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Engineering Design and Performance Analysis of a Multi-Chamber Filtration System for Induction Waste Incinerator Using Fluid Flow and Thermal Simulation

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ABSTRACT

The increasing generation of inorganic waste has intensified the need for efficient and environmentally friendly waste treatment technologies. Small-scale incinerators are widely used due to their ability to significantly reduce waste volume; however, they often lack proper emission control systems. As a result, uncontrolled exhaust gases contribute to air pollution and pose environmental and health risks. This study addresses the limitation by proposing an improved incinerator design equipped with a multi-chamber filtration system. The main contribution of this research lies in the development of an integrated engineering design that combines airflow control, thermal management, and emission reduction in a small-scale incineration system. In addition, this study provides a simulation-based evaluation framework for assessing system performance under high-temperature conditions. The methodology involves engineering calculations based on fluid mechanics and thermodynamics principles, including airflow rate, velocity, and air density analysis. A multi-chamber system was designed to facilitate staged cooling, filtration, and gas flow stabilization. Computational simulations were conducted using SolidWorks to analyze airflow patterns, temperature distribution, and structural stress. Key operational parameters such as flow rate (0.174 m^3/s), temperature (~275°C), and pressure were used to evaluate system performance. The results show that the proposed system achieves stable airflow distribution with minimal turbulence across chambers. The velocity of airflow is effectively reduced in the filtration stages, allowing heat dissipation and partial gas condensation. Thermal analysis indicates improved temperature control compared to conventional systems, while structural simulations confirm that all components operate safely within material limits. Furthermore, the multi-chamber design significantly enhances emission management and reduces the risk of direct pollutant release. In conclusion, the proposed multi-chamber filtration system improves the environmental performance and operational stability of small-scale incinerators. This design offers a practical and scalable solution for sustainable waste management applications.

1. Introduction

The increase in inorganic waste in recent decades has become a serious challenge for environmental management, particularly in developing countries that still face limited waste management infrastructure (Adiyanto et al., 2024). This problem is increasingly relevant in urban Southeast Asia, where waste has become one of the most visible environmental issues due to rapid urban growth since the late 1980s. Population growth, urbanization, industrialization, changing consumption patterns, economic growth, and changing income levels have driven an increase in the volume and diversity of solid waste generated. This situation places significant pressure on waste management systems, especially as many cities still face institutional, funding, technological, regulatory, knowledge, and public participation limitations in managing waste effectively (Bariyah et al., 2025; Ngoc & Schnitzer, 2009).

Conventional methods such as waste collection, transportation, and disposal are considered insufficiently effective in preventing health risks as well as economic and environmental impacts (Dereli et al., 2024). Therefore, various waste management technologies continue to be developed, although each method has different advantages, limitations, scope of application, and level of effectiveness. One technology widely used to address this issue is the incinerator. Waste incineration is the thermally induced oxidation of waste within a combustion unit designed to convert the organic components of waste into inert ash and also to sterilize or destroy hazardous chemical and biological agents (Adu et al., 2022; Brunner & Morf, 2025; Tang et al., 2023). However, the use of small-scale incinerators still faces a major obstacle, namely the lack of an adequate emission control system, so that the resulting exhaust gas has the potential to be directly released into the environment without going through an effective filtering process.

Most existing small-scale incinerator designs still focus on improving combustion efficiency, such as increasing combustion chamber temperature, optimizing residence time, and reducing fuel consumption (Yaqoob et al., 2022; Zakaria et al., 2022). While these aspects are important for ensuring a more complete combustion process, this approach is insufficient to guarantee environmental safety (Shalini et al., 2021). Combustion gases still contain solid particles, smoke, and hazardous compounds that require further treatment through flue gas treatment systems. Therefore, filtration and emission control systems should be an integral part of incinerator design, not simply an add-on component.

In large-scale incineration systems, emission control is generally achieved using technologies such as cyclone separators, scrubbers, bag filters, and electrostatic precipitators (Jayadi, 2024; Yulianto et al., 2026). These technologies have proven effective in reducing emissions, but they are limited in their implementation on a small scale due to their high cost, large installation space, and operational and maintenance complexity. This creates a need for simpler, more compact, and more economical filtration systems that can still improve emission control performance in small-scale incinerators.

One approach that can be used to address these issues is the implementation of a multi-chamber system (Asadollahfardi et al., 2025; Elmansy et al., 2022; Liu et al., 2026). This configuration allows the gas flow to pass through several chambers gradually, resulting in a decrease in flow velocity, an increase in residence time, and a gradual release of heat (Ding et al., 2023; Zhu & Zhang, 2024). Furthermore, a multi-chamber system can also help stabilize the flow and reduce turbulence, thereby improving the effectiveness of the filtration process. However, in many previous studies, the relationship between chamber configuration, fluid flow behavior, and temperature distribution has not been analyzed in an integrated manner, especially in small-scale incinerator designs.

Advances in computational simulation technology provide opportunities for more systematic design evaluations. Computational Fluid Dynamics (CFD)-based simulations and thermal analysis allow for visualization of flow patterns, velocity distributions, temperature gradients, and potential turbulence within the system. CFD is also a method that can be used to design and run simulations without the need to build a physical model (Sarakikya et al., 2021).

Computational work is crucial in current research due to its lower cost and accuracy with tiny errors (Johari et al., 2012; Vanierschot et al., 2023). Furthermore, structural analysis can be used to ensure that designed components can withstand thermal and mechanical loads during operation. This study proposes the engineering design of a multi-chamber filtration system integrated into a small-scale induction waste incinerator. Unlike conventional incinerators, induction-based systems allow for more controlled heat distribution and more stable operating temperatures, thus requiring a flue gas treatment system design capable of handling both flow and thermal conditions simultaneously. This research focuses not only on design development but also on quantitative system performance analysis through fluid flow and thermal simulation approaches. The evaluation is conducted by examining key parameters such as flow velocity distribution, fluid flow patterns, temperature gradients, and structural response to thermal loads. The proposed multi-chamber system is designed to produce a gradual decrease in flow velocity, increase gas residence time, and facilitate heat dissipation before reaching the final filtration stage.

2. Method

2.1. Engineering Design of the System

This research uses a simulation-based engineering design approach to design a multi-chamber filtration system for a small-scale induction waste incinerator. The system design was developed using SolidWorks in the form of a three-dimensional model consisting of an induction-based combustion chamber, connecting channels (ducting), a multi-chamber filtration unit, and a blower as a driver of the exhaust gas flow (Chen et al., 2024; Harding et al., 2020). The multi-chamber configuration is designed to create a staged flow, where the gas flow velocity decreases progressively as it moves between chambers. This design aims to increase gas residence time, reduce turbulence, and allow heat dissipation before the gas reaches the final filtration stage. Variations in the geometry of each chamber are also applied to support flow stabilization and improve the effectiveness of the filtration process.

2.2. Fluid flow and thermal analysis

An initial analysis was conducted using principles of fluid mechanics and thermodynamics to determine the flow characteristics and thermal conditions within the system. The relationship among flow rate, cross-sectional area, and flow velocity is shown in Eq. (1).

$$Q = A.v \tag{1}$$

Where flow rate (Q) is obtained from the blower specifications, while flow velocity (v) is calculated at each section of the system to ensure the flow remains stable and does not cause excessive turbulence. Next, a thermal analysis was conducted to evaluate the effect of high temperatures on fluid properties. Air density was calculated using the ideal gas Eq. (2).

$$\rho = \frac{P}{RT} \tag{2}$$

This analysis was used to understand changes in flow characteristics due to high temperatures and to determine cooling requirements prior to the filtration process. The integration of flow and thermal analysis provides the basis for evaluating overall system performance.

2.3. Computational simulation and performance evaluation

System performance evaluation was conducted using SolidWorks Flow Simulation to analyze fluid flow patterns, velocity distribution, temperature distribution, and pressure conditions within the system. The inlet flow rate of 0.174 m^3/s was determined based on a blower capacity of 626 m^3/h, while the inlet temperature was set at 275°C as the assumed simulation operating conditions. The simulation results were analyzed based on several key performance parameters, namely flow velocity distribution, velocity drop between chambers, fluid flow patterns, and temperature distribution.

In addition, a structural analysis was conducted to ensure that the system components were able to operate within safe limits against thermal and mechanical loads. These parameters were used to assess flow stability, heat dissipation effectiveness, and the reliability of the filtration system in supporting exhaust emission reduction

3. Results and Discussion

The simulation results from the CFD analysis led to a comprehensive overview of fluid flow behavior and thermal distribution in a multi-chamber filtration system incorporated with an induction waste incinerator. The evaluation was performed to investigate the effect of the chamber configuration on the flue gas flow characteristics such as velocity distribution, temperature, pressure, and turbulence intensity in each part of the system. The target of this analysis is to evaluate the effectiveness of the design to provide a more stable flow, better heat dissipation, and a more optimal flue gas filtration process. The CFD results are given in Fig. 1.

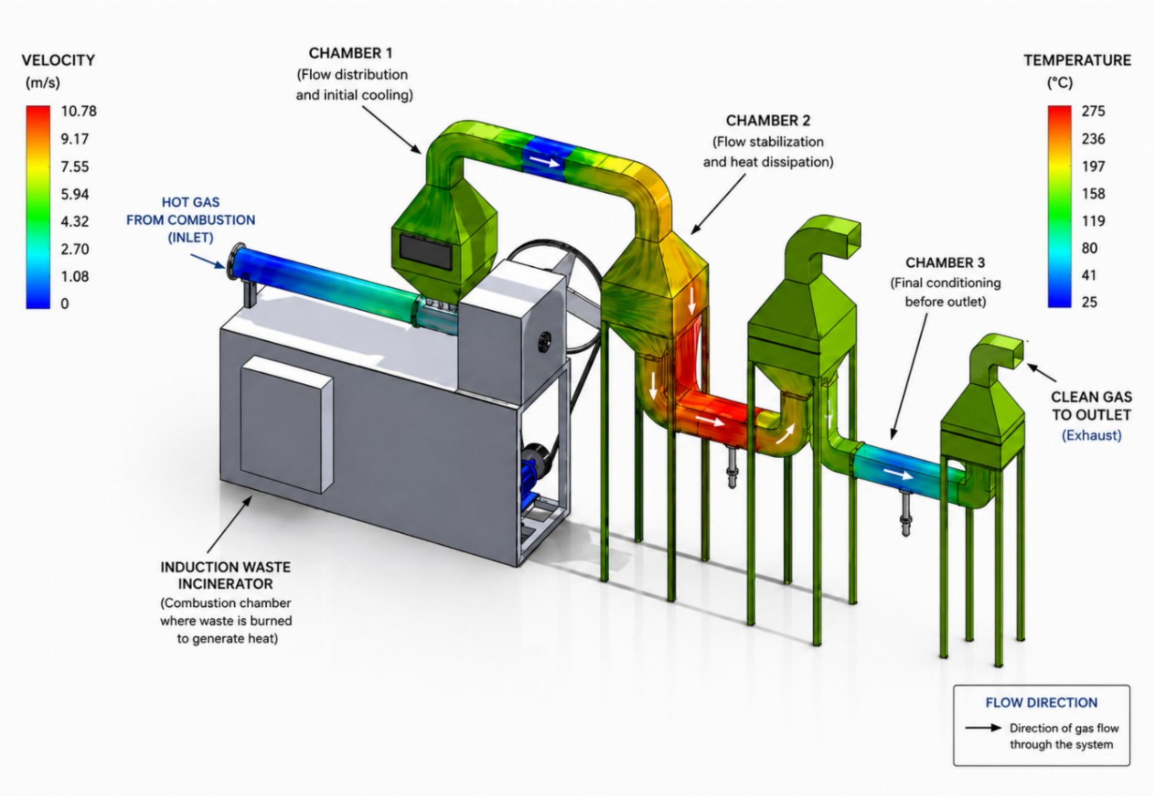

Fig. 1. Visualization of Computational Fluid Dynamics (CFD) simulation results.

The result of a CFD simulation of a multi-chamber filtration system combined with an induction waste incinerator is shown in Fig. 1. This visualization shows the velocity contour and temperature contour of the flue gas flowing through the duct and three filtration chambers before it exits through the outlet. The induction waste incinerator on the left side of the figure is the main combustion chamber in which the waste is burned to produce hot gas. The hot flue gas is introduced into the system through the hot gas from combustion (inlet). There is a color gradient in the simulation contour, which indicates that the flow has a high temperature and flow characteristics at this early stage. The gas then flows into Chamber 1, a flow distribution and initial cooling region. At this point, the flow begins to change direction and spatial distribution, resulting in a decrease in velocity and the occurrence of initial cooling. The flow then goes into Chamber 2, used for flow stabilization and heat dissipation.

In this chamber, the flow is more stable, and the heat released is more important because of changes in the flow path and the increased residence time of the gas in the system. Chamber 3: The final conditioning chamber prior to the outlet. Here the gas flow is further reduced and the temperature lowered so that the gas is now conditioned before it enters the final stage. The conditioned gas then flows out through the clean gas section to the outlet (exhaust). The velocity contour color distribution indicates that the flow from the inlet to the outlet is decelerating and stabilizing. The temperature distribution at the same time shows that the gas temperature decreases gradually in the entire system, which indicates that the multi-chamber configuration can work as a passive cooling mechanism. Moreover, the flow pattern shown in the figure is evidence that each chamber contributes to reducing the turbulence, flow stabilization, and better control of the thermal characteristics of the exhaust gas. The multi-chamber configuration can not only provide support for the filtration process by increasing residence time and particle-wall interaction but also contribute to controlling the distribution of exhaust gas velocity, pressure, and temperature, thus improving the overall performance of the gas treatment system (Hu et al., 2025; Huai et al., 2008; Qiu et al., 2025).

3.1. Velocity distribution and flow patterns

Fig. 2 shows the velocity distribution. It is discussed at five major points: the inlet, Chamber 1, Chamber 2, Chamber 3, and the outlet. The inlet is the first passageway where hot exhaust gas emitted from the combustion chamber enters the filtration system. In this case, the flow velocity is high at 10.78 m/s. When entering Chamber 1, the gas velocity reduces to 7.62 m/s because of the change in flow direction and expansion of the chamber. In chambers 2 and 3, the decrease continues at 5.18 m/s and 3.61 m/s, respectively, and reaches 2.54 m/s at the outlet. With this multi-chamber setup, it is possible to gradually reduce the kinetic energy of the exhaust gas (as can be seen by the reduction of velocity). Each chamber is a flow-conditioning zone in which the gas is diverted, the chambers are enlarged and the flow is dispersed. This mechanism lowers the flow and stabilizes it before it gets through the outlet. The plot of velocity cross-section shows that the flow distribution becomes more uniform after each chamber. The flow is still concentrated at the inlet and the velocity distribution in the following chambers becomes more homogeneous. The multi-chamber system provides an effective stabilization of the exhaust gas flow and improves the filtration process.

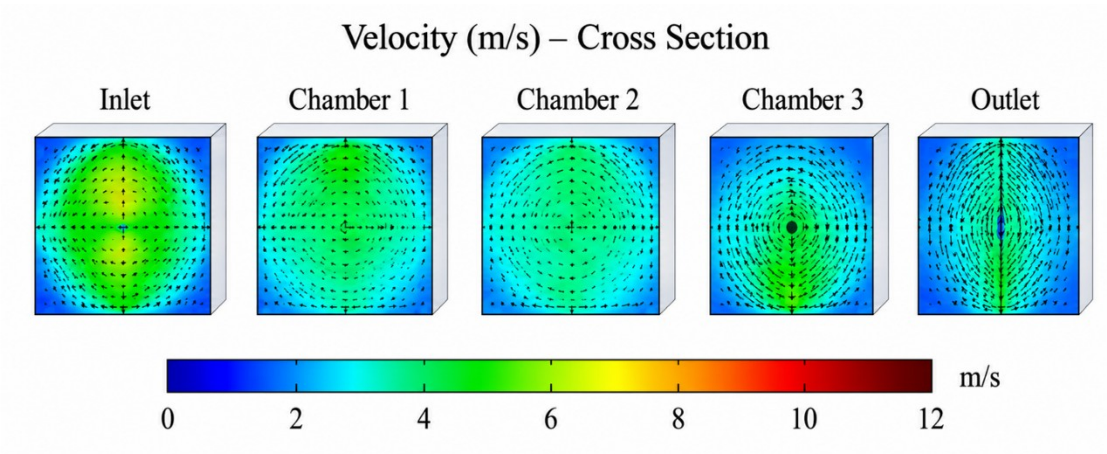

Fig. 2. Distribution of flow velocity at the inlet, chamber 1, chamber 2, chamber 3, and outlet cross sections of the multi-chamber filtration system.

3.2. Temperature distribution and cooling mechanism

Fig. 3 shows the temperature distribution across the cross-section at five main points of the system: inlet, chamber 1, chamber 2, chamber 3, and outlet. The color scale indicates the temperature range from 25°C to 275°C, with blue indicating low temperatures, green indicating medium temperatures, and yellow to red indicating high temperatures.

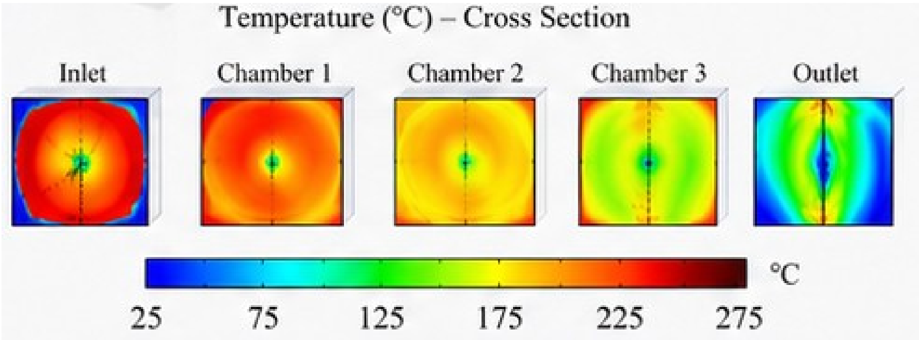

Fig. 3. Temperature distribution at the inlet, chambers, and outlet of the multi-chamber filtration system.

At the inlet, the temperature distribution is dominated by red and orange, which means that the exhaust gas still has a high temperature after leaving the combustion chamber. The high temperature is concentrated in a large cross-sectional area, which indicates that the cooling process is not significant in the initial flow stage. In the entrance of the gas into chamber 1, the temperature is still quite high, but there are starting to be changes in the heat distribution. The red-orange color is still dominant, but the heat intensity is more spread out. This effect is a consequence of the change in the geometry and the expansion of the chamber space. This means that chamber 1 is the first step in the process of heat dissipation.

In chamber 2 the temperature starts to drop more noticeably. The dominant color becomes yellow to orange, indicating that the heat is starting to drop off with respect to the inlet and chamber 1. The temperature distribution seems to be also more uniform, which indicates that the gas flow starts to be thermally stabilized. Chamber 3 is characterized by green and yellow colors, and the decline in temperature is more pronounced here. This means that the exhaust gas is cooled further before it arrives at the outlet. The third chamber is the final conditioning zone, in which the temperature of the gas approaches a safer condition for the final stage of discharge or filtration. At the outlet, the temperature distribution is dominated by blue-to-green colors, which means a strong decrease in the gas temperature. The blue area in the middle of the cross section is a low temperature zone. The green around it shows that the temperature is now more controlled than before. This means that the multi chamber system is capable of decreasing the temperature of the exhaust gas as it is expelled from the system. The total figure illustrates the multi-chamber configuration as a potential passive cooling mechanism. The decrease in temperature from inlet to outlet shows that every chamber works in the heat dissipation process through lengthening the residence time of the gas, changing the flow direction, and increasing the flow space. Therefore, the system works as a path for flue gas flow and a thermal control system to enhance the safety and efficiency of the filtration process.

3.3. Pressure distribution and turbulence

Simulation results show a gradual decrease in pressure from 88.6 Pa in the inlet to 42.3 Pa in chamber 1, then to -92.1 Pa in the outlet. The pressure drop indicates that energy is lost due to friction, change of flow direction, and geometric expansion inside the system.

Fig. 4 illustrates the pressure contour in a multi-chamber filtration system coupled with an induction waste incinerator. The color scale indicates the pressure in the range of about 120 Pa to -160 Pa, where red and orange correspond to relatively high pressure and blue to low or negative pressure. The pressure is relatively high in the vicinity of the combustion chamber and the first duct, shown by the dominance of yellow and orange colors. This condition means that the exhaust gas still has much thrust energy when it leaves the combustion chamber. The flow goes through the following ducts and chambers and the pressure starts to slowly decrease. This decrease is shown by the change of color to green then light blue and blue at the end of the system.

This pressure drop is characteristic of the pressure drop in flow path. There are many technical reasons for pressure loss: friction between gas and duct walls, change of flow direction at the elbow, expansion of the chamber space, and resistance from the filtration system. The pressure drop here indicates that the flow is being conditioned, not just that energy is lost. The pressure is gradually decreased, which reduces the kinetic energy of the gas, suppresses turbulence, and makes the flow more stable before reaching the outlet.

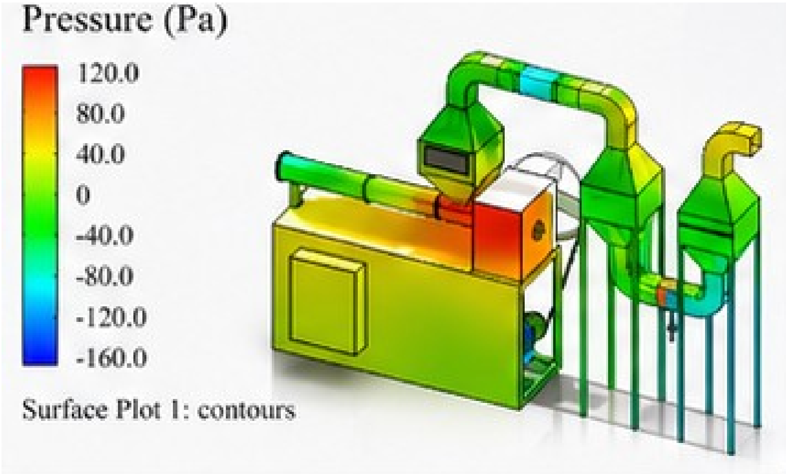

Fig. 4. Pressure distribution in the multi-chamber incinerator filtration system

These results are in accordance with the design principles of incinerator and flue gas treatment systems since the flow, pressure, and temperature characteristics should be controlled to improve the combustion performance and emission treatment. Huai et al. (2008) presented the use of CFD for incinerator shape and operating parameter optimization, including understanding of flow conditions and gas mixing in the incinerator. The study pointed out the importance of geometric design for the quality of flow and the performance of the incinerator system. The pressure drop from the inlet to the outlet indicates that the multi-chamber configuration is used to control the gas flow in a progressive manner, instead of allowing the gas to flow directly without any control.

These results also agree with the findings of Sarakikya et al. (2021), who reported that the CFD modeling of an incinerator can predict the temperature distribution and flow behavior inside the combustion chamber and outlet. The study proposed the importance of numerical assessment of fluid flow, temperature, and operational parameters in the design of the incinerator to ensure the system's efficiency. Thus, the visualization of pressure distribution in this study highlights the importance of using CFD simulation for design verification before the system is fabricated.

Moreover, flow barriers in the emission control unit contribute to the pressure drop from the filtration system perspective. Lin et al. (2020) demonstrated a remarkable effect of the pollution control devices of the incinerator (e.g., fabric filters) on the reduction of gaseous and particulate pollutants in the exhaust gas. But the emission control unit also modifies both the flow distribution and the system resistance. In this design, the lower pressure area at the outlet shows that the gas has passed through several flow barriers before it is released, including the duct, chamber, and filtration unit. More specifically, Morcos (1996) has shown that the pressure drop in a bag filter system increases with increasing dust load on the surface of the filter. The dust accumulation was not experimentally tested in the study; however, the results of the pressure contour suggest an important trend: the presence of a filtration system and changes in the geometry can create pressure drops that need to be considered in the design. Thus, a multi-chamber system has to be designed to decrease the gas velocity and temperature without excessive pressure drag (Doppalapudi et al., 2025; Dula et al., 2024; Smail & Mohiuddin, 2020).

The comparison of these simulation results with the previous research indicates that the pressure drop pattern of the proposed system can be considered engineering sound. The high pressure at the beginning indicates the flow boost from the combustion chamber, and the low pressure at the end indicates that the flow energy has been reduced after passing through the chamber and filtration channels. This corresponds to the goals of the multi-chamber design: to have a more stable flow, to extend the residence time of the gas, and to increase the efficiency of the filtration process before the exit of the exhaust gas into the environment.

4. Conclusion

This study was performed to develop and evaluate a multi-chamber filtration system coupled with a small-scale induction waste incinerator as suggested in the Introduction. The main expectation was that the multi-chamber design could improve the exhaust gas conditioning by reducing the flow velocity, increasing the residence time, stabilizing the gas flow, and helping the heat dissipation before the gas arrives at the outlet. The results presented in the Results and Discussion section confirm these expectations. The CFD simulation showed a gradual reduction in gas velocity from 10.78 m/s at the inlet to 2.54 m/s at the outlet, indicating that each chamber contributed to the reduction in kinetic energy of the exhaust gas and generation of a more stable flow pattern. This finding proves the compatibility of the research objective with the simulation results. The thermal analysis also showed that the proposed system reduced the exhaust gas temperature in a sequential manner along the flow path. The temperature distribution ranged from high temperature zones at the inlet to low and controlled temperature zones at the outlet. This indicates that the multi-chamber system can act as a passive cooling mechanism through chamber expansion, flow redirection, and increased residence time. The pressure distribution also showed a gradual pressure drop through the system, indicating controlled flow resistance due to duct geometry, chamber configuration, and filtration pathways. These results confirm the initial assumption that the performance of exhaust gas treatment in small-scale incinerator systems can be improved by a compact multi-chamber design. The proposed multi-chamber filtration system appears to be a promising potential practical, compact, and economical solution to enhance emission control in small-scale induction waste incinerators. The results show that the system can help stabilize the flow, dissipate the heat, and condition the gas before releasing it into the environment. However, this work is limited to the numerical simulation for now. Therefore, future work should be the experimental validation on a physical prototype, the measurement of particulate and gaseous emissions, the evaluation of filtration efficiency, and the long-term performance assessment under real operating conditions. Further development may also include optimization of the chamber geometry, inclusion of additional filter media, and evaluation of the applicability of the system for community-based or small-scale waste treatment facilities.

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