Justification of a software-integrated system of technical devices for dust and gas mixture removal from the chimney of a coal-fired thermal power plant

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Abstract

This study addresses the critical issue of air pollution from coal-fired power plants, aiming to develop an optimized emission control system. The research focused on designing an integrated, environmentally friendly system capable of superior dust and gas capture compared to conventional methods. To achieve this, a multicriteria analysis selected the optimal system design, complemented by temperature distribution analysis to ensure efficient pollutant removal within a controlled temperature range. Structural strength calculations validated the system's durability under operational stress, while minimizing material usage for cost and environmental benefits. Results indicate the system's ability to achieve comprehensive pollutant separation, and its seamless integration into existing plants with minimal modifications. The system's design allows for the extraction of byproducts like sulfuric acid and gypsum, particularly beneficial in regions with byproduct demand. The practical feasibility of the solution is enhanced by governmental incentives supporting emission reduction and byproduct reuse, highlighting the potential for widespread industrial application of this sustainable technology

Keywords

Air pollution, emission control, dust capture, multicriteria analysis, sustainability

1. Introduction

Coal-fired thermal power plants (TPPs) remain a vital energy source globally due to their cost-effectiveness [1]. However, they are major contributors to air pollution, emitting harmful flue gases [2]. Existing emission control technologies, such as electrostatic precipitators and scrubbers, often struggle with cost, complexity, and reliability, highlighting the need for improved solutions [3]. This study addresses this need by developing an innovative, integrated system designed to efficiently capture and remove dust and gas emissions from TPP chimneys. By combining multiple technologies into a single, optimized unit, this approach aims to enhance pollutant capture, reduce costs, and improve system resilience and integration. The research utilizes multicriteria analysis and temperature control to ensure efficient pollutant removal, contributing to environmental protection and sustainable TPP operation.

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2. Literature review and problem statement

This review synthesizes findings from seven articles [1-7] and patent [8] concern-ing emission control technologies in coal-fired thermal power plants (TPPs). Wang et al. [1] highlight the necessity of flue gas desulfurization (FGD) for SO_2 removal, noting post-combustion methods as most scalable, yet lacking quantitative efficiency data. Chen et al. [2,6] introduce an integrated high-temperature dust removal and denitration system, demonstrating promising pilot plant results but missing comparative analyses and scalability assessments. Zhang et al. [3] advocate for multi-pollutant control strategies, showing higher net benefits despite increased costs, but lacking detailed cost and pollutant reduction metrics. Fu et al. [4] focus on improving thermal efficiency, quantifying CO_2 capture penalties but omitting comparisons with other optimization technologies. Sani and Oyelaran [5] provide a comprehensive review of exhaust gas treatment, identifying gaps in particulate matter collection and the need for integrated multi-pollutant systems. Romero and Wang [7] review conventional emission controls, highlighting the need for quantitative performance metrics and scalability studies.

Patent [8] and articles [9-11] propose innovative systems for pollutant separation and repurposing, emphasizing high capture rates and byproduct conversion. However, they lack quantitative operational data, market feasibility analyses, and energy consumption assessments.

Collectively, these sources reveal persistent gaps: the absence of comprehensive quantitative assessments in practical applications, economic viability uncertainties in byproduct utilization, energy efficiency challenges in advanced systems, and scalability issues across diverse TPPs. These gaps highlight the need for further research focusing on real-world testing, detailed cost-benefit analyses, and integrated multi-pollutant control strategies to enhance the effectiveness and sustainability of emission control technologies in coal-fired TPPs.

3. The aim and objectives of the study

This study aims to develop and optimize an integrated system for comprehensive dust and gas removal from coal-fired power plant emissions. The objectives are to: 1) design a multi-technology system for efficient pollutant capture and processing; and 2) analyze temperature distribution and structural strength to ensure durability and cost-effective material use, minimizing environmental impact.

4. Materials and methods

This study hypothesizes that a novel system, integrating existing technologies, can convert coal-fired power plant emissions into valuable byproducts, establishing a "green" TPP [8-10]. To evaluate this, a multicriteria analysis, using AHP or MAUT, will compare the proposed system with alternatives, considering capture efficiency, cost, reliability, space, and environmental impact. Expert-weighted criteria will optimize design selection, focusing on an efficient electrostatic precipitator (ESP). A mathematical model will quantify ESP performance, incorporating adaptability (X7), using linear convolution ($U(x)=\Sigma wixi$). Economic analysis will determine implementation costs ($F=(Ki-Ci)\cdot Si$), timelines ($T=F/E$), and deviation from target states ($N=(Ci/Ki)/I$, $H=(Pi/Ki)/I$, $E=(Pi-Ci)\cdot Si$).

System feasibility will be validated through computational fluid dynamics (CFD) simulations, analyzing gas flow and temperature distribution within an additional chimney. This will optimize design and pollutant removal. Structural integrity will be ensured by finite element analysis (FEA), considering self-weight, thermal stress, wind, and seismic loads. Compound plastic materials will be evaluated for their suitability, addressing temperature constraints. Experimental validation and comparisons with existing systems will provide feedback for iterative improvements.

Simulate the heat transfer and thermal interactions within the chimney system to ensure the temperature of the gas mixture remains within optimal ranges for efficient pollutant removal by using energy Equation (3D form):

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P V \cdot \nabla T = K^2 \nabla^2 T + q, \tag{1}$$

where ρ: gas density (kg/m3); C_P: specific heat capacity (J/kg·K); T: temperature (K); V: velocity vector (m/s); K: termal conductivity (W/m·K); q: heat source term (W/m3).

The coupled heat transfer model ensures that the gas cools sufficiently for pollutant condensation and removal without damaging the equipment. The temperature gradient facilitates better pollutant capture, as seen in the scrubber efficiency.

Model the behavior of dust particles in the chimney system to evaluate the capture efficiency of the filtration unit have been accomplished based on Eulerian-Lagrangian Method for Particle Tracking. Governing Equations: Eulerian for Gas Phase: Continuity and Navier-Stokes equations for fluid dynamics. Lagrangian for Particles: Newton's second law:

$$F_P = m_P(dV_P/dt) = Fd + Fg + Ft, \tag{2}$$

where F_P: particle force; Fd: drag force ($6\pi\mu r_P(V - V_P)$); Fg: gravitational force (mPg); FT: turbulent dispersion force.

Ensures thermal control for efficient pollutant condensation and removal. Eulerian-Lagrangian Tracking helps evaluate and enhance dust particle removal by capturing particle dynamics under varying flow conditions. The model allows for optimizing the deflector angles and filter placement to maximize efficiency. These methods, when integrated, provide comprehensive validation for the system's effectiveness in handling thermal and particulate interactions.

5. Results of justification an innovative system of technical devices for the removal of all dust and gas mixture

5.1. Develop a concept for a system removing all dust and gas from a chimney of a TPP

This study employs a multicriteria analysis, using the Analytic Hierarchy Process (AHP), to evaluate the proposed emission control system against alternatives. Key performance criteria include capture efficiency, cost, durability, byproduct yield, implementation ease, environmental impact, and operational reliability. Table 1 presents the comparative results of this analysis.

Table 1

Overview of calculated results based on the proposed indicators

Option	Efficiency (X1)	Capital Cost (X2)	Operating Cost (X3)	Reliability (X3)	Space requirements (X4)	Envieron-mental impact (X5)	Weighted score (X6)	Rank
Option A	9,0	7,5	8,0	9,0	8,0	8,5	8,33	1
Option B	8,0	8,0	7,0	8,5	8,5	8,0	8,0	2
Option C	7,5	9,0	7,5	8,0	7,5	7,0	7,75	3
Option D	7,0	8,5	6,5	7,0	9,0	7,5	7,58	4

Calculation Explanation. Step 1: Assign Criteria Weights. Each criterion is weighted based on its importance: efficiency (0.25), capital cost (0.2), operating cost (0.15), reliability (0.2), space requirements (0.1), and environmental impact (0.1). **Step 2: Normalize Scores.** Raw scores (X_1 to X_6) are normalized on a 0–1 scale and multiplied by their respective weights. The weighted score for **Option I** is calculated as:

$$\text{OptionI} = \sum 16(Wj \times Wij).$$

Step 3: Compute Weighted Scores. Using these weights, the overall score is determined for each option. Option A, the proposed gas removal system, ranks highest due to its balanced efficiency, reliability, and environmental impact. Options B and C are based on sources [7] and [5], respectively. Option D [8] ranks lowest, performing poorly in efficiency and reliability despite high space efficiency.

System Design. For coal-fired power plants, the authors propose innovative dust and gas exhaust systems (Fig. 1, 2) [12, 13]. Future studies will analyze material properties and refine the geometric, kinematic, and dynamic parameters of key components.

The system consists of:

- Main Chimney (1) – A heat-resistant attachment (2) (steel/plastic) is fixed at the upper base;
- Additional Chimney (3) – Connected through a hole in attachment (2), aligned vertically and curving near the base of the main chimney;
- Storage Unit (4) – Positioned at the lower end of Chimney (3), it separates solid particles (ash) from smoke using scrubbers, cyclones, and filters;
- Support Device (5) – Provides structural stability to Chimney (3).

The system optimizes draft and gas velocity, ensuring efficient dust and gas removal.

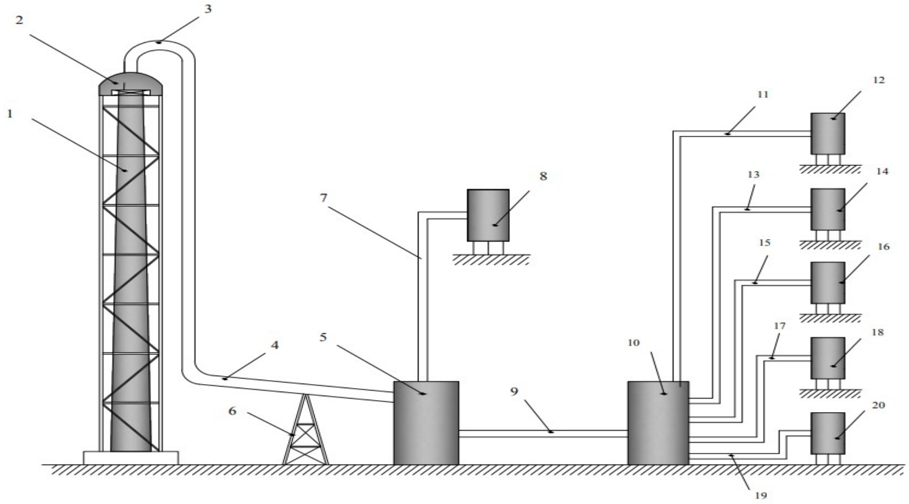

Figure 1: Emission Removal and Conversion System.

1 - Main Tower – Extracts dust and gases; 2 - Stabilizing Cable – Ensures structural stability;3 - Outlet Duct – Channels extracted emissions;4 - Connecting Pipe – Transfers materials to processing units; 5 - Support Frame – Reinforces the connecting pipe; 6 - Base Structure – Supports the entire system;7 - Primary Collector – Captures initial separated materials; 8 - Electric Separator – Electrically filters fine particles; 9 - Secondary Collector – Further collects separated particles; 10 - Intermediate Chamber – Transfers materials for final processing; 11 - Water Supply Pipe – Provides water for cooling or processing; 12 - Drainage Pipe – Removes excess liquid; 13 - Clamps – Secure system components;14 - Corner Brackets – Reinforce vertical structures; 15 - Vertical Posts – Support system stability; 16 - Cross Braces – Strengthen against lateral forces; 17 - Special Nozzle – Directs processed materials; 18 - Main Chimney – Releases treated emissions; 19 - Support Device – Stabilizes the chimney; 20 - Final Collector – The last stage before emission release.

After solid particles are removed from flue gases in the main chimney, ash is transported to a collector for processing, where valuable elements such as rare earth metals, uranium, gold, and base metals are extracted. The cleaned gases then pass through successive subsystems equipped with filters and membranes that separate carbon oxides, nitrogen oxides, hydrogen sulfide, methane, and ammonia, each directed to dedicated collectors for conversion into useful products – methane into methanol, hydrogen sulfide into sulfur and oxygen, nitrogen oxides into nitric acid, and carbon oxides into building materials or fuel. An alternative system design (Fig. 2) features a vertical cylindrical exhaust with conical sections, stabilizing cables, and an electrostatic precipitator at the outlet, integrated with ash and gas collectors, high-voltage components, water and drainage systems, and structural supports. This configuration ensures pollutant capture, optimized airflow, and stable draft conditions while enabling efficient removal and transformation of dust-gas mixtures from thermal power plant chimneys.

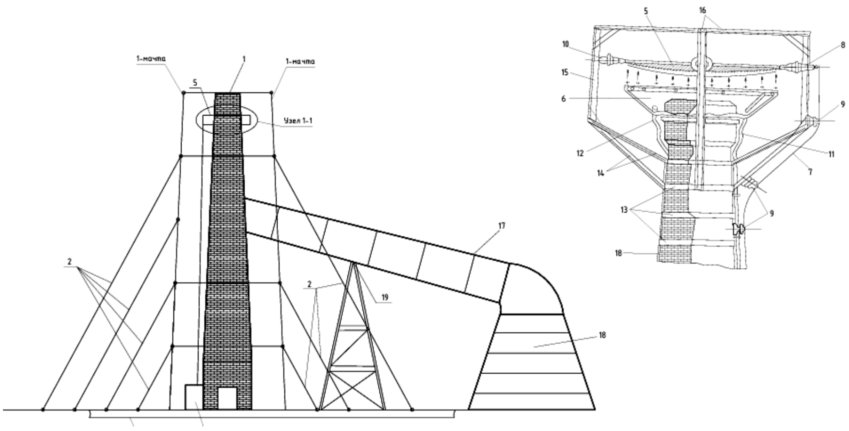

Figure 2: The system separates and processes solid particles and gases from power plant emissions into useful products.

1 - Dust and gas extraction (cylindrical body), 2 - Stabilizing cable, 3 - Platform, 4 - Ash separator, 5 - Electric separator, 6 - Fume or dust collector, 7 - High voltage cable, 8 - High voltage bushing, 9 - High voltage support insulators (first), 10 - High voltage support insulators (second), 11 - Water supply pipe, 12 - Drainage pipe, 13 - Clamps, 14 - Corner brackets, 15 - Vertical posts, 16 - Cross braces, 17 - Special nozzle, 18 - Main chimney, 19 - Support device

The system removes dust and gas emissions by directing the mixture from the main chimney through a nozzle into a rib-reinforced plastic exhaust of conical sections, stabilized by cables and connected to a platform with an ash collector. The gases then pass through an electrostatic precipitator, where charged electrodes and a water-based precipitation electrode capture impurities that settle on the conical surface; the contaminated water is filtered, separating ash and harmful gases such as carbon oxides, nitrogen oxides, hydrogen sulfide, methane, and ammonia. Ash-laden water is sent to the collector, while cleaned gases exit safely into the atmosphere. The cylindrical exhaust pipe is dimensioned to sustain draft and flow, while its design also dissipates heat and lowers chemical concentrations, ensuring safe operation under flue gas temperatures of 100-150 °C.

5.2. Explore and analyze integral parts ensuring structural integrity and safety of the system

The objective of this study is to simulate and analyze the flow dynamics of dust and gas mixtures in a coal-fired power plant chimney to validate the efficiency and feasibility of an innovative emission control system. Using CFD tools (ANSYS Fluent), a scaled chimney model (100 m height, 6 m diameter) with flow deflectors, filters, and scrubbers was developed. Simulations considered gas velocity of 15 m/s, dust concentration of 150 mg/m^3, and a composition of 70% N_2, 15% CO_2, 10% H_2O, and 5% SO_2 at 120–180 °C, with boundary conditions of velocity inlet, atmospheric outlet, and insulated non-slip walls. A high-resolution tetrahedral mesh was refined around critical components, while the Eulerian–Lagrangian approach with k-ε turbulence modeling and coupled heat transfer captured realistic flow behavior. Pollutant removal mechanisms were analyzed through particle deposition on filters and SO_2 absorption in scrubbers, with CFD calculations providing velocity fields, pressure drops, and flow rates to demonstrate the system's pollutant capture performance.

Problem Statement. Given Data: chimney height (H): 50 m, inner diameter (D): 1.8 m, temperature (T): 300°C, gas density (ρg\rho_gρg): 0.8 kg/m³ (at 300°C, approximated for flue gases), flow rate (Q): 10,000 m³/h, dynamic viscosity (μ): 2.1×10−5 Pa/cdotps.

Step 1: calculate the velocity of the gas mixture. The velocity (V) is given by:

$V = Q/A$, where $A = \pi D2/4$ (cross - sectional area of chimney). $A = \pi(1{,}8)2/4=2{,}544$ m².

$V = 10{,}000/(3600 \cdot 2{,}544) = 1{,}096$ m/s.

Step 2: calculate Reynolds number. The Reynolds number (Re) determines whether the flow is laminar or turbulent:

$$Re = \rho_g VD/\mu. \tag{3}$$

Substitute the values: $Re = (0{,}8) \cdot (1{,}096) \cdot (1{,}8)/2{,}1\times10\text{-}5 = 74{,}857$.

Since $Re > 4{,}000$, the flow is turbulent.

Step 3: estimate pressure drop. For turbulent flow, the Darcy-Weibach equation is used:

$$\Delta P = f(L/D)\cdot(\rho GV2)/2, \tag{4}$$

where f is the friction factor (estimated using the Colebrook equation for turbulent flow, assuming roughness $\mathcal{E} = 0{,}01$ m):

$$f = 0{,}25/[log_{10}((\mathcal{E}/3{,}7D)+(5{,}74/Re^{0{,}9}))]^2=0{,}25/[log_{10}((0{,}01/3{,}7\times1{,}8)+(5{,}74/74857^{0{,}9}))]^2 \approx 0{,}022 \tag{5}$$

Substitute f into the pressure drop equation:

$$\Delta P = 0{,}022\cdot(50/1{,}8) \cdot (0{,}8\cdot1{,}962)/2 \approx 0{,}267 \text{ KPa}.$$

Step 4: Calculate power required for the fan. The power required (P) to overcome pressure drop is given:

$$P = \Delta P\cdot Q \tag{6}$$

Convert Q to m³/sec: $Q = 10{,}000/3600 = 2{,}778$ m³/sec.

$$P = 0{,}267\cdot2{,}778 = 0{,}742 \text{ kW}.$$

Results: velocity of gas mixture: 1.096 m/s, Reynolds number: 74,857 (turbulent flow), pressure drop: 0.267 kPa, fan power requirement: 0.742 kW.

The temperature distribution is often a function of several factors including the type of fuel used, the efficiency of combustion and the design of chimney itself. Below is a simplified model for temperature distribution in a chimney: 1. Base (combustion zone): temperature can range from 300 °C to 500 °C due to combustion of fuel. 2. Middle section: as the gases rise, heat loss due to conduction the chimney walls and radiation. Temperature may decrease to around 200 °C to 300 °C. 3. Upper section: by the time the exhaust reaches the upper section, temperature can range from 100 °C to 200 °C, influenced by the cooling effect of ambient air and the distance traveled. 4. Outlet: at the outlet, as specified in the system description, the temperature should be controlled between 100 °C to 150 °C to ensure efficient dispersion and compliance with environmental standards.

Here is a simple linear temperature gradient model:

$$T(y) = Tbase - (Tbase - Toutlet)y/H \tag{7}$$

where: $T(y)$ is the temperature at height y; $Tbase$ is the temperature at the base of the chimney; $Toutlet$ is the temperature at the outlet H, and H is the total height of the chimney.

Assuming: $Tbase = 400$°C, $Toutlet = 125$°C, $H = 100$ m. The temperature at any height Ym within the chimney can be calculated using the above formula (7). For instance, at the midpoint ($y = 50$ m): $T(50) = 400 - (400 - 125)(50/100) = 262{,}5$°C.

To perform a strength calculation for a chimney, we need to consider several factors including wind load, self-weight, material properties, and geometric dimensions. Example, given data: 1. Height of the chimney $H = 50$ meters. 2. Outer diameters $D_{outer} = 2$ meters. 3. Inner diameter $D_{inner} = 1{,}8$ meters. 4. Material: reinforced concrete. 5. Density of concrete $\rho = 2400$ kg/m³. 6. Modulus of elasticity E = 30 GPa. 7. Wind load W = 1,5 KN/m^2 (based on local wind speed and shape factor). 8. Safety factor SF = 1,5.

1. Calculation the cross-sectional area:

$$A = \pi/4(D_{outer}{}^2 - D_{inner}{}^2) = \pi/4{*}0{,}76 = 0{,}598 \text{ m}^2 \tag{8}$$

2. Calculate the moment of inertia:

$$I = \pi/64(D_{outer}{}^4 - D_{inner}{}^4) = 0{,}269 \text{ m}^4$$

3. Calculate the weight of the chimney:

$$W_{weight} = \rho{\times}A{\times}g{\times}H = 2400\text{kg/m}^3{\times}0{,}598 \text{ m}^2{\times}9{,}81\text{m/s}^2{\times}50 \text{ m} = 704{,}94 \text{ k} \tag{9}$$

4. Calculate the wind load:

$$W_{wind\ load} = W{\times}H = 1{,}5 \text{ kN/m}^3{\times} \text{ 50m} = 75 \text{ kN} \tag{10}$$

5. Calculate the bending moment due to wind load:

$$M = (W{\times}H^2)/2 = 1875 \text{ kN·m} \tag{11}$$

6. Calculate the maximum stress: using the bending stress formula:

$$\sigma = (M{\times}C)/I \tag{12}$$

where C is the distance from the neutral axis to the outer fiber:

$$(D_{outer}/2){:}c = 1\text{m}, \sigma= (1875\text{kNm}{\times}1 \text{ m})/0{,}269 \text{ m}^4 = 6{,}97 \text{ MPa} \tag{13}$$

Check the material strength: for reinforced concrete, assume a permissible stress of around 10 MPa. Applying the safety factor:

$$\sigma_{allowable} =\sigma_{permissble}/SF = 10\text{MPa}/1{,}5 = 6{,}67 \text{ MPa} \tag{14}$$

Since the calculate stress 6,67 MPa is slightly above the allowable stress of 6,67 MPa, this indicates that the chimney may require additional reinforcement or redesign to ensure safety.

If we replace reinforced concrete with a compound plastic material for the chimney, we need to adjust the given parameters to reflect the properties of the plastic. Compound plastic materials are generally lighter and may have different elastic properties compared to concrete. Here is how the calculation would change. In this case we have:

$$W_{weight} = \rho{\times}A{\times}g{\times}H = 2400 \text{ kg/m}^3{\times}0{,}598 \text{ m}^2{\times}9{,}81 \text{ m/s}^2{\cdot}50\text{m} = 352{,}47 \text{ kN} \tag{15}$$

Check the material strength: assume a permissible stress for compound plastic is around 25 MPa. Applying the safety factor SF = 1,5:

$$\sigma_{allowable} =\sigma_{permissble}/SF = 25\text{MPa}/1{,}5 = 16{,}67 \text{ MPa} \tag{16}$$

Since the calculated stress σ = 6,97 MPa is well below the allowable stress of 16,67 MPa, the design is considerable safe.

Using compound plastic materials significantly reduces the weight of the chimney and increases the allowable stress, indicating that such materials could be move efficient in this application. However, it is important to consider other factors such as temperature resistance and long-term durability of the plastic material in real-world conditions. To evaluate the temperature resistance of a chimney made from compound plastic materials, we need to consider the material properties, particularly its thermal expansion, thermal conductivity, and maximum service temperature. Here's an example calculation. Given data: 1. Height of the chimney H = 50 meters. 2. Outer diameters D_{outer} = 2 meters. 3. Inner diameter D_{inner} = 1,8 meters. 4. Material: compound plastic. 5. Density of compound plastic material ρ = 1200 kg/m^3. 6. Modulus of elasticity E = 2 GPa. 7. Thermal expansion coefficient (α), α = $100{\times}10^{-6}/^{o}\text{C}$ (typical value for plastics). 8. Thermal conductivity (k), k = 0,2 $W/(\mathrm{m\cdot k})$ (typical value for plastics). 9. Maximum service temperature: 120°C. 10. Operating temperature range: from 20°C (ambient) to 150°C (maximum exhaust temperature). 11. Wind load $W = 1{,}5\ \mathrm{KN/m^2}$ (based on local wind speed and shape factor). 12. Safety factor $SF = 1{,}5$.

Step-by-step calculation:

1. Thermal expansion calculation: the linear expansion of the chimney due to temperature change can be calculated using formula:

$$\Delta L = \infty \times L \times \Delta T \tag{17}$$

Where ΔL is the change in length; ∞ is the thermal expansion coefficient; L is the original length; ΔT is the change in temperature. For the given chimney:

$$\Delta L = 150°\mathrm{C} - 20°\mathrm{C} = 130°\mathrm{C}$$
$$\Delta L = 100\times 10^{-6}/°\mathrm{C}\times 50\ \mathrm{m}\times 150°\mathrm{C} = 0{,}65\ \mathrm{m}$$

The chimney will expand by 0,65 meters (65 cm) when heated from 20 °C to 150 °C.

2. Thermal stress calculation: thermal stress can be calculated if the expansion is restricted. This is given by:

$$\sigma_{thermal} = E\times\infty\times\Delta T \tag{18}$$

Where E is the modulus of elasticity. For the compound plastic (assume E = 2 Gpa):

$$\sigma_{thermal} = 2\times 109\mathrm{Pa}\times 100\times\Delta 10^{-6}/°\mathrm{C}\times 130°\mathrm{C} = 26\cdot 106 = 26\mathrm{MPa}$$

Thermal conductivity and heat transfer: the rate of heat transfer through the chimney wall can be calculated using Fourier′s law:

$$Q = (k\times A\times\Delta T)/d \tag{19}$$

where Q is the heat transfer rate; k is the thermal conductivity; A is the surface area; ΔT is the temperature difference; d is the wall thickness. Assuming the wall thickness d = 0,1 m (for simplicity):

$$A = \pi\times d_{inner}\times H \tag{20}$$
$$A = \pi\times 1{,}8\mathrm{m}\times 150\mathrm{m} = 282{,}74\mathrm{m}^2$$
$$Q = (0{,}2W/(m\cdot k)\times 282{,}74\mathrm{m}^2\times 130°\mathrm{C})/0{,}1\mathrm{m} = 7355{,}24\ \mathrm{W}$$

This is the rate at which heat is conducted through the chimney wall.

The coupled heat transfer model ensures that the gas cools sufficiently for pollutant condensation and removal without damaging the equipment. The temperature gradient facilitates better pollutant capture, as seen in the scrubber efficiency.

The problem is to simulate heat transfer in a 100 m × 6 m chimney so the gas mixture stays in the optimal temperature range for pollutant removal. The model assumes 200°C inlet gas at 15 $\mathrm{m^3/s}$, steel walls (k = 50W/mK, $thickness$ = 0.02 m), and an external water-cooled jacket (h = 150 $\mathrm{W/m^2{\cdot}K}$); typical profiles range from 300-500°C near the base, cool to ~200-300°C mid-height, and reach 100-200°C toward the top, with the outlet controlled at 100-150°C. CFD (based on governing equations (1)-(2)) indicates gas cooling from 200°C to 100°C, wall temperatures stabilized at 90-95°C by the cooling system, and a wall heat flux of ~25 kW; finer meshes and geometry/particle coupling can refine these estimates. To compare electrostatic precipitator (ESP) designs, apply a multi-criteria framework: define criteria, gather data, normalize, weight, aggregate, and rank, using X1 – efficiency, X2 – capital cost, X3 – operating cost, X4 – reliability, X5 – space, and X6 – environmental impact.

To normalize and compare different designs of electrostatic (ESPs) for cleaning flue gases from thermal power station, you can use a systematic evaluation framework based on multiple criteria. This framework typically involves the following steps: 1. Identify evaluation criteria. Gather data.

3. Normalize data. 4. Weight criteria. 5. Aggregate scores. 6. Compare and select the best option. Step-by-Step evaluation framework.

Step 1. Identify evaluation criteria. First, identify the criteria on which the ESP design will be evaluated. X1 – efficiency: practical removal efficiency. X2 – capital cost: initial investment cost. X3 – operating cost; X4 – realibility: frequency and impact of breakdowns or maintenance needs. X5 – space requirements. X6 – environmental impact.

Step 2. Gather data. Collect data for each criterion from different ESP designs. This data might come from manufacturer specifications, operational data from existing installations or expert estimates.

The data that have being got from manufacturer specifications, operational data from existing installations or expert estimates are represented in Table 2.

Table 2
Performance and cost parameters of ESP design alternatives

ESP design	Efficiency (X1)	Capital cost (X2)	Operating cost (X3)	Reliability (X4)	Space requirements (X5)	Environmental impact (X6)
Design A	95%	\$1.000.000	\$50.000/year	9,0	100 m^2	Low
Design B	90%	\$800.000	\$60.000/year	Medium	80 m^2	Medium
Design C	90%	\$800.000	\$55.000/year	\$55.000/year	90 m^2	Low

Step 3. Normalize data.

Normalize the data to a common scale, typically whether 0 or 1, where 1 represents the best performances for each criterion and 0 if it is not apparent. Normalize formula:

$$Nnormalized\ value = (Aactual\ value - Mmin\ value)/(Mmax\ value - Mmin\ value) \tag{21}$$

The results of normalizing and comparing the different designs of electrostatic (ESPs) for cleaning flue gases based on approaches of multiple criteria are given in Table 3.

Table 3
Normalized criteria values for ESP design alternatives

ESP design	Efficiency (X1)	Capital cost (X2)	Operating cost (X3)	Reliability (X4)	Space requirements (X5)	Environmental impact (X6)
Design A	1,00	0,00	1,00	1,00	0,00	1,00
Design B	0,00	1,00	0,00	0,00	1,00	0,5
Design C	0,5	0,5	0,5	1,00	0,5	1,00

Step 4. Weight criteria. Assign weight to each criterion based on its importance to the overall evaluation. The sum of all weight should be 1,0. In the Table 3 represents the values of each the criteria.

Table 4
The weights of each criterion

Criterion	Efficiency (X1)	Capital cost (X2)	Operating cost (X3)	Reliability (X4)	Space requirements (X5)	Environmental impact (X6)
Weight (W)	0,3	0,2	0,2	0,1	0,1	0,1

Step 5. Aggregate scores.

Calculating the weight scores for each design by multiplying the normalized value by the corresponding weight and then summing the results for each criterion have been obtained represents in Table 4.

Step 6. Compare and select the best option.

Compare the weighted scores to select the most efficient and cost-effective ESP design. In this example design A has the highest weighted score (0,7) indicating that it is the most efficient and cost-effective option based on the chosen criteria and their respective weights.

6. Discussion of experimental results

This article proposes an eco-friendly system for coal-fired power plant chimneys that channels emissions into an auxiliary exhaust where pollutants are comprehensively treated and converted into valuable byproducts. The design integrates electrostatic precipitators, wet scrubbers, and catalytic converters in a novel configuration that captures particulates, SO_2, NO_x, and heavy metals simultaneously, improving efficiency and reducing costs compared to separate treatment units. Pollutants are transformed into sulfuric acid, gypsum, and fly ash, creating economic incentives for adoption. CFD modeling and structural calculations confirm reliable flow, thermal performance, and strength, showing that composite plastic materials lower weight and stress, with thermal expansion reaching 0.65 m and stress at 26 MPa. The system's modular elements simplify assembly, while automated monitoring and operator training ensure stable operation. Although initial costs are high, savings from reduced penalties and byproduct sales enhance feasibility, and pilot projects are recommended to validate scalability and compliance under varied conditions.

7. Conclusion

This article presents the development and justification of an innovative, eco-friendly system for removing dust and gas emissions from a coal-fired power plant's chimney into an auxiliary chimney, followed by complete processing of the extracted ash and gases into valuable products. Two design concepts for this system are proposed. Despite its seemingly complex structure, the system comprises simple elements for quick assembly and disassembly. Placing the electrostatic precipitator on the auxiliary chimney, rather than the main chimney, enhances efficiency and maintenance safety. Additionally, a highly efficient and cost-effective electrostatic device for dust and gas separation has been designed.

The study analyzes the structural integrity and safety of the auxiliary chimney under various operating conditions. Four combustion zones – base, middle, upper, and outlet – have been identified, with temperature distribution modeled using a linear gradient at different heights. A strength analysis of the chimney considers factors such as wind load, self-weight, material properties (reinforced concrete and composite plastic), and geometric dimensions. Findings show that composite plastic significantly reduces chimney weight while increasing allowable stress, making it a promising material choice. The thermal resistance of a composite plastic chimney is evaluated based on thermal conductivity and maximum service temperature. Thermal expansion calculations indicate an increase in chimney length by 0.65 meters, and if constrained, the resulting thermal stress is 26 MPa. The heat transfer rate through the chimney wall is 7355.24 W.

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Declaration on Generative AI

During the preparation of this work, the authors used OpenAI ChatGPT and Grammarly solely for grammar and spelling checking. The intellectual content, scientific ideas, analysis, results, and conclusions are entirely the authors own. After using these tools, the authors carefully reviewed and edited the manuscript and take full responsibility for the content of the publication.

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