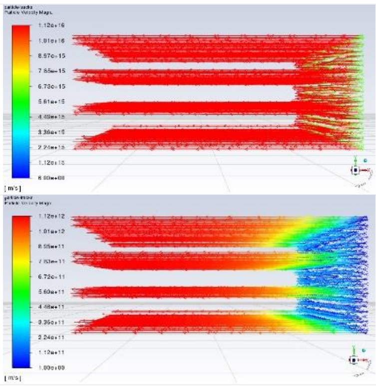
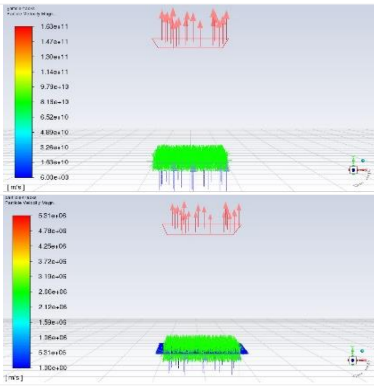


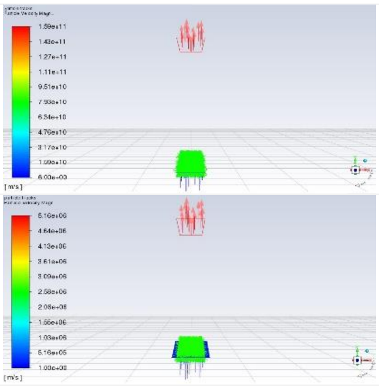
M4



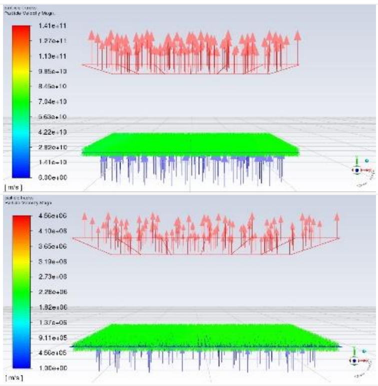
M5



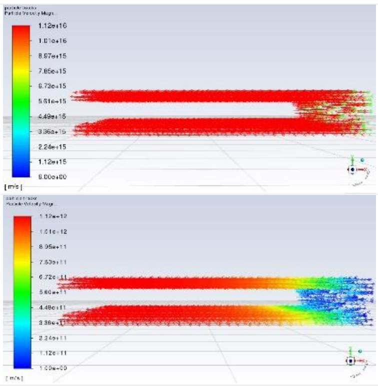
M6



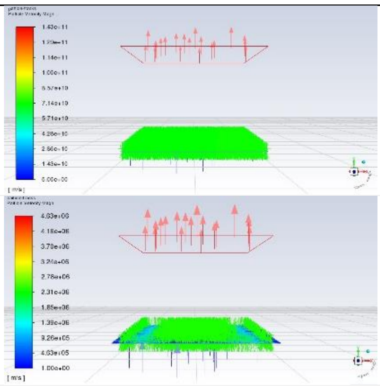
M7



M8



M9



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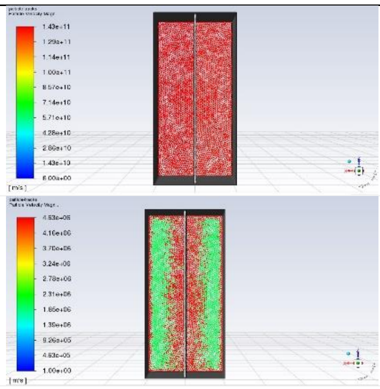

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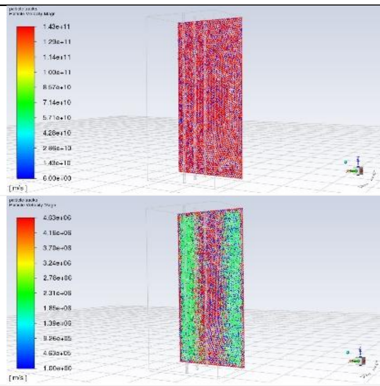
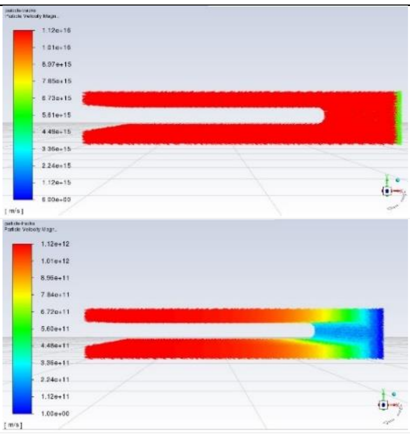
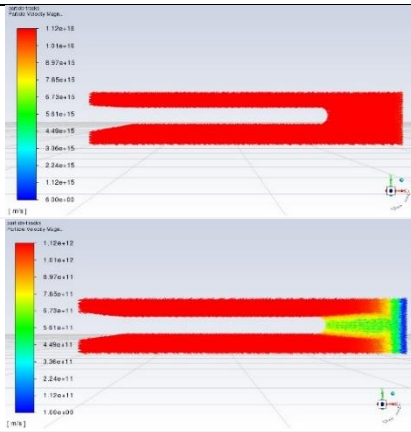


M10

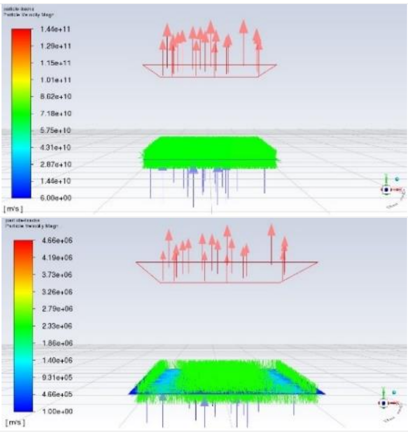
Table 3. The air velocity and the behavior of Nickel and Sulfur particles with a diameter of 0.1 and 10 microns at an inlet air velocity of 6 and 1 m/s, from the top view of the window in models 9 and 10



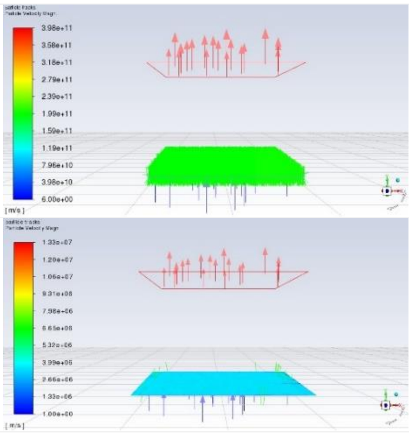
M9 Nickle



M9 Sulfur



M10 Nickle



M10 Sulfur

Table 4. The average of air velocities and temperature after passing through the coils cooled with Refrigerant and TEC

Cooling type	Average air velocity at the outlet (m/s)	Average air temperature at the outlet (°C)
Refrigerant (R-410)	1.0016079	43.448551
Thermoelectric	1.0016083	43.132512

Fan performance

Table 5 details the average air velocity at the window inlet and the exhaust fan outlet across different pressure jumps. The study evaluated various pressure jump values, with the effects of three distinct pressure modes on airflow behavior illustrated in Figure 6. According to Table 5, the average air velocity at the window opening, influenced by the fan, ranged from 0.22 to 0.63 m/s. The calculated ventilation rate (Air Changes per Hour, ACH) for the sitting room and floor area are also provided in Table 5.

The calculated ventilation rate and ACH significantly exceed the values recommended by ASHRAE for residential spaces. The ASHRAE standard 1-62 (Ashrae, 2019) stipulates a minimum requirement of 0.3 liters per second per square meter. For a sitting room of 44 m² (refer to Figure 4), this translates to a required ventilation rate of 13.2 l/s. However, the minimum airflow rate affected by the exhaust fan in the absence of wind is equal to (0.7*1.5)*0.2*1000=210 l/s

Besides, at the minimum wind velocity (1 m/s), the airflow rate is equal to: (0.7*1.5)*1.0*1000=1050 l/s

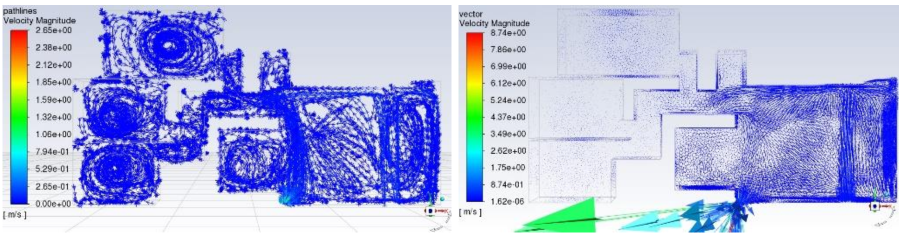
Table 5. The average air velocity at the inlet (window opening) and outlet (exhaust fan) for different pressure

Pressure jump	Poly nominal (Coefficient:60)*	Constant pressure jump: 250	Constant pressure jump:500
Average air velocity at the inlet (m/s)	0.22	0.36	0.63
Average air velocity at the outlet	6.84	12.52	19.75
ACH (Sitting room)	(0.22* (0.70*1.50) * 3600)) / 123 = **7**	(0.36* (0.70*1.50) * 3600)) / 123 = **11**	(0.63* (0.70*1.50) * 3600)) / 123 = **19**
ACH (floor)	(0.22* (0.70*1.50) * 3600)) / 315 = **3**	(0.36* (0.70*1.50) * 3600)) / 315 = **4**	(0.63* (0.70*1.50) * 3600)) / 315 = **8**

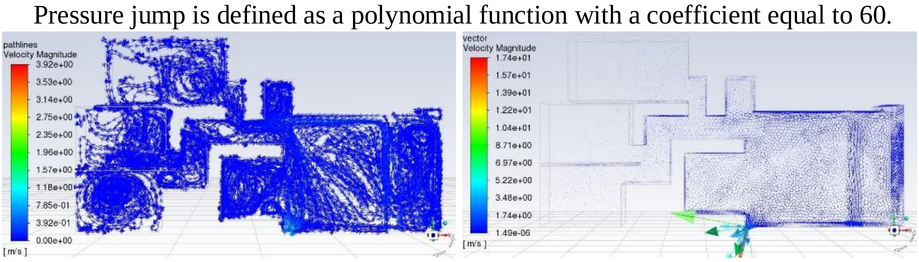
* The pressure jump can be obtained from the relationship between volumetric flow rate and fan pressure changes. Pressure jump or pressure discontinuity caused by fan operation is calculated as a function of fan velocity. This function can be a constant, polynomial, piecewise-linear, or piecewise-polynomial function. With equation 3 (polynomial form), the pressure-jump values can be calculated as a function of the air velocity normal to the fan:

$$\Delta p = \sum_{n=1}^{N} f_n^{v^{n-1}}$$

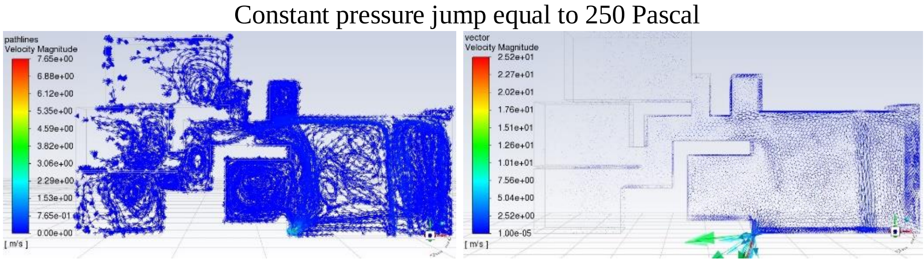
Δp: pressure jump (Pascal) f_n: polynomial coefficients v: magnitude of the local fluid velocity normal to the fan



Pressure jump is defined as a polynomial function with a coefficient equal to 60.



Constant pressure jump equal to 250 Pascal



Constant pressure jump of 500 pa

Fig 6. Airflow pathlines (left) and velocity vectors (right) in the indoor spaces affected by an exhaust fan with different pressure jump

CONCLUSION

The findings indicate that the proposed electrostatic precipitator (ESP) system is effective in providing dust-free fresh air for residential spaces. Although the initial costs and energy consumption might be high, the health benefits associated with reducing exposure to pollutants justify these considerations. The energy consumption is deemed reasonable in light of the ESP's performance in removing particles. Prior research has explored methods to reduce the energy consumption of ESPs, particularly in HVAC systems, and utilizing photovoltaic panels could potentially supply the required energy.

The system demonstrated its efficiency by completely removing copper, nickel, and sulfur particles, regardless of their diameters (0.1 and 10 microns) and the air velocities (1 and 6 m/s).

As illustrated in the figures from Table 2, reducing the distance between the inlet and the outlet of the electrostatic precipitator, which corresponds to the length of the collecting electrode, causes the electric field to push particles out of the inlet before they have a chance to move toward the collecting plates. When this distance is increased, fewer particles, which are moving toward the plates at high velocities, are trapped and removed from the airflow. This indicates that increasing the distance between the inlet and outlet results in less efficient particle capture. Variations in air velocity did not impact the particle trapping efficiency. Although a lower air velocity increases the persistence of the charged particles within the electric field, it does not enhance particle removal. Similarly, increasing the particle diameter from 0.1 microns to 10 microns did not affect the efficiency of particle trapping.

Considering the above findings, it can be concluded that, within the scope of this study and at a constant voltage, the primary factor influencing the behavior of charged particles in the electric field of the precipitator system is the distance between the inlet and the outlet of the system.

The use of cooling coils does not significantly impact the reduction of air temperature. The time available for air to pass through the coils is insufficient to achieve substantial cooling. Therefore, energy simulations can be used to determine the total hours during which thermal comfort is maintained through natural ventilation.

The required ventilation rate can be met by the minimum wind velocity. However, if the wind speed is insufficient, a fan with a pressure jump between 250 and 500 pascals can be employed to achieve the necessary airflow and meet the minimum ventilation rates recommended by the standard.

This study emphasizes parameters that are crucial for architectural design. The proposed system integrates seamlessly with the building and is user-friendly for residents. It can be utilized either during the design phase or for retrofitting existing buildings.

Some important activities that could follow this research include investigating the effect of voltage differences on system performance, proposing an energy supply system such as photovoltaic panels, and exploring the integration of other purification technologies, such as activated carbon adsorbents for VOCs and gaseous pollutants. Additionally, proposing solutions to control byproducts like ozone, despite its lower production in this scale being within permissible limits, and comparing experimental and numerical results are suggested for future research. These activities are beyond the scope of architectural research.

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